SPREADSHEET MODELING OF THERMAL AND DAYLIGHTING PERFORMANCE

David Lord
dlord@calpoly.edu
California Polytechnic State University
San Luis Obispo, CA 93407 USA

ABSTRACT
A series of linked spreadsheets has been developed for the analysis and modeling of thermal and daylighting effects on the flow of energy in buildings. Spreadsheet software is widely available, easily operated and readily adaptable to particular circumstances. Standard engineering formulas are used for heating, cooling, solar radiation and daylighting calculations. "What-if" relationships are established by varying assumptions and measuring their effect on the result. This technique allows rapid iteration for evaluating different design scenarios, and gives both numerical and graphical output. The spreadsheets are well-suited for educational use.

INTRODUCTION
There is a growing awareness that in the choice of building materials for construction and energy for building operation, the designer must consider not only the requirements of the building owner and user, but also the regional, national and global resource base. There is a need for energy accounting to manage the short term effects of the dislocation of supply and demand. The effects of energy and materials use are often interrelated, making the evaluation of targets for analysis complex.

For example, construction materials used for solar gain avoidance and passive cooling have a great effect on cooling load and the use of air-conditioning, which consumes close to 10% of the world's total energy, mostly in the form of electricity, and is one of the fastest growing energy consumption sectors. The release of refrigeration gases to the air is also responsible for environmental degradation. Also, in commercial buildings, as much as half of air-conditioning is required to remove waste heat from electric lighting. Use of available on-site solar resources for daylighting can displace the need for electricity for both lighting and for air-conditioning. In this instance, analysis should include climatic factors, thermal characteristics of building materials over time, as well as daylighting potential.

Another factor in analysis is the timing of design decision making. It is useful if computer analysis tools are available in the early stages of design to evaluate the impact of proposed building designs against environmental sustainability of local, regional and global supply of energy and materials.

SPREADSHEETS
Spreadsheet software makes it easier to explore problems that are time-consuming and impractical to perform by hand calculation. Therefore, these tools increase an architect's or engineer's productivity. The spreadsheet makes it possible to organize and perform calculations, analyze data, produce graphic interpretations of professional quality, and to program these steps in a single, easy-to-use package.

Contemporary spreadsheet software is well-suited for engineering calculation and display, with graphics, macro programmability, and database functions. Electronic spreadsheet programs use standard mathematical functions with numeric precision that makes them exceptionally useful engineering tools. Complex engineering calculations are reduced to simple, easily interpreted output in both numeric and graphic form. For example, engineering data tables can be generated using spreadsheet functions. Alternative building designs can be considered and compared against rational criteria, resulting in better and more rapid decisions. Spreadsheets do not replace advanced analysis programs, detailed technical handbooks or skilled consultants using professional judgment.

The spreadsheet software stores reports, analyses and projections in computer memory. The design scenario can be changed with a few keystrokes. One of the best reasons for using the spreadsheet is that the user can establish "what-if" relationships, varying assumptions and measuring their effects on the variable being studied.

The examples described in this paper have been developed using formats that can be applied to most popular spreadsheet packages. An important factor of consideration in the choice of spreadsheet software is the capacity to establish an interface with other designer productivity tools. Contemporary electronic spreadsheets allow the importation of drawings and linked data from computer aided design databases and the exportation of text and graphics to word processing programs for report generation.

Spreadsheet templates and routines are probably limited in their capacity to providing technical advice in the early stages of building design for both envelope-load dominated and for single zones of internal-load dominated buildings.

Spreadsheets are capable of representing most numeric operations in life-cycle cost accounting, heating and cooling, comfort control, water and waste, climate analysis, daylighting, and electric lighting.

Celestial motion and radiation formulas in a spreadsheet allow quick calculation of the sun's position and the quantity of solar radiation falling on any building surface at any time of the year in any geographic location.

Spreadsheet calculations can be repeated automatically to simulate the dynamic behavior of construction materials and the flow of heat, air, light and sound as they move around, into and through buildings.

Simulations of building performance based on established numeric methods give the designer a sense of how a design will perform under real conditions. The accuracy of such studies is reported to be remarkably high: in a study of computer methods of simulating energy consumption of college buildings and a community hospital, it was found that results of spreadsheet simulations were capable of predicting within an accuracy of ten percent the actual energy use of buildings (Waltz, 1992).

