- ○ **Computers for Windows:**

Interactive Optimization Tools for Architects designing openings in walls (IOTA)

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ABSTRACT

Size, shape and disposition of windows in walls has long been an integral expression of style in architecture. As buildings have grown taller the relationships of the windows to the ground plane and to the surrounding environments have become more complex and difficult to predict. Traditionally architects have had to use their own knowledge, experience and feelings in the design of windows. There may be few, if any, scientific bases for their decisions. The difficulty in making good design decisions is compounded because many criteria for window design, such as daylight, sunlight, ventilation, sound, view and privacy have to be considered simultaneously. It is here that computers can help, on the one hand, by providing 'expert knowledge' so that architects can consult the cumulative knowledge database before making a decision, whilst on the other hand, evaluations of the decisions taken can be compared with a given standard or with alternative solutions.

'Expert knowledge' provision has been made possible by the introduction of hypertext, the advancement of the world wide web and the development of large scale data-storage media. Much of the computer's value to the architects lies in its ability to assist in the evaluation of a range of performance criteria. Without the help of a computer, architects are faced with impossibly complex arrays of solutions. This paper illustrates an evaluation tool for two factors which are important to the window design. The two factors to be investigated in this paper are sunlighting and views out of windows.

Sunlight is a quantitative factor that can theoretically be assessed by some mathematical formulae provided there is sufficient information for calculation but when total cumulative effects of insolation through the different seasons is required, in addition to yearly figures, a design in real-time evolution requires substantial computing power. Views out of windows are qualitative and subjective. They present difficulties in measurement by the use of conventional mathematical tools. These two fields of impact in window design are explored to demonstrate how computers can be used in assessing various options to produce optimal design solutions. This paper explains the methodologies, theories and principles underlying these evaluation tools. It also illustrates how an evaluation tool can be used as a design tool during the design process.

Keywords: Sunlight, View, Window Design, Performance Evaluation, Expert Systems, Simulation, Fuzzy Logic

Introduction

Size, shape and disposition of windows in walls has long been an integral expression of style in architecture. The rules governing the relationships of solid and void, scale, rhythm and proportion have varied in their complexities over time and where traditionally available building materials and techniques limited the opening size nowadays with advanced structures and glass windows can be of practically any shape or form.

As the restrictions of construction have been cast off new imperatives have been imposed: the need for green production processes and for energy efficiency throughout the lifespan of the building. The relationships of the windows to the ground plane and to the surrounding environments have become more complex and difficult to predict as buildings have grown taller. The impacts of high-rise buildings, one on the other, produce results that are difficult, if not impossible, to simulate using conventional methodologies.

Traditionally, architects have had to use their own knowledge, experience and feelings in the design of windows. There may be few, if any, scientific bases for their decisions. The difficulty in making good design decisions is compounded because many criteria for window design, such as daylight, sunlight, ventilation, sound, view and privacy have to be considered simultaneously. It is here that computers can help, on the one hand, by providing ‘expert knowledge’ so that architects can consult the cumulative knowledge database before making a decision, whilst on the other hand, evaluations of the decisions taken can be compared with a given standard or with alternative solutions.

‘Expert knowledge’ provision has been made possible by the introduction of hypertext, the advancement of the world wide web and the development of large scale data-storage media. Relevant information worldwide can be accessed easily through the internet. The raw information is in pieces and in a state of relative disorder. Computers can be used as data organizers to manage the information in organized formats. Will, Wong and Chu (1996) showed an example of using hypermedia applications in the building industry for curtain wall design, fabrication, erection and maintenance by applying these organizational/techniques to sample high-rise buildings in Hong Kong.

