BEEM: A SIMPLIFIED PROCEDURE TO CALCULATE DAYLIGHTING AND OTHER IMPACTS OF FENESTRATION

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ABSTRACT

A simplified procedure is described, to model daylighting, cooling, and heating impacts of vertical glazing in commercial buildings. Both annual **and peak impacts are calculated, as well as cooling-equipment-sizing impacts.** Simple economic analyses **(present worth and simple** payback) are included. The name BEEM is used, for Building Energy Estimation Module.

The public domain procedure is implemented in spread-sheet software, available at nominal charge for materials and handling. The spread-sheet format was chosen to allow easy graphing, analysis, printing, saving, and customization of results. A help telephone number is provided for free assistance.

The work was sponsored by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), the Empire State Electric Energy Research Corporation (ESEERCO), and ten other sponsors over a period of eight years.

The paper presents a summary of derivation methodologies and sample applications, e.g., optimizing glass and shading with daylighting, economics of lighting controls for daylighting.

Earlier papers on basic derivation and validation are referenced and briefly described.

The fenestration treated may include glazing, overhangs and fins, fixed shading devices, automatic retraction of shading devices for all or part of the time that direct sun is not on the facade, and automated-angle louvers. Other inputs include: city, exposure, illumination required, installed lighting density, occupancy information, unit fuel costs, unit first costs (fenestration, lighting controls, cooling), and years of energy cost to treat as present worth (present worth factor).

Outputs include workplace daylighting levels, fractional lighting savings, annual and peak energy impacts (lighting, cooling, and heating), cooling sizing impact, present worth of energy cost impacts, first costs (fenestration, cooling, lighting control), and total economic impact. Thus, intermediate results are readily available and further development of the calculation is practical. The analysis is applicable to new or retrofit construction.

Derivation was based on a 'first principles' approach, starting with ASHRAE, Illuminating Engineering Society of North America (IESNA), and standard physical formulae.

INTRODUCTION

A simple procedure has been developed to calculate the energy use, peak demand, and other impacts of a given window configuration. The calculation is embodied in a computer spreadsheet program. The procedure treats lighting, cooling, and heating impacts and interactions, including the utilization of daylighting. Various window configurations are compared to determine the most desirable design.

Users would include architects, mechanical and lighting designers, utilities, vendors of fenestration products and lighting controls, government energy offices, building energy code development and enforcement bodies, etc.

Inputs include:

- City and exposure, e.g., Minneapolis, south-facing
- Glazing and shading device characteristics
  - Including automated louvers, overhangs, fins, shades, drapes, or blinds
- Fraction of time shading devices are withdrawn when no direct sun
- Lighting: illumination required and watts density
- Occupancy information
- Fuel unit costs
- Unit costs (fenestration, lighting controls, cooling)
- Years of energy cost impact to treat as first cost.

Results include:

- Annual and peak:
  - Lighting savings
  - Cooling cost
  - Heat cost (annual)
- Daylighting levels and savings
- Peak demand (KW) impacts
- First cost impacts
  - Present worth of utility cost impacts
  - Cooling (per peak load and input unit cost)
  - Fenestration (per input size and unit cost)
  - Lighting control (per input unit cost)
  - Total present worth associated with window configuration.

Background

A previously derived and documented procedure (Rundquist 1982 and 1984, and Rundquist and Garoutte 1985) is used to calculate the annual energy impacts of a window configuration. The procedure was named "BEEM" (Building Energy Estimation Module). This will be referred to as the "existing" calculation herein. A more recent project added the calculation of the following impacts: peak electric demand, cooling equipment sizing, and the effects of overhangs, fins, and adjustable louvers.

Current research will add four permissible orientations (NE, SE, SW, and NW) and additional latitudes beyond the 40 degrees latitude now assumed for peak effects.

The calculation is innovative in that it treats issues never calculated before (e.g., automated louver effects) and treats certain issues in a simple program for the first time (e.g., overhangs and fins, and automatic shading withdrawal when direct sun is not on the window). Significantly, the program treats diverse fenestration impacts interactively (i.e., daylighting, lighting reduction, and all cooling impacts).

General Derivation Method

The method used to derive the algorithms was generally to find, from existing literature or by new analysis, the relation between physical parameters (e.g., for adjustable louvers, how light on the workplace is related to solar profile angle), then finding time-integrated values for energy and instantaneous values for peak demand, generally expressed as multipliers relative to some base-case conditions (e.g., for adjustable louvers, the base-case is blinds set at 45 degrees).

