TOOLS FOR DESIGNING CLIMATE RESPONSIVE BUILDINGS

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ABSTRACT

The term 'Computer-Aided Design' for some people is reserved exclusively for drafting systems that provide a 2- or 3-dimensional graphic representation of a building. But many other issues bear on the final form of a building, issues that initially cannot be represented in a drawing of that building. These issues include thermal performance, lighting, economics, behavioral factors, acoustics, structural safety, etc. Architects in the future will have a whole kit of computer-aided design tools to help them address all of these non-graphic issues.

A "design tool" might be defined as something that helps an architect make a better decision. But the development of design tools also has a hidden agenda: they leave the architect with a richer understanding of the underlying issues involved. In other words, they also teach.

INTRODUCTION

It can be argued that the reason the architecture profession has such a miserable record in designing climate responsive buildings is that no one has developed for them the tools they need to address these issues. For instance, an architect may express a sincere desire to design a building that responds precisely and elegantly to its unique spot on the planet, but what tools are available? Yellow trace and soft pencils? Auto-CAD? DOE-2? Givoni's or Watson's books? Weather Bureau reports? Over the past twelve years at UCLA we have developed half dozen different design tools to help address environmental and energy issues.

A critical ingredient in the effectiveness of these design tools is that they have been developed specifically for architects, with special attention to more effective methods of communicating with right-brain thinkers. This research effort at UCLA has directly influenced our curriculum. For instance, in the course in Building Climatology these
design tools have been integrated into a series of weekly projects that evolve by the end of the course into a final building design. We have learned a great deal from this experience about how to develop better design tools, and we have even had some success when these design tools reach architectural practice.

THE NEED TO UNDERSTANDING THE LOCAL CLIMATE

The first kind of information that the architect needs is a detailed understanding of what the local climate is like. What are its unique assets and liabilities? How can it be harnessed to create comfortable interior environments? What design guidance can be extracted from the data? Shelves full of weather data are available, but how can it all be translated into a form that is useful for architects? Normal means and extremes data summaries are published for hundreds of stations, but tables of numbers do not communicate a very clear image, certainly not to architects. They need a design tool that shows a richly detailed graphic picture of their climate, but more importantly they need some help in translating these data into design guidelines.

CLIMATE CONSULTANT: Weather data for all 8760 hours in a typical meteorological year (TMY) are now available for hundreds of stations. Selected data for some stations are commercially available on one single 360 KB floppy. CLIMATE CONSULTANT reads this data, statistically analyzes it, and plots it out in various graphic formats. The objective is to make the details of the climate more comprehensible to visually-oriented (right-brain) architects.

The plot of dry bulb temperatures is one of the simplest and easiest to understand. It shows the monthly average high and low, record high and low, along with an estimate of the design envelope (Fig. 1). The design envelope is defined as the smallest range that contains 95% of all temperature recordings for that month. When the occupant’s comfort zone is added to this plot, the architect can see at a glance a great deal more about the site conditions than can be learned by looking at the table of numbers containing these same data. Additional study will reward the architect with a more detailed understanding of the subtle transitions that occur in the design envelope throughout the year as outdoor temperatures sweep into and out of the comfort zone.

Another cut through these same data can be plotted as a kind of topographic map on a timetable, with the 24-hours of the day on one axis and the 365 days of the year on the other axis (Fig. 2). It gives a concise image of the time of day and days if the year when the outside environment is in the comfort range, when it is too hot, when it is too cold, and when it is below freezing or even sub-zero. If these temperatures are aggregated into weekly or monthly averages, the picture becomes more general and easier to grasp. But when data are plotted for each hour of each day the picture is more detailed and the architect can better understand the patterns of short term phenomena and weather anomalies such as infrequent wind events like our Santa Ana’s in Southern California. This plot can tell, for instance, at what hour of the day and what days of
Figure 1: Annual Temperatures plotted by CLIMATE CONSULTANT show how often design temperatures fell within the comfort zone.

Figure 2: The Timetable of Bioclimatic Needs plotted by CLIMATE CONSULTANT shows at what times dry bulb temperatures are too hot or too cold for comfort.

Figure 3: On the Psychrometric Chart CLIMATE CONSULTANT plots THV data for all 8760 hours of the year. This scatter plot shows high mass (7 and 8) will be a successful strategy.