Much of the computer’s value to the architects lies in its ability to assist in the evaluation of a range of performance criteria. Without the help of a computer, architects are faced with impossibly complex arrays of solutions. Evaluation factors can be roughly classified into two categories, quantitative and qualitative. Conventionally only engineering performances have been attempted but this paper illustrates how qualitative aspects such as views and users' satisfaction with windows can be evaluated. For example sunlight is a quantitative factor that can theoretically be assessed by some given mathematical formulae provided there is sufficient information for calculation. But when total cumulative effects of insolation through the different seasons is required, in addition to yearly figures, a design in real-time evolution requires substantial computing power. Conventional methods such as graphical representations, photographic methods, model simulations and on-site inspections are too time-consuming to incorporate into the analysis and design changes mean time-consuming and frustrating delays. This paper suggests a way of analyzing the sunlight using 3D computer models to simulate the sunlight direction and intensity at any time in a year. Additionally other factors such as sun control devices, glass types, 'smart' glasses, overall reflectivity/absorption characteristics, laser-cut deflectors and active light scoops can be accommodated within the tool if required. The overall result of the sunlighting performance can be seen on the computer screen in real time. Architects can receive real-time feedback when any of the parameters are changed.

Unlike sunlight, views being qualitative and subjective present difficulties in measurement by the use of conventional mathematical tools. This paper introduces another approach to this analysis – fuzzy reasoning. Fuzzy logic is used because there is no simple applicable mathematical model and processing of linguistically formatted 'expert knowledge' is required. The performance of a building design with respect to the visual aspects is tested against the existing surrounding context by fuzzy reasoning. Similarly as for the evaluation tool for sunlight, architects can change the design parameters of the building and can obtain real-time responses to the changes.

The main objective of this system is to change general design approaches by introducing a new comprehensive design tool for the designers. This paper explains the methodologies, theories and principles underlying these evaluation tools. Two fields of impact, sunlight and view, in window design are explored to demonstrate how computers can be used in assessing various options to produce optimal design solutions.

Evaluation of Sunlighting

As green architecture is playing an important in modern architecture, sunglighting becomes a significant aspect for consideration when designing a building. Ushering sunlight into buildings, not only, can minimize the demand on energy for artificial lighting, but also, can be used to decorate the interior. Sunlight can also give the occupants a warm feeling of being closer to nature.

In order to optimize sunlighting, it is necessary to know precisely where the sun interfaces with the building at an early stage of the design process. The most commonly used methods in studying the penetration of sunlight into buildings are sunpath diagrams, such as stereographic diagrams and gnomonic diagrams. A stereographic diagram is a projection of the sun position onto a plane with the point of testing at the center of the plane. The sun is considered to be rotating about the earth across the sky vault in the shape of a hemisphere. The path of the sun on the vault is projected onto a plane which is the horizon. Figure 1 shows a stereographic diagram.

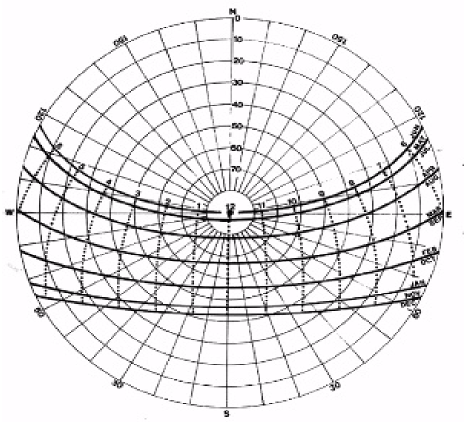

Figure 1

A gnomonic diagram is similar to the stereographic diagram except that the sunpath is projected onto the wall of the building instead of the horizon.