CALCULATION STRUCTURE

A flow chart of the calculation is shown in Figure 1. Both energy and peak demand impacts are calculated for daylighting, cooling, and heating. Cooling equipment sizing and various first cost impacts are also calculated.

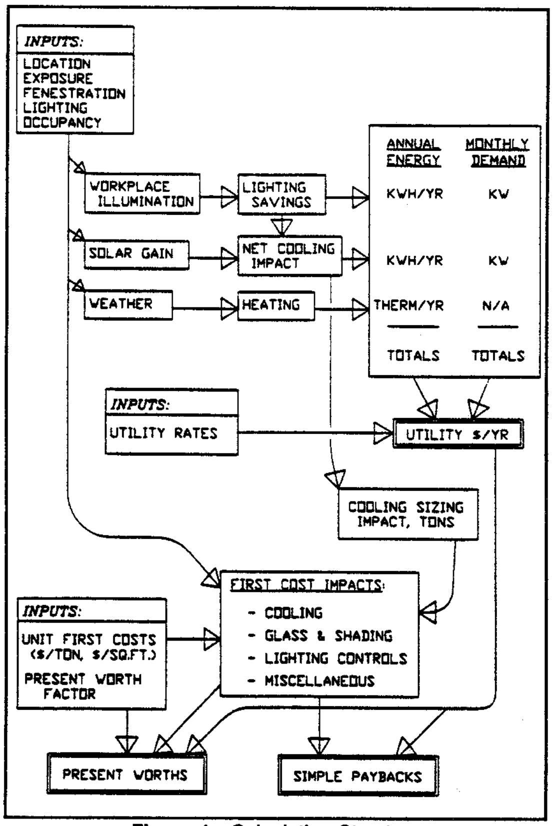

Figure 1. Calculation Structure

The effects of a fenestration on both energy consumption and peak electric demand are calculated:

1. Lighting reduction due to daylighting
2. Cooling reduction associated with reduced lighting
3. Cooling increase due to increased solar and conduction gain.
4. Heating fuel (energy only)

Peak demand effect of the fenestration is calculated for three months: June, December, and March (September similar). Interpolation and cooling season length are applied to obtain monthly and annual effects.

Two or more fenestrations' net impacts (cost or savings relative to solid wall) are compared to find the impact relative to each other.

Daylighting

Separate annual and peak daylighting and lighting savings are calculated, as for cooling.

Instantaneous daylight predictions are based on the IES Recommended Practice of Daylighting (IES 1984; Libbey-Owens-Ford 1976). A simplification of the IES method was derived (Rundquist 1982), which reduced the number of calculation coefficients to one (dependant on shading device type), with very little sacrifice in accuracy. As in the source prediction method, it is assumed that a shading device blocks all direct sun. Thus, a bare window is allowed only on a north exposure. Windows need not be continuous, but must be spaced closely enough to provide fairly even daylighting in the workplace.

Basic assumptions made in illumination analyses were: reflections, ceiling 80%, wall 50%, floor 30%, ground 20%; workplace ten feet from window; and electric lighting controlled in fifteen-foot-deep zone. Four types of photosensor lighting control are treated: on-off, two-stage, dimming-to-off, and dimming-to-30%-power.

Cooling

Cooling impacts include solar gain, conduction gain, and reduced heat-from-lights due to reduction for daylighting. Annual cooling effects are calculated starting with a driving force based on solar gain during the cooling season, assuming economizer operation. The pre-calculated driving force is tabulated by city and exposure. Peak impacts are calculated at 3 p.m. solar time, using methods derived from (ASHRAE 1975, and ASHRAE 1989).

Systems effects are treated in a simplified manner using system Coefficients of Performance (COPs). Separate COP values for seasonal and peak cooling were calculated considering typical chillers, pumps, and fans, using appropriate conditions and equipment efficiencies, and assuming economizer operation.