Figure 4: A list of Design Guidelines is printed out by CLIMATE CONSULTANT in rank order according to the percentage of hours effective.
year a window should be totally shaded, or when it should be in full sun for passive solar heating.

The psychrometric chart is perhaps the most powerful way to display climatological data in a format that can give the architect direct design guidance (Fig. 3). It has dry bulb temperatures across the bottom axis and absolute humidity up the vertical axis. Watching the hour-by-hour sequence of a year’s worth of data points ‘zoom’ around the psychrometric chart gives the architect a new image of the climate. If each day’s data traces out long flat loops in the lower right-hand of the chart, it signals a hot arid climate with low humidity, clear hot days and cool nights. On the other hand, if the daily loops form narrow, tight spirals in the upper right corner of the chart, the architect should expect overcast, hot humid conditions. When the hour-by-hour data points seem to get stuck on the saturation curve at the left edge of the chart, it means the site will be subjected to long periods of fog or rain. In a classic Mediterranean climate the data points seem to wander leisurely in and out of the comfort zone in the middle of the chart. If it is cold and clear in winter, the data points will show a large diurnal variation.

This program can also aggregate and plot many other kinds of data in the form of bar charts, including percentage sunshine, inches of precipitation, wind velocities, or the number of clear, partly cloudy, and cloudy days.

DESIGN GUIDANCE DERIVED FROM THE CLIMATE

Being given a complete description of the climate, no matter how richly detailed or elegantly analyzed, still leaves the architect a long way from the final building design. The architect needs a design tool that analyzes the raw climate data, recommends an overall building design strategy, and then produces a detailed list of design guidelines or instructions about how to put together such a building.

DESIGN GUIDELINES: Translating climatic data into architectural design guidelines is a classic problem for an expert system. In fact, CLIMATE CONSULTANT integrates the expertise of Baruch Givoni in order to identify the best overall building design strategy on the psychrometric chart, for summer and for winter. It uses the expertise of Don Watson and Ken Labs to produce a detailed list of design guidelines, based on the scatter-plot of hours on the psychrometric chart (Fig. 4).

Givoni has blocked out different zones to show when indoor comfort conditions can be achieved by using various building design strategies such as high mass, natural ventilation, evaporative cooling, or passive solar heating. When each hour of the year is plotted on Givoni’s chart, the resulting scatter-plot gives the architect a clear picture of the relative effectiveness of each of these different building design strategies.

To identify the best overall building strategy, the program simply counts the hours during the year that fall into each zone on the psychrometric chart and then prints out the
percentage of time each design strategy will be able to maintain human thermal comfort. Because some of the summer cooling strategy zones overlap, the total percentages of time the different strategies are effective might add up to more than 100%. In fact, two quite different design strategies may have equally high percentages and thus will be equally effective. In this case the architect can make the choice on the basis of compatibility of the best summer design strategy with the winter heating period strategy.

Still more design-relevant information can be shown on this same plot if each hour is coded to show the co-incidence of a third variable. For instance, the wind speeds from 0 to 5 mph might be shown by a red dot, 6 to 10 mph by a yellow dot, and above 10 mph by blue. If it turns out that most of the dots falling within the ventilation design strategy zone are red, then natural ventilation probably will not be successful most of the time. On the other hand if they are predominantly blue, then it tells the architect that natural ventilation has a good chance of success. Other climate variables can also be plotted in this same way, for instance the proportion of orange dots in the passive solar zone could tell the architect something about the likelihood of clear skies during those hours of the year. Based on the data that CLIMATE CONSULTANT plots out on the psychrometric chart, the architect can establish the best overall building design strategy for summer and for winter.

The program contains a list of over eighty individual design guidelines, each of which applies to certain specific zones on the psychrometric chart. Once the overall strategy has been selected, a list of applicable guidelines is printed out in order according to the number of hours each is effective. The architect can define the period of interest to anything from the full year to only selected hours of the day (i.e., during office hours) or certain months of the year (i.e., during the school year). If the architect intends to design a modifiable envelope, the two separate periods can be defined and two different sets of design guidelines will be printed out.

MODELING SUN MOTION

Up to this point our computerized design tools have helped the architect understand the climate, select the best overall building design strategy, and identify a set of detailed design guidelines. The architect now needs a set of design tools that address tangible physical three-dimensional problems like how to protect a window from the sun in summer yet collect solar heat in winter.