In order to analyze the penetration of sunlight into the building, it is necessary to plot the windows on the sunpath diagrams. For the stereographic diagram, the window outlines must be plotted with correct distortion on a prescribed stereographic diagram. A stereographic diagram can usually be obtained from a local weather bureau. Window outlines can be marked on the diagram with the help of a shadow angle protractor but is not easy to produce an accurate diagram nor to read the result of the analysis from the stereographic diagrams. It is, furthermore, impossible to read from the diagram how far can the sunlight can penetrate into the building. For the gnomonic diagram, there is no problem in plotting the window outlines because they are not distorted. However, unlike stereographic diagrams, a gnomonic diagram is dedicated for a particular wall of the building at a particular direction. Many gnomonic diagrams may be needed to investigate all the windows in a building. Due to the weaknesses of these graphical analytical methods, the effect and impact of sunlighting on the building cannot be accurately estimated. The designer may also need to accompany these graphical methods with some *in-situ* analytical tools, such as photography, a TNO insolation meter, mirror dials, or mechanical tracking devices, to assess this factor so as to produce a more reliable result (CIBSE 1987). However, the primary limitation of these *in-situ* analytical methods is that these tests are all based on the existing environment of the site. The impact of a new building on the existing environment cannot be seen from the analysis. The designers have to predict the effects of the new building on the existing environment using their own knowledge and experience.

This problem can be solved by the use of a model. Shadows on the buildings and the relationship between the new building and the existing environment can be observed from the model directly. This can be achieved by placing the model in a sighting device. Shining of the sunlight can be simulated either by rotating the model under the "sunlight" or by moving the light source around the model. Most of the weaknesses of those graphical prediction methods and *in-situ* analytical methods can be overcome. However it is still hard to see the penetration of sunlight within the building. An endoscope may be used to look at the internal aspects of the building. As a physical model of the building is needed, the testing can only be done at the later stages of the design process.

In this paper, computers are proposed for the analysis of the sunlighting. The system proposed in this paper places special emphasis on its use as an design tool rather than as an evaluation tool at the end of the design process. Designers can obtain important design information from this system. The module provides an interactive interface for designers to manipulate the design. The designer can change the form of the building, orientation of the building, shape and size of the windows and the glazing types. Weather information is also incorporated into the module.

Methodologies

This module simulates a sundial system in a virtual environment. The sun is treated as a point source. The program reads in a 3D model of the landscape provided by the designer. The designer then locates the site boundary on the pseudo model. A preliminary building of a rectangular shape is then placed inside the boundary. The preliminary building covers the site boundary as much as possible. By default the height of the building is set to be the maximum height governed by the plot ratio provided by the designer. The designer can put the plot ratio into a data file which will be read by the program immediately after reading the landscape model. The interactive interface provided by the module can be used to change this value afterwards. The preliminary building can be tested against the sunlighting factor as the designer requires. The results of the test can be visualized immediately.

This module uses a set of solar positions data described in another data file provided by the user. The file contains the following fields: date, time, azimuth and altitude of the sun at the corresponding date and time. This data can either be obtained from the relevant bureau of the local government or be computed by available software. The IPW (Image Processing Workbench) by the U. S. Environmental Protection Agency, for example, provides a very useful program for computing the solar position at various hours, dates and latitudes.

For the sake of testing, the building under evaluation is divided into square blocks of dimensions 3m in length and width. The height of each block is the floor to floor height of the building. The availability of sunlight from a point of observation inside a block is determined by emitting rays from that point towards the positions of the sun at various hours and dates. By eliminating those rays blocked by other surrounding buildings, the time at which the point of observation can be illuminated can be found, and thus the duration of "possible" sunshine. This value can be very useful to the designer if the goal is to maximize the sunshine duration, especially for areas in northern regions such as northern Europe and northern Asia.

However, this is just the maximum possible sunshine duration if it was sunny all the time. In order to simulate the real situation, the probability of bright sunshine is incorporated into this module. As a result one of the reference values provided by this module is the sunshine duration.

$$SunshineDuration = \sum R_i P_i$$

$$\text{where} \quad R_i = \begin{cases} 1 & \text{if the ray is not blocked by other surrounding building} \\ 0 & \text{if the ray is blocked by other surrounding building} \end{cases}$$

$$P_i = \text{Probability of bright sunshine at the } i^{th} \text{ month in the year}$$

Besides the probability of sun, the intensity of the sunlight also varies with time and dates. The intensity of sunlight for summer dates is undoubtedly higher than that for winter dates. The sunlight intensity at noon is the highest within a day. By multiplying the sunshine duration by the intensity factor, the total solar energy penetrating into the building can be roughly predicted.