ORGANIZATION

The spreadsheets described here are grouped by topic into modules, called workbooks, that are convenient to operate on personal computers with ordinary configuration of speed, memory and storage. For ease and speed of operation, each workbook is kept under 300 kilobytes in size. Each workbook is further subdivided into a collection of individual worksheets with calculation routines, charts and macro sheets. Workbooks and worksheets can share data, both internally and externally with other programs. The workbooks are organized around the topics described in the following paragraphs.

THERMAL MODELING

This workbook gives an overview of building thermal performance using standard formulas from A.S.H.R.A.E. (1993) and Duffie (1991). The following data are required to begin the analysis.

a. Climate Data
- a.1 summer and winter design temperatures.
- a.2 monthly average ambient temperature.
- a.3 summer and winter thermostat settings.

b. Building Data
- b.1 building dimensions.
- b.2 number of occupants, power density.
- b.3 ventilation rate per person.

c. Materials Data
- c.1 opaque material R values.
- c.2 glazing center, edge and frame R values.
- c.2 design cooling load factors.
- c.3 design equivalent temperature differential.

Performance calculations reveal the following energy use parameters:

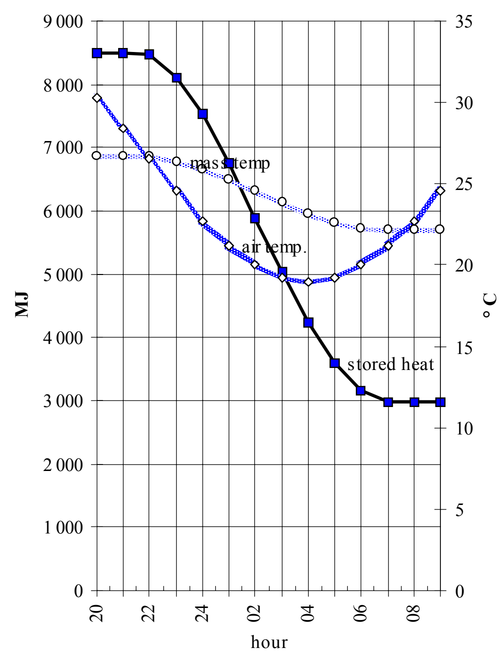

Fig. 1: Example graphic output for spreadsheet modeling of night ventilation of thermal mass, showing air temperature, mass temperature and stored heat.

a. Design heat loss, by component (U x A).
b. Balance point temperature.
c. Effect of using air-to-air heat exchanger.
d. Monthly degree days, heating loads, fuel costs.
e. Peak heat gains; use of heat exchanger.
f. Ventilative cooling; cross and stack ventilation.
g. Evaporative cooling rule of thumb sizing.
h. Night ventilation of thermal mass.
i. Approximate size of H.V.A.C. Systems.

SOLAR RADIATION

Based on building location, shape and orientation, this workbook calculates and graphically presents the total hourly and daily solar radiation on each vertical and horizontal building surface as well as a single south-facing tilted surface. The workbook allows the user to rapidly compare the solar advantage of different building orientations and collector tilt angles during different months. A rapid approximation of photovoltaic collection area and battery size can be made. The following data are required to begin the analysis.

a. Climate data--measured monthly average daily radiation on a horizontal surface.
b. Site data--latitude, longitude, date, time zone, reflectivity of ground surface.
c. Orientation, tilt and area of building surfaces.
d. DC and AC load information.

Array Sizing **55.2** ° tilt

Total Average Load:	**384**	Ah/day
Imp	**3.05**	Amps
tput Derating Factor:	**.90**	
Battery Efficiency:	**.95**	

Peak Hours of Insolation kWh		Total Output Ah/day
6.1	DEC	**510**
6.1	JAN/NOV	**509**
6.7	FEB/OCT	**558**
6.9	MAR/SEP	**578**
6.3	APR/AUG	**524**
5.6	MAY/JUL	**464**
5.4	JUN	**449**

recommended number of modules: **27**

Fig. 2: Example numeric display for photovoltaic array sizing approximation, showing hours of insolation and total solar array output

Each of the following performance measures is calculated and displayed:

a. Hourly solar geometry.
b. Solar radiation on building surfaces.
c. Approximate photovoltaic array size.
d. Approximate battery size.