Cooling Equipment Sizing

The impact of fenestration on peak cooling demand (KW) is assumed to also define the impact on chiller and fan sizing, since the maximum cooling requirement generally occurs (indeed usually causes) the peak building electric demand. This sizing impact, multiplied by an input equipment marginal unit cost, is a component in net first cost due to fenestration

DERIVATION METHODS, SHADING DEVICE EFFECTS

Louvers, Static and Automatically Adjustable

Workplace illumination due to various blind and louver configurations was determined. Sensitivities to solar-profile and blade angles were derived from the daylighting coefficients in (Brackett 1983), and from mathematical analysis of cutoff angles and free areas, for typical louver geometries. Louvers should be automatically controlled to qualify for treatment as "automatic" in the procedure. "Static" or "fixed" here refers to blades that are either physically fixed in position or requiring human intervention to change position. Various energy and peak multipliers (relative to standard blinds) account for:

- Vertical-axis fixed blinds
- Horizontal-axis automated louvers
- Vertical-axis automated louvers.

Automated louvers are assumed to always open far as possible (up to level for horizontal blades) without admitting direct sunlight

Response factor analysis (ASHRAE 1989) was used to find the cooling load effect of the dynamic louver operation, so that peak effects are sensitive to earlier operation.

The user may specify louver operation that opens only far enough to admit required workplace illumination, thereby eliminating solar gain with no beneficial daylight.

Overhangs and Fins

Three types of building projections were treated: overhangs, fins normal to building, and fins slanted 45 degrees from normal. The slant-fin was treated because normal fins allow unwanted sharp cooling load spikes on east and west exposures in summer, as is well recognized. For analysis, slant-fins are slanted toward the south on east and west exposures and toward the east on north and south exposures, thereby reducing summer afternoon cooling peaks.

Four types of effects are calculated:

- Lighting energy (summer, winter)
- Cooling energy (annual)
- Lighting peak (3 typical months)
- Cooling peak (3 Typical months).

To determine the reduction in workplace illumination by overhangs and fins, three exterior illumination components were treated separately:

1. Direct sun: reduced according to the fraction of direct sun obstructed at any given hour
2. Diffuse sky: reduced according to the overhang and fin equations in (Olgyay and Olgyay 1976, and Jones 1980)
3. Ground-reflected:
   a. Overhangs: no significant effect
   b. Fins: same attenuation equations as used for light from diffuse sky.

The size of the projection was characterized by the ratio of the distance the overhang or fin projects, to the distance from the projection to the bottom of window or edge of window. The projection distance for slant fins (45 degrees) is measured along the slant, not normal to the building.

Validation

As described in an earlier paper (Rundquist and Garoutte 1985), the calculation produces daylighting values and energy results in good agreement with those predicted by the DOE-2 computer program.

ANALYZING REAL SITUATIONS

Method

Typically, almost all inputs will be predetermined for a given job. For example, the architect often has a certain height continuous window in mind. He or she may want shades. The shade transmittance may be negotiable, but not the glass type. Other options (e.g., overhangs or automated louvers) may not have been considered.

When deciding how to adjust a given input to minimize total utility costs, a clue can be had from daylighting levels. When electric lighting is automatically controlled by daylight sensing controls, it is usually true that:

> If workplace illumination, as indicated by the summer and winter peak workplace illumination, is generally less than required, then changing any input value so as to increase illumination will reduce total utility costs.

This is true because whenever an input is changed so as to increase useful daylight, the added lighting savings will more than offset added cooling and heating costs. Thus, there is usually a window size (or glass type, etc.) at which utility costs optimize--some window that results in lower utility costs than for no window.

Note that all inputs can have large impacts on results, and should be determined carefully, even if they are fixed. It's especially significant, for example, whether or not shading is automatically withdrawn during shaded half days on east or west exposures.

Establishing proper values for all inputs (and finding out which ones are negotiable) will normally require a frank, up-front interchange with the client and/or another design professional. This interchange is essential in any design process, but is often avoided, for a myriad of reasons.

Example plots and data

The plots below show utility cost savings versus the size of window, for various window configurations.

Table 1: Inputs used for all examples (except as noted)

City: New York City
Glass: Green Tint, Dual (or varies for plots) Glazing = 4-foot high continuous Visible Transmittance = .68 Shading Coefficient, Glass = .55
Shading: Shades, Visible transmittance = .25 Shading Coefficient, with shades = .33 Shade not withdrawn when no direct sun No overhangs or fins
Lighting: 60 fc required, 1.8 W/ft^2, 10 hour/day Control for daylighting: Dimming to 30% power
Utilities: Electric: $.10/KWH, $10/KW (12 months) Gas (heat): $.80/therm

Note that these results are for one set of input conditions, shown in Table 1. Only the variables noted with each plot were changed. Sensitivities could vary substantially with glass type, shading type and characteristics, automatic shading withdrawal, utility rate structure, etc., indicating the need for an interactive program such as BEEM, as opposed to a limited set of plots or rules.