$$Solar\ Energy\ Gain \propto \sum R_i I_i$$

$$\text{where} \quad R_i = \begin{cases} 1 & \text{if the ray is not blocked by any other surrounding building} \\ 0 & \text{if the ray is blocked by other surrounding building} \end{cases}$$

$$I_i = \text{Total Solar Radiation at the } i^{th} \text{ month}$$

By default, the probability of sun and the solar radiation at various time in Hong Kong are used. The user can change these values by changing the data file. Table 1 shows the probability of bright sunshine and the solar radiation at various dates in Hong Kong respectively.

Month	Probability of Bright Sunshine (%)	Solar Radiation (MJ/m^2)
Jan	45	11.63
Feb	30	10.69
Mar	26	11.24
Apr	29	13.14
May	38	16.12
Jun	40	16.55
Jul	56	19.15
Aug	52	17.61
Sep	49	16.49
Oct	54	15.46
Nov	55	13.39
Dec	54	12.03

Source: Monthly Weather Summary February 1997, Royal Observatory, Hong Kong

Table 1

The designer can choose one of these evaluation values, such as the sunshine duration and the solar energy gain, for display. The results of the evaluation are shown on the model of the building as different shading colors. The color goes from bright red to green and then to deep blue. For the sunshine duration, red represents long duration, blue represents short. For the energy gain, red means high energy, blue means low. For the ease of looking at the internal spaces of the building, this module can decompose the building into individual floors. Figure 2 and Figure 3 show the sample outputs of this module.

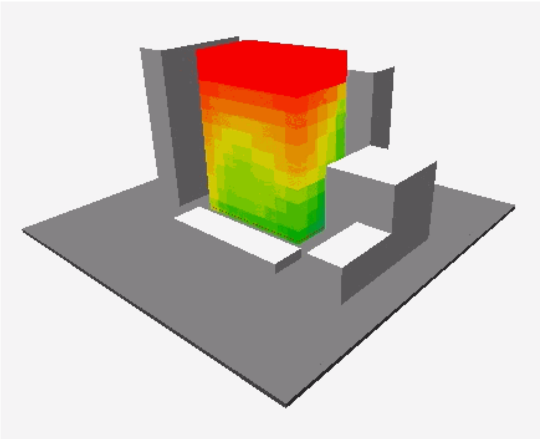
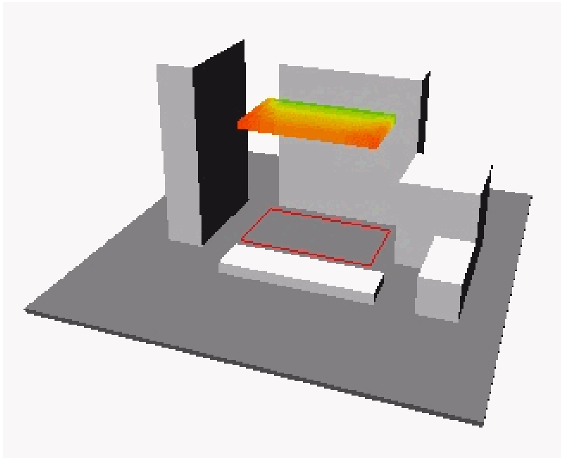

Figure 2 Figure 3

Although the form of the preliminary building is set to be rectangular by default, it can be changed at will by the designer to any other shape. The mechanism of changing the forms of the buildings is briefly described later in this paper under the Modelling Tool session. Besides the building form, the size and shape of the windows can also be manipulated in this module. The designers can make the judgment on the choice of shape and size of the windows based on the evaluation result. In this module, all the walls are assumed to be transparent at the beginning so that the designer can see the immediate result of choosing the site, setting the orientation and choosing the form of the building. The wall is no longer transparent once a window of precise shape and size is defined for the wall. The program will compute the penetration of the rays according to the opening of the windows.