SOLAR-2: One of the first design tools we developed allows an architect to design a window and add an overhang and/or fins, then see the sunlight penetration patterns plotted out through the room for each hour of each month (Fig. 5). SOLAR-2 also can plot an axonometric view to help the designer conceptualize how the sun moves relative to the building (Fig 6). It can print out tables of the percentage of the window in full sun and the direct solar radiation load on the glass.
Figure 5: The sunlight penetration patterns across the floor of a room can be plotted by SOLAR-3 for any window with any combination of fins and overhang at any orientation for any month.

Figure 6: SOLAR-3 can also plot an axonometric to show the designer how well the sun shades work at any hour.

Figure 7: Any kind of wall or roof can be designed using OPAQUE. The temperature drop is plotted across the section from indoors to outdoors.

Figure 8: OPAQUE also plots various measures of wall performance throughout the year, such as heat gain/loss.
With this design tool the architect can see immediately a picture showing exactly which hours on which months the sun reaches the glass and in fact where it falls within the room. This can then be compared with against the timetable printed out by CLIMATE CONSULTANT that shows on which hours of which months the windows should be shaded, and which hours it needs to be fully exposed for passive solar gain.

PREDICTING WALL AND ROOF PERFORMANCE

The architect also needs a design tool that shows how to design a climatologically appropriate wall and roof.

OPAQUE: One of our newest design tools is called OPAQUE. It actually is the fourth generation of one of our earlier programs called SOLAR-3. It allows the architect to design an opaque wall or roof section of any material, painted any color, for any orientation and at any latitude (Fig. 7). It then displays a whole series of plots of hour-by-hour performance, for any month according to criterion such as heat gain and loss, surface (sol-air) temperature, or solar radiation incident in the surface (Fig. 8). It displays these data in a three dimensional plot for every hour of every month of the year, which helps the architect check if this design is meeting the guidelines for each different season. The architect can immediately see how something as apparently insignificant as changing surface color causes a huge impact on surface temperature, which in turn directly affects heat gain. Even more impressive is seeing the way adding mass can flatten out the heat gain/loss curve and push it backwards in time. It is also enlightening to see how something as seemingly minor as switching the location of the insulation and mass in a wall section produces unexpected results. OPAQUE also draws a cross section of the wall or roof detail, then calculates and plots the temperature drop across it from inside air to outdoor air temperature. This can help the architect see if there will be any condensation problems in the air space or within the insulation.

SEEING THE WHOLE BUILDING'S PERFORMANCE

With the set of design tools described thus far, the architect can go from raw weather data to the fine tuned performance of various separate components of the building envelope. The final piece of the puzzle is a design tool that analyzes the entire building and displays its hour-by-hour performance as a single integrated picture.

SOLAR-5: Here all the pieces begin to come together. The most complex of our design tools is SOLAR-5. It has been in development since 1978 and now contains dozens of unique features which make it both powerful and user-friendly (Fig. 9).

One of the unique features of SOLAR-5 is its expert system, which creates a climatologically appropriate basecase building based on just four pieces of information supplied by the architect: building type, climate station, square footage, number of stories.
Figure 9: A collection of screen images from SOLAR-8 gives a flavor of how the architect can work interactively with this design tool, beginning with the tutorial that shows how to interpret the graphic plots, and running through the final HVAC output, total energy costs, and even showing a way to compare the total loads of two different designs.
The architect uses this basecase to compare the performance of all subsequent buildings to see if the design is evolving in the right direction.

For a model of this complexity, the output printed in a table of numbers would be essentially incomprehensible, overwhelming, and therefore ultimately would have little or no impact on most architects' design process. An important feature of SOLAR-5 is that it displays this annual thermal performance data as a three-dimensional picture showing each hour of each month. Right-brain thinkers such as architects are amazingly adept at understanding these 3-D plots and extracting some very subtle distinctions. A built-in tutorial shows first-time users that the heat gain plot of good passive buildings is "saddle-shaped," while bad passive buildings look like "heat mountains". These two graphic metaphors are powerful enough to quickly push the user far up on the learning curve. New users soon begin making impressive design manipulations based on their understanding of such concepts.