The plots below show utility savings (y-axis) versus glass transmittance for various exposures, fenestration configurations, and other variables. Shading coefficient with and without shading were also varied; a fairly high performance glass was assumed, with visible transmittance 25% greater than shading coefficient.

Note that:

- The y-axis is utility savings--that is, the higher the point plotted on the graph, the more beneficial the window.
- Utility costs include lighting (with effects of daylighting), cooling, and heating. Demand charges are included for lighting and cooling. Units are utility dollars per year per perimeter foot, for one floor.

Caution: Figures are examples only; results depend on specific set of inputs.

Figure 2 shows how workplace illumination increases as glazing transmittance increases, as expected. In this as in all figures variables have the values shown in Table 1 except as noted. For example, this illumination is for a continuous window four feet high with 25%-percent-transmittance shades never withdrawn. On this south exposure winter illumination is slightly higher than summer. The difference would be larger except that these illuminations are weighted average of clear and overcast days. They are the peak illumination for the day, here at noon.

Figure 3 shows how the fraction lighting saved (box symbols) increases less rapidly at high transmittance. This

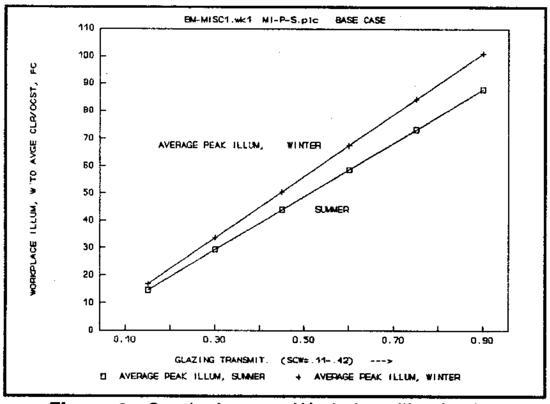

Figure 2. South, Average Workplace Illumination

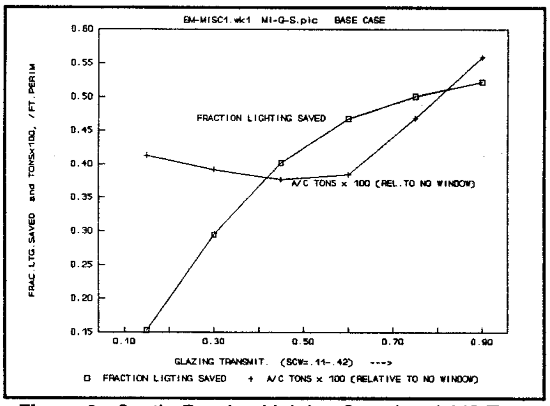

Figure 3. South, Fraction Lighting Saved and A/C Tons

is as expected since the higher illuminations bring diminishing returns. It is seen that air conditioning tons (relative to no window) minimizes at a medium transmittance glazing; at lower transmittances peak lighting (heat) reduction is increasing faster than solar gain.

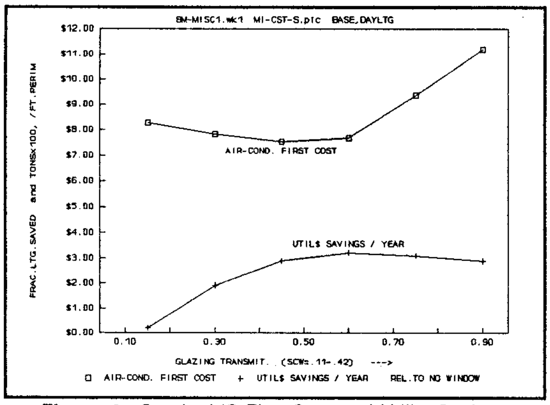

Figure 4. South, A/C First Cost and Utility Savings

Figure 4 shows the fenestration impacts on air-conditioning first cost (box symbols) and utility savings per year. Utility savings include lighting, cooling and heating. Savings maximize at medium transmittance, and air conditioning first cost minimizes, at medium transmittance. This would indicate the optimum size window, although variations in glass cost with transmittance are not considered here. (They could be input.)

Figure 4 also shows electric consumption and demand savings. Demand savings maximize at a lower transmittance than does consumption savings because demand savings are figured on a clear day when a lower transmittance is required.

The next two figures show the importance of shading assumptions on north, east and west.