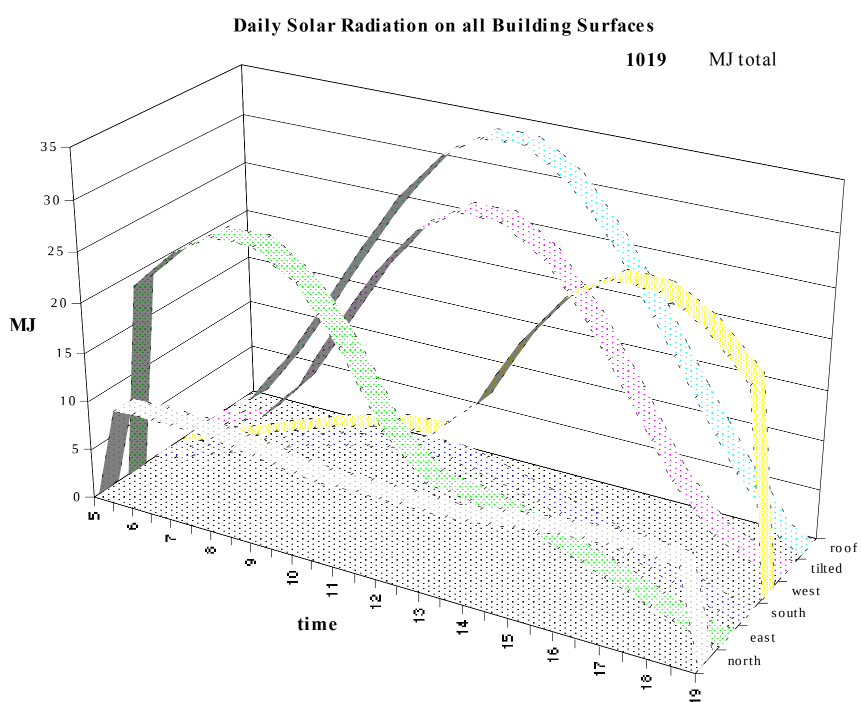

Fig. 3: Example graphic output for solar radiation on building surfaces, showing hourly total solar radiation on each of five building surfaces for a given month, orientation and location.

COOLING LOADS
A separate spreadsheet workbook calculates cooling loads, based on the accepted A.S.H.R.A.E. Total Equivalent Temperature Difference / Time Averaging (TETD/TA) method. Hour-by-hour heat gains and cooling loads are calculated to give a 24-hour performance curve for each building shell component. In addition to climate data previously described, the following data are required to perform the analysis:

a. Reflectivity, transmissivity, thermal conductivity, decrement and time lag characteristics of building materials.
b. Internal heat gains from people, lights and equipment.
c. Schedule for lighting and occupancy.

Each of the following performance measures is calculated and displayed:

Roof Construction

Group:	**20**	
U-factor:	**0.45**	W/m²-K
Time Lag:	**12**	hours
Decrement:	**0.2**	0 - 1
Max Temp:	**60**	°C sol-air
Min Temp:	**18**	°C sol-air

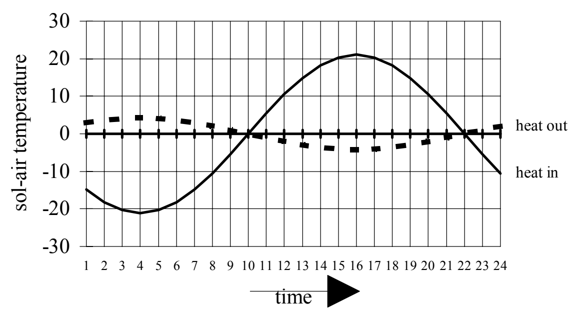

Fig. 4: Example input and graph of decrement and time lag for cooling loads, with a plot of sol-air temperature and thermal time lag.