Modelling Tool

For use as a design tool, real-time 3D solid modelling up to and including virtual reality environments is the best choice among computer graphics techniques because of its realism in visualization and its ability to adapt to change. In general practice, modelling in the surrounding environment is either neglected or kept at a very low level of detail because a highly detailed environment with multiple 3D models requires very high-end computing power. Putting additional less-important details into the model will decrease the performance of the computer without a comparable increase in accuracy of response. A methodology for providing realistic 3D computer modelling environments for architecture must therefore be fast in the input process, elegant in storage demands and quickly alterable as the design progresses. Additionally, the user must have command of the choice of viewpoint and of the camera paths through the system.

The objective of this module is to provide an interactive design environment for designers. Also the system must be able to maintain the 3D models at a high degree of realism without significant demands on the computational power. A realistic model not only can give an impression to the viewer, but also can help the designer to forecast the impact of the real environment on the building design, and vice versa. The output of this module, that is the design, can be tested in real-time by the other evaluation modules which can compare or measure the performance of the design with a known database. As the design work under study is in a digital format, the designer is at liberty to preview the preliminary results at a early stage.

Methodologies

The Context

In order to make the 3D model of the site environment realistic without increasing the loading on the computational power, texture mapping is incorporated in this modelling tool. Real-time texture mapping capabilities of modern graphic workstations are harnessed with respect to their applications in the interactive design process. The advantage of texture mapping is that photo-realistic visualization can be achieved easily without having to increase the complexity of the 3D model. The demand on extra computational power is low if there is a hardware texture mapping device. As a result real-time photo-realistic 3D computer models can be visualized on the computer monitors while the designers are making their buildings using this modelling tool.

Texture mapping techniques are used to simulate complex building images. A picture of a complicated facade can be mapped onto a simple surface to give a photo-realistic appearance to what, in essence, is a basic geometric solid. Texture mapping offers a powerful technique for adding realism to computer-generated scenes of simulated environments without the recourse to high performance graphic hardware and complex input programming.

The texture mapping techniques developed are not only applicable to basic geometric solids, but also to complex three-dimensional objects. Trees, for instance, that form an integral element of the landscape, can also be constructed by texture mapping. Traditionally, 3D models of trees are usually used in the architectural rendering. As the geometry of tree is quite complex, unnecessary rendering overhead will be produced for handling the trees. By texture mapping techniques, the model of a tree can be reduced to be few 3D faces. Figure 7a shows the rendering of a detailed 3D model of a tree which composed of 650 faces whilst Figure 7b shows another tree rendering with texture mapping which is just consisted of 32 faces but seems to be more realistic.

(a) Rendering of a 3D tree model (b) Texture Mapping

Figure 7

The Building Design

Besides the environmental context, the main concern of this modelling tool is the building design. In the early design stages of the design process, most decisions about the design are not yet made nor is the geometrical information of the design stabilized. Most of the existing commercial computer-aided design software are not suitable for the early design stages because they all require a certain amount of information about the design geometry in order to build the 3D model. They do not, moreover, respond easily to the amendments of the design once the 3D model is input. This modelling tool is built so as to make the use of the evaluation tool at the earliest design stages. The detail of this modelling tool is fully described in the paper for the CAAD Futures ’97 Conference (Li and Will, 1997). An extended summary of this module is described in this section.

For the sake of evaluation and of presentation of the results, the shapes of the buildings are approximated by square blocks of 3m in length and width. The height of the block is the floor to floor height of the building. A block represents a unit of space which may not necessarily be empty. There may be rooms, corridors, staircases or internal partitions penetrating a block. A designer can start designing the building form by specifying the number of floors, location and dimensions of the building on the site. As a default value a building of rectangular form is assembled accordingly as a stack of blocks which occupies the whole site as much as possible. The default height of the building is set to be the maximum height under the plot ratio provided by the designer.