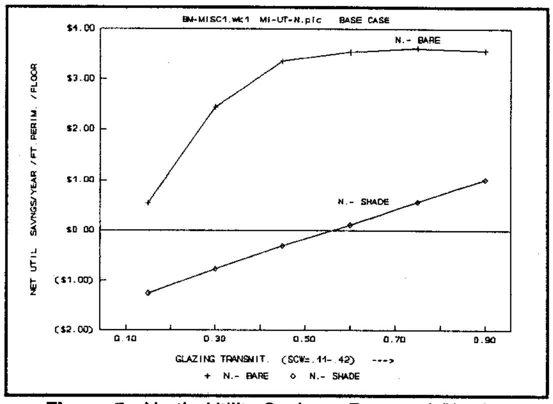

Figure 5. North, Utility Savings, Bare and Shades

Figure 5 shows utility savings versus glazing transmittance for a bare window and a window with a 25%-transmittance shade. The large difference between the curves is due to the much larger lighting savings for the bare window. For example, at 45% transmittance the bare window saves 44% of perimeter lighting while the window with shade saves only 14%. (Not shown in plot.)

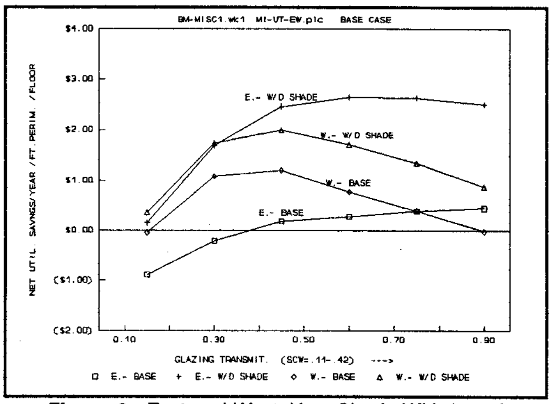

Figure 6. East and West, Vary Shade Withdrawal

Figure 6 shows utility savings versus transmittance for east and west exposures both with and without automatic shade withdrawal when there is no direct sun on the window. The shade withdrawal has a much larger effect on the east exposure because on the east withdrawal occurs in the afternoon when peak demand is set. On the west the shade is withdrawn in the morning and saves only the energy component of costs.

Four types of lighting controls for daylighting are permitted in the BEEM procedure. Their effects are shown in the next two figures in terms of lighting savings and total utility cost impact.

In Figure 7 lighting savings versus glass transmittance is shown for four types of lighting controls. Dimming-to-off control generally has the highest lighting savings, because it proportionally controls lighting down to zero lighting power with only a small parasitic control loss. Dimming to 30% power has a lower efficiency at high transmittances because of the portion of light that remains on. On-off control has the lowest savings because it doesn't "kick in" until a medium transmittance value of glass. Two-stage control is intermedi-

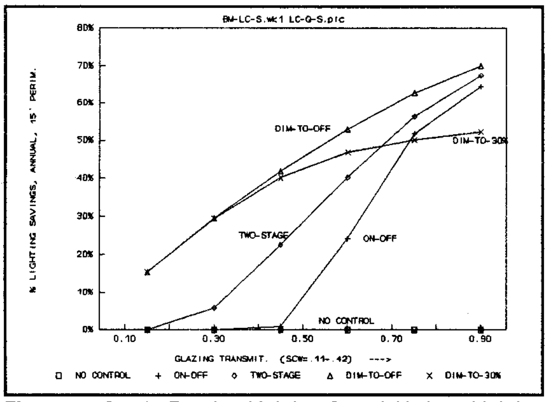

Figure 7. South, Fraction Lighting Saved, Various Lighting Controls

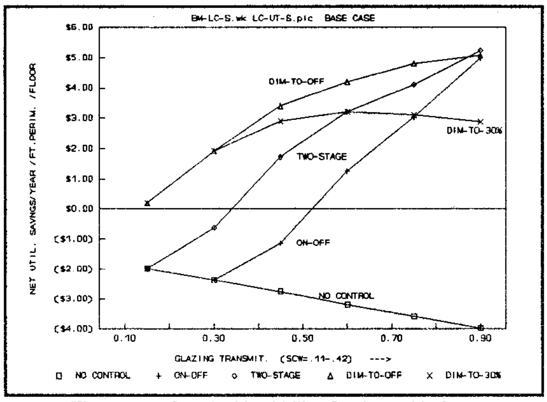

Figure 8. South, Net Utility Savings, Various Lighting Controls

ate in ineffectiveness.