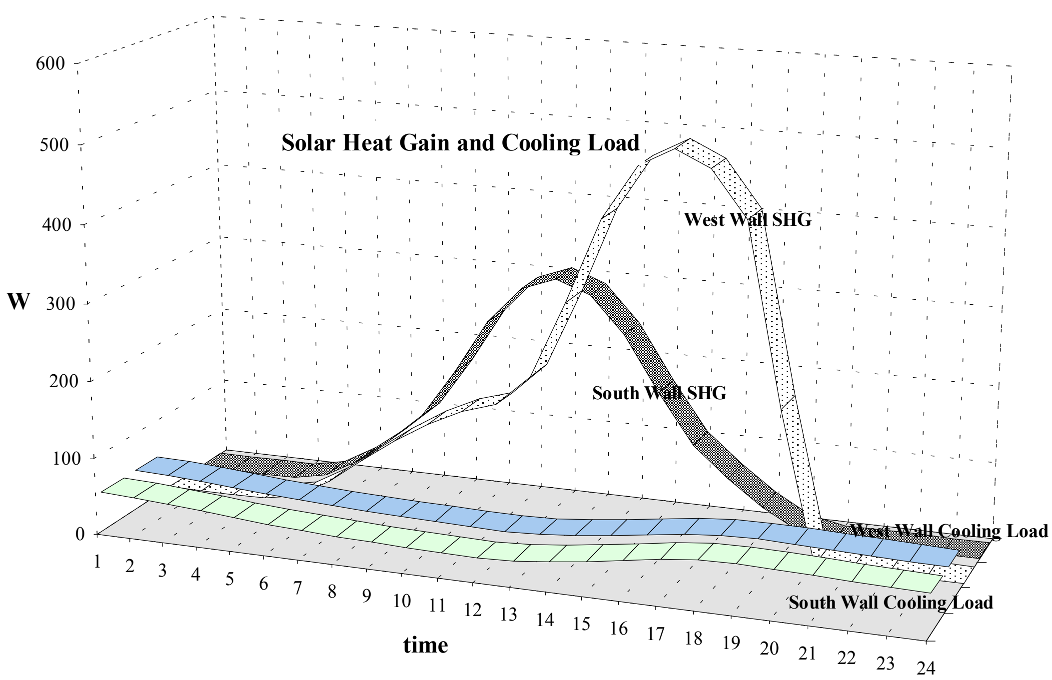

Fig. 5: Example graphic output comparing solar heat gain and cooling loads for individual building surfaces.

a. Hourly sol-air temperatures of each building surface.
b. Hourly solar heat gain factors for each building surface.
c. Instantaneous hourly radiant cooling load.
d. Hourly convective cooling load.
e. Instantaneous hourly sensible heat gains.
f. Hourly latent cooling load.
g. Comparison of hourly heat gains and cooling loads.

DAYLIGHTING

This spreadsheet workbook uses standard formulas from the Illuminating Engineers Society of North America (I.E.S.N.A.) Handbook to yield graphical information on daylighting. The following data are required:

a. Climate data--location, orientation, sky condition.
b. Interior illuminance conditions and requirements.
c. Room dimensions and reflectances, workplane height, aperture locations.
d. Glazing transmittance, orientation.

Each of the following daylighting performance measures is calculated and displayed:
a. Glazing size recommendation.
b. Exterior illuminance, vertical and horizontal.
c. Source luminance.
d. Interior illuminance.
e. Sidelighting illuminance, I.E.S.N.A. method.
f. Illuminance, Area Source Method, from windows and skylights.
g. Displacement of Electric Lighting.

STEPS IN PERFORMING AN ANALYSIS

1. Begin the analysis by making selections from collected databases for climate and materials characteristics. Relevant data has been compiled into a single volume for the student with references to primary sources. Data can be modified to reflect special or local conditions.

2. Continue the analysis by entering the basic building dimensions, orientation, and other characteristics.

3. Establish performance scenarios as desired by changing input cells according to the effect on output cells.

Make changes as desired in building characteristics to generate additional solutions for further evaluation.