The designer can remove unnecessary cubes from the rectangular block to form the shape that is required. When the basic 3D building form is established, the designer can then insert different elements such as slabs, windows, cores and internal partitions into the massing model. This module also provides an interactive interface for the designers to change the outermost square blocks to polyhedrons so that the building form can be approximated more accurately. The designers can add or remove vertices on the blocks. In addition to changing the building block by block, the whole building can be extruded upward or compressed downward to form a tall and slim building or a short and flat building so that the building can be changed to other shapes easily whilst keeping the plot ratio constant. The whole building model can be moved and rotated freely within the site boundary so that the designer can choose the best position for the building related to the design criteria.

Interactive Visualization

As in all true 3D modelling systems the ability to view solid objects within an environment and to move between around these objects is a prime objective. This module provides these attributes but most importantly, in addition, it also permits the simulation of a view from within an object viz. the building under study. The main goal of this module is to give a preview of scenes from the non-existing building as it progresses through the design iterations.

Each window of the building design contains the information of its default view point and a default viewing direction. The direction is horizontal to the ground. Once the viewer activates the window, the computer can switch to the view available from that particular window. In this 3D environment, the designers can then walk around virtually and freely inside the building and change the viewing direction at will. Figure 8 shows an example of a view out through a window. The surrounding buildings seen are all formed by mapping textures on simple rectangular blocks.

Figure 8

Conclusion

A design tool is a tool that a designer can use integrally during the design process. It can be used either in recording the design or in exploring the designer's inspiration. To a certain extent, assisting designers in making a better decision is also a part of the functionality of a design tool. Evaluation tools are conventionally used after the design process because the design phase and evaluation phase normally have to be clearly separated when interactivity of computing is limited. The function of evaluation tools is to provide information to the architects about their design so that the architects can amend their design accordingly. However, in the traditional practice, an architectural design can be tested only after a physical model of the preliminary design is made because no physical model can be built without an almost completed design scheme. When problems are found at this stage, making changes is tedious. Making major changes may lead to a delay of the project and an increase in the cost. As a result evaluation tools are limited in their applicability.

With the help of high speed computers, nowadays, the situation has changed. Physical models are no longer needed for most performance testing. These tests can be done electronically with by the use of pseudo models or abstract data representations. These design representation methods are more dynamic to the changes in the design. It is not necessary for the designers to postpone the testing processes to the end of the design process. The designers can assess their designs by themselves at any time they feel necessary and thus the results of the evaluations can be incorporated easily and at an early stage into their designs. Thus an interactive evaluation tool can also be treated as a design tool depending on the usage. Besides introducing the IOTA system, another purpose of this paper is to demonstrate the use of evaluation tools in the design processes as a method of assisting architects in making better design decisions. The two evaluation factors considered in this paper are sunlighting and the quality of view. Sunlighting is a quantitative factor that can be computed by mathematical formulae provided there is sufficient information for the calculations whereas view is a qualitative aspect which is very difficult to be measured using conventional mathematical models. This paper shows that computers can handle both qualitative and quantitative factors with a high degree of interactivity.

In this paper, a comprehensive computer system, the Interactive Optimization Tools for Architects System (IOTA), for architecture is proposed. The main objective of this system is to change general design approaches by introducing a new comprehensive design tool for the designers. Instead of using computers as drafting tools only, they can be used in a more constructive way and provide supporting information, analyses and comparisons. Building forms, floor to floor heights, floor to ceiling heights, window placement, slabs, core structures and internal partitions are factors that can be evaluated in this system with respect to the sunlighting, the view out, etc. Designers can receive real-time feedback when any of the parameters are changed. They can thus give solid evidence to support their decisions on the design.

Three modules of the system, the evaluation module on the sunlighting, the evaluation module on the quality of view and the modelling tool, are introduced. By the same token, other factors, such as wind load, fire safety, ventilation, sound, means of escape, etc., can also be evaluated by similar processes. More modules can be added to the system to enhance its ability to handle more parameters and to provide more thorough and logical solutions for the designer. The modules are plug-ins and can be used individually or in concert. Obviously the more plug-ins that are switched on the greater the demand on computing power and the slower the overall process but the advantage is that more realistic and rational decisions can be made.

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