Figure 8 shows net utility cost savings versus glass transmittance for the four types of lighting controls and for no lighting control. Results are related closely to lighting savings in the previous figure. The difference in the y-values between a control curve and the no-control curve, at any transmittance, yields the savings due to that lighting control for that transmittance. The units are dollars saved per foot perimeter per floor per year, and include all utility impacts of the window including daylighting.

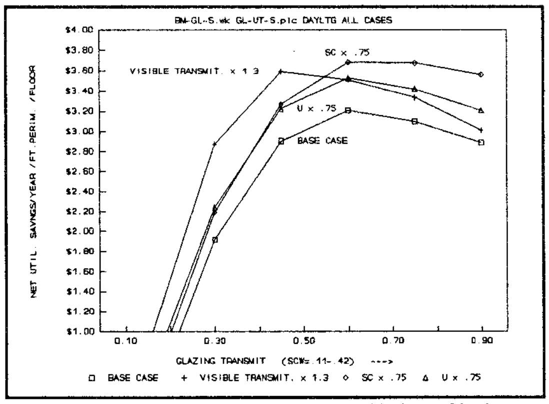

Figure 9. South, Net Utility Savings, Various Glazings

Figure 9 shows the net-utility-savings impact of changing the visible transmittance, shading coefficient and U-value one at a time, so as to be more beneficial. At low glazing transmittance increasing the transmittance has the greatest benefit, whereas at high transmittance, where there is enough daylight on the workplace, improving the U-value and shading coefficient are more beneficial.

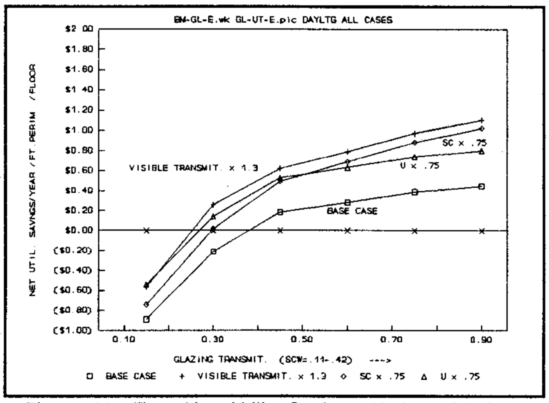

Figure 10. East, New Utility Savings, Various Glazings

Figure 10 shows utility savings on the y-axis versus transmittance. Transmittance, shading coefficient and U-value all have similar benefits for the changes indicated. Note that if shades were withdrawn when no direct sun, utility savings would be much improved generally.

The following five figures show impacts of various shading options on south, east and west exposures. In each figure the curve marked "SHADES" is the base case with 0.25-transmittance shades. Shade withdrawal means that the shades are withdrawn during all periods when there is no direct sun on the window. Overhang, fins, and slant-fins here have a projection equal to one-half of the distance to the far edge of the glass. (Values of 0 to 1 times the distance-to-far-edge are permitted in the calculation.)

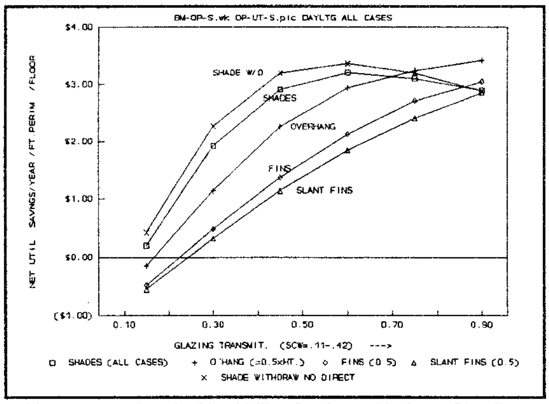

Figure 11. South, Net Utility Savings, Various Shading

Figure 11 shows the impact shading options on total utility savings. Shade withdrawal has a only moderate benefit, since it increases daylighting savings marginally. Overhangs, fins and slant-fins all have a negative impact (due to daylight losses), except at the highest glazing transmittance, where marginal lighting savings are overcome by marginal solar gain. The overhang has a less deleterious effect than do fins or slant-fins because the overhang reduces daylighting savings less at time of peak demand. (Data not shown.)

The next two figures examine the same shading options for east exposure.