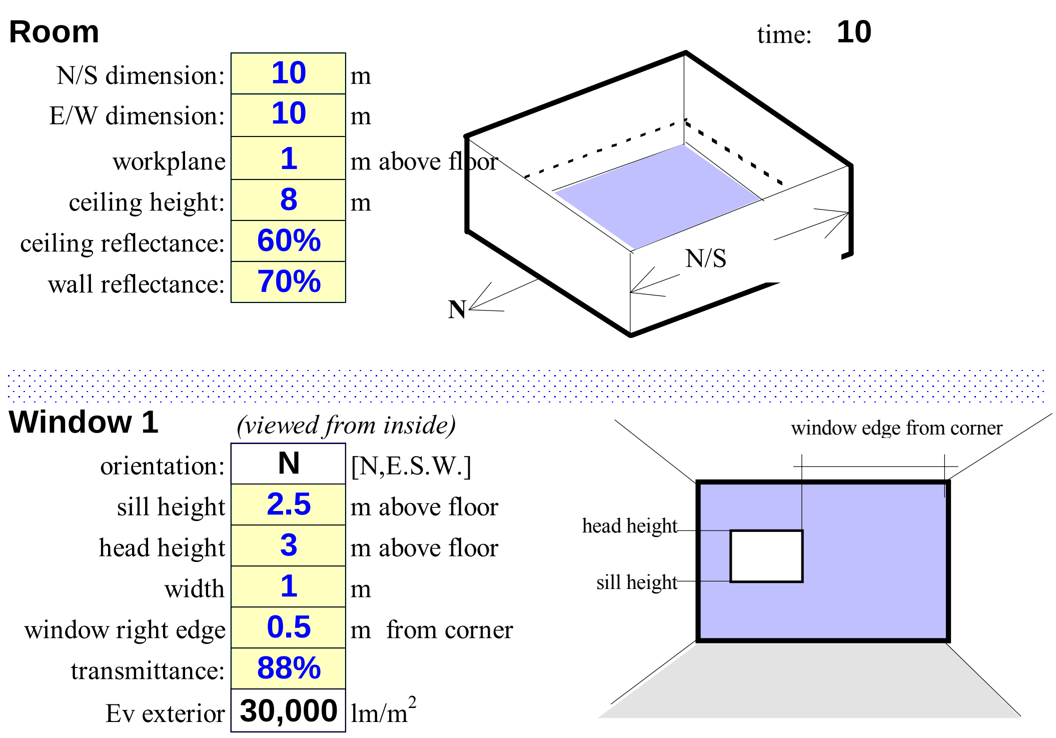

Fig. 6: Example data input for daylighting illuminance on the workplane. Both toplighting and sidelighting apertures can be modeled.

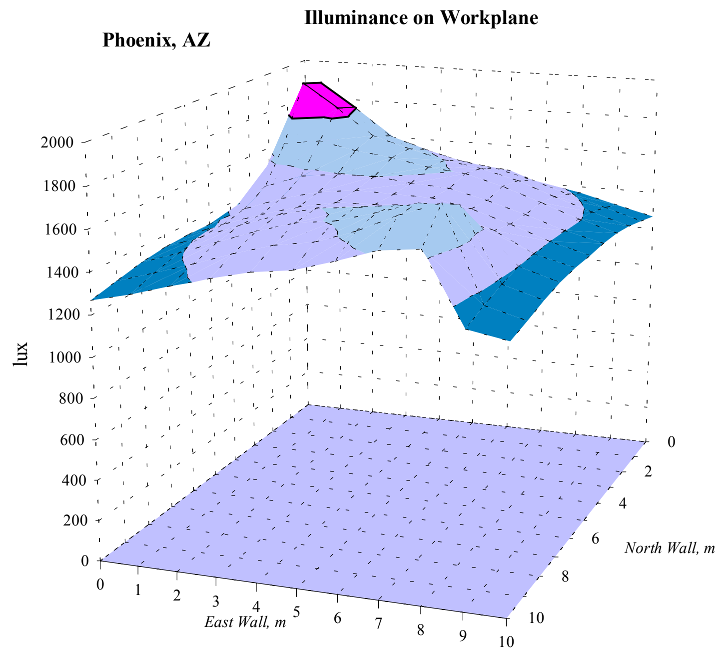

Fig. 7: Example graphic output for daylighting illuminance on the workplane, showing distribution of light from two windows and a skylight for a 10 m^2 room in Phoenix, AZ.

FUTURE DEVELOPMENT

Planned future development of the spreadsheet workbooks include the establishment of links to a drawing database to permit a more direct observation of thermal and daylighting performance during early stages of design.

ACKNOWLEDGMENTS

I am grateful for the support of the administration and staff of the College of Architecture and Environmental Design, to my colleagues, and to the students of environmental control systems who have helped in troubleshooting and perfecting the spreadsheets.

REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers, A.S.H.R.A.E. Handbook - Fundamentals, SI Edition. A.S.H.R.A.E. Atlanta. 1993.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Cooling and heating load calculation manual. 2nd ed. A.S.H.R.A.E. New York 1992.

Duffie, John, W.A. Beckman. Solar Engineering of Thermal Processes, 2nd ed., Wiley, New York. 1991.

Illuminating Engineers Society. Handbook, Reference Volume, I.E.S. New York. 1984.

Waltz, J.P. Practical experience in achieving high levels of accuracy in energy simulations of existing buildings. ASHRAE Transactions AN 92-1-2 p. 606. 1992.