As a tool for the design of environmentally responsive buildings, SOLAR-5 can be used both early and late in the project. At the very beginning of the process, the architect can gain an overall picture of the project's energy design assets and liabilities, or can rapidly test alternative design ideas such as the size of overhangs on a south window. Towards the end of the design process, SOLAR-5 can be used to fine tune the building in terms of the relative contribution of each of the many components. The final objective is to produce a flat plot of energy costs, in other words, to design a building that uses no fuel for heating or cooling. In truth, it is seldom achievable, but architects feel an immense amount of satisfaction once they understand how to make design changes that whistle away at the various lumps and bumps on the plot of energy costs. While SOLAR-5 can not guarantee perfection, it at least helps the architect see how to approach it.

THE FINAL BUILDING DESIGN

The object of all these microcomputer design tools is to help make better buildings. None of them actually generates a complete building design, in the sense that an architect does. Instead they aid the architect in making design decisions. But they also perform another function, not always part of the "un-aided" design process; they can provide for explicit evaluation of the way the hypothetical building will perform. For instance, SOLAR-5, can be easily used in this way.

It can be argued that two different models of the building exist: one in the architect's mind as a three-dimensional image of its physical reality, and the other in the computer, as a theoretical abstraction of its energy performance. The two models are almost totally separate; they have only a small area of overlap that allows them to communicate with each other. The architect tells the computer about the physical dimensions of the building, then the computer tells the architect about its energy performance. The two
iterate back and forth, and at each step the building usually becomes better from the energy models' point of view and more complete from the architect's point of view.

CURRICULAR IMPACT OF COMPUTERIZED DESIGN TOOLS

In an architecture curriculum many concepts can be taught far more effectively using a computerized design tool than any other method. These tend to be topics for which we have explicit quantitative evaluation criteria, such as structures. But we also can successfully automate topics that can have more than one equally correct answer. These are topics where professional judgement comes into play. In the area of Building Climatology, the most interesting problems can have many correct answers.

In the ten-week long Building Climatology course students learn:

1. how to analyze and interpret climate data;
2. how to translate that data into design specific guidelines;
3. what kind of passive heating or cooling system is most appropriate for the given climate;
4. how the sun moves around the site and how to design sun protection against overheating;
5. how to design an architectural facade that provides heat in winter and shade in summer
6. how to design the floor plan and site plan to control natural ventilation
7. how to design the appropriate opaque envelope wall and roof elements;
8. how to optimize heat gain and loss in a complete building;
9. how the energy codes embody collective wisdom and help solve design problems;
10. how to predict the overall performance of the final design.

Thus far we have succeeded in developing design tools to address most of the topics we cover in the course, and that are useful enough that students naturally carry them into practice as part of their "kit of tools". Our ultimate goal is to develop a full kit of microcomputer design tools to provide everything an environmentally sensitive architect needs to design a climate responsive building. This kit of design tools must be integrated, which means for example that they all must be able to read each others results, and use the same internal protocols and have the same "look" and "feel" so that architects would not be forced to learn different procedures to use for each system.

WHAT WE HAVE LEARNED ABOUT DEVELOPING DESIGN TOOLS

Experience has shown that the availability of these design tools in a teaching situation in effect multiplies what can be taught. The level of comprehension, the depth of understanding, and the breadth of topics covered all expand when computer-aided design tools are in hand. Using interactive design tools demands from the student the kind of
active involvement that imprints comprehension based on first-hand experience, far more effectively than passive modes like reading or watching a slide lecture.

Because so much of the interaction between the computer and the human is graphic, these micro-computer design tools stimulate a kind of direct right-brain communication with no intervening verbal translations to slow down and dilute the process. Direct graphic communication requires the architect to develop a mental model or hypothesis which can accept the incoming information. The architect must actively interrogate segments of the computer’s graphic image to test and validate his/her mental model. With a static image the recipient becomes quickly bored and is soon impatient to move on, or turn the page. But computer generated images can move, new information can pop up, and so the intellectual challenge of computer generated image can be far more intense. Perhaps this explains why computer-aided design tools are able to engender in the architect a deeper intuitive understanding of fundamental principles.

No verbal explanation was ever presented, yet soon the architect could correctly predict how changing the form of the building would change its response to the climate.

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FOOTNOTES

1. Weather data for selected cities is available on 360 Kb disks from Ray Bahm, Microcomputer Design Tools, Inc., 2513 Kimberly Ct., N.W., Albuquerque, NM, 87120. Full TMY Data fills 1.1MB files in ASCII format.