Figure 12 shows that shade withdrawal has a highly beneficial impact on net utility savings due to window. This

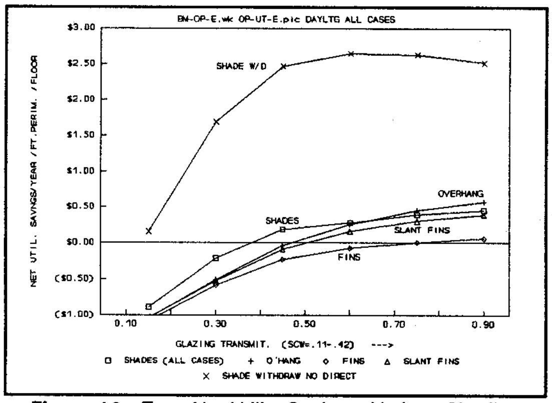

Figure 12. East, Net Utility Savings, Various Shading

is because the afternoon shade withdrawal increases both average lighting savings and reduction at peak demand. Utility cost benefit is approximately $2.00 per perimeter foot per year. Building projections have a fairly small impact, generally negative.

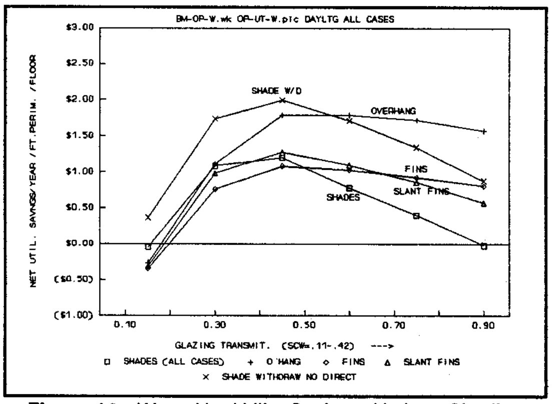

Figure 13. West, Net Utility Savings, Various Shading

Corresponding results for west exposure are shown in Figure 13. Shade withdrawal has only a moderate benefit, because the increased daylighting due to shade withdrawal occurs during non-peak-demand periods, unlike on the east exposure.

The next two figures show the effects of louver-type shading devices, including those whose blade angle is automatically controlled in accordance with solar profile angle. The base case in these figures is the curve marked "blinds"; otherwise the configuration is the base case (Table 1). All of the devices except blinds and vertical blinds are on the exterior of the window, offering reduced solar gain to the space.

Figure 14 shows that only shadescreen offers lower lighting savings than the base case blinds. Vertical blinds offer nearly the benefit as the two automated devices, whose blade angle opens to admit maximum illumination without allowing direct penetration.

Figure 15 shows the corresponding utility saving impacts. Shadescreen has little net impact, the small daylighting decrease offset by the reduced solar gain due to the exterior placement of shadescreen. The other devices offer significant increases in utility savings, due to improved illumination and (for the automated exterior devices) reduced solar gain. The benefits of vertical blinds are rather significant and are due to the improved transfer of daylight from the exterior to the workplace compared to standard horizontal blinds.

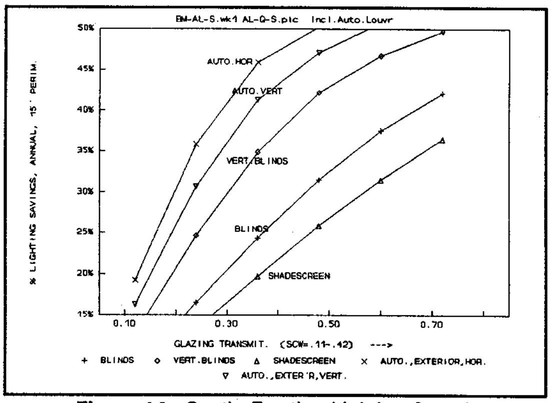

Figure 14. South, Fraction Lighting Saved, Louver Options

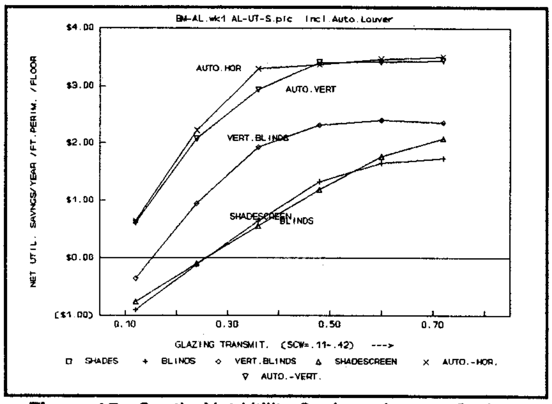

Figure 15. South, Net Utility Savings, Louver Options

------INPUTS (Partial)---==RESULTS* (partial)==

RUN	SH.DEV.	TS	LTG. CNTRL	PS	PW	Q
1	BLINDS	N/A	No	17	8	0
2	BLINDS	N/A	Yes	17	8	0.14
3	Shades	0.25	No	30	14	0
4	Shades	0.25	Yes	30	14	0.25
5	BARE	N/A	No	119	54	0
6	BARE	N/A	Yes	119	54	0.68

* Note: TS = Visible transmittance, shade
PS, PW = Average peak summer, winter workplace illumination (fc)
Q = Fraction lighting saved, 15' perimiter zone, annual

UTILITY SAVINGS / YEAR; COST; PAYBACK
(UTIL.: per foot perim., rel. to solid wall)

SHADING	UTILITY SAVE/YEAR	CONTROLS COST	PAYBACK ON CONTROLS
With Blinds:	$2.44	$15.00	6.1 years
With Shades:	$4.31	$15.00	3.5 years
Bare Window:	$10.16	$15.00	1.5 years

Figure 16. Typical Payback Analysis, Lighting Controls (Daylighting)

In Figure 16 the cost effectiveness of automatic lighting controls (to utilize daylighting) is examined for various shading options, on north exposure in an actual building in New York City.

With blinds, workplace daylight illumination is fairly low (about 17 and 8 footcandles, summer and winter, respectively), and the payback on lighting controls is fairly long, 6.1 years. Switching to an open weave shade almost doubles the illumination levels, and reduces the payback for lighting controls to 3.5 years. If outside brightness is not a problem, a bare window offers significant daylight and reduces the payback on lighting controls to 1.5 years.

This analysis (unlike previous figures) is for clear glass, 50% of a 10-foot high wall, 0.30 fin-to-window-width ratio, 60 footcandles required, 2 W/ft², dimming-to-off photosensor control costing $1.00 per square foot controlled, and a demand-intensive utility rate ($16 to $20 per KW, $.05 per KWH).

A similar analysis for a south-facing window with blinds yielded a payback on lighting controls of 2.0 years. Paybacks here ignore possible cooling downsizing benefits with daylighting controls, determined to be not applicable in this retrofit.

Many more plots and data sets could be developed examining other variable effects or showing other results (e.g., total present worth, demand effects, etc.). Since results are sensitive to input values (e.g., utility rates), it is recommended the user input appropriate values and examine variable effects in the context of a particular job or building.

CONCLUSIONS

A calculation procedure has been developed to calculate a given window and shading configuration's impact on a building's annual energy consumption and peak electric demand. The impact calculated is the impact relative to a solid wall, and two or more such results can be compared to find the impact of one fenestration configuration relative to another. Fenestrations treated includes glazing, overhangs and fins, fixed shading devices, and automated louvers.

Both annual energy and peak demand (for various months) are calculated. Energy and demand components include lighting savings (due to daylighting), cooling impact (net of heat-from-lights reduction and solar/conduction gain, and heating (annual energy only). Also calculated is the impact of fenestration on cooling equipment sizing, various first costs, total present worth associated with a window and shading configuration, and relative paybacks.

Intermediate results include daylight levels on the workplace, fractional lighting savings, and many constituent impacts (e.g., the effect of overhangs on cooling peak).

A spreadsheet program template embodies the calculation, allowing quick comparison of many alternatives. The spreadsheet approach was selected to allow easy graphing, printing and customization of results.

The program is innovative in that it treats issues never calculated before (e.g., automated louver effects) and treats certain issues in a simple program for the first time (e.g., overhangs and fins, and automatic shading withdrawal when direct sun is not on the window). Significantly, the program treats diverse fenestration impacts interactively (i.e., daylighting, lighting reduction, and all cooling impacts). Peak demand and energy consumption are calculated separately, to maintain sensitivity to different electricity rate structures.

In current research, the procedure will be extended to additional exposures and latitudes. In the long term, the following could be added to the calculation: a quantitative glare calculation, consideration of direct sun penetration, files of manufacturers' data on fenestration properties, and the use of bidirectional solar-optical properties of fenestration (now being developed elsewhere).

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