{ TC "'CHAPTER FIVE: DAYLIGHTING"' \l 1 }CHAPTER

FIVE

DAYLIGHTING

5.1 Introduction{ TC "5.1 Introduction" \l 2 }

This chapter presents the method and results of an analysis of daylighting for the retail building. The objectives are to determine whether there are cost effective daylighting measures that could have been installed in the building, what energy savings might have been achieved by those measures, and how the cost and energy savings of the daylighting measures compared to the cost effectiveness of the insulation measures required by ASHRAE Standard 90.1.

The daylighting measures examined in this thesis were two types of toplighting. The first was plastic-domed skylights that are factory made and widely available. They come in a variety of glazing and housing materials with different optical and thermal performance characteristics. The second type of daylighting examined was sawtooth roof monitors that are custom-designed for specific buildings and are therefore more expensive than skylights. They can, however, be designed to offer better thermal characteristics than skylights by using vertical glazing and high performance windows. Roof monitors also can be designed to limit solar heat gains to a space from direct sunlight by including overhangs or by positioning them so that the windows face north. A schematic of a sawtooth roof monitor is shown in Figure 5.1.

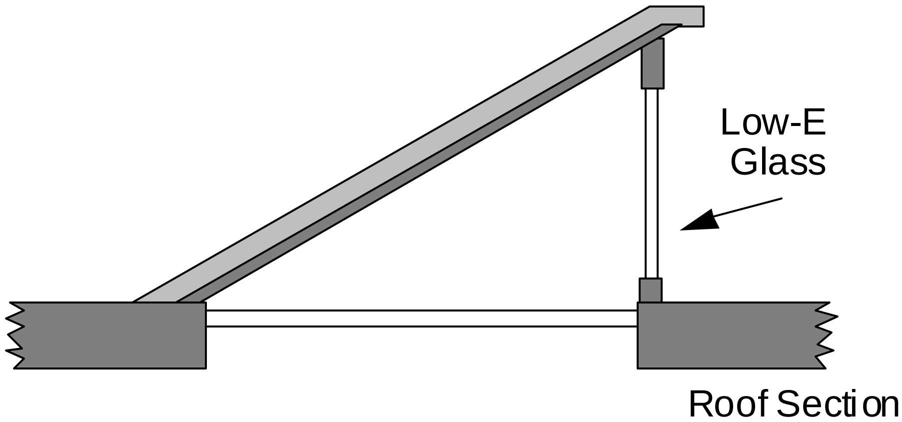

Figure 5.1 Sawtooth roof monitor.{ TC "Figure 5.1 Sawtooth roof monitor." \l 5 }

The same five locations that were used for analyzing the building envelope measures in Chapter 4 were examined for applicability of daylighting measures .

ASHRAE Standard 90.1 makes some allowances for changes in the building envelope criteria for buildings using daylighting measures with controls. The standard allows a higher window-to-wall ratio in buildings that use perimeter daylighting controls in some locations in the U.S. The standard does not allow this credit for "those climates which do not usually require space cooling by means of mechanical refrigeration" (ASHRAE, 1989). The prescriptive tables for Madison and Seattle do not allow the credit, but the other three locations studied in the thesis do allow the perimeter daylighting credit.

The ASHRAE standard also allows a daylighting credit for skylights in the building envelope compliance. Skylights for which the daylighting credit is taken can be excluded from the calculation of the overall thermal transmittance (U-value) of the roof. The thermal losses associated with the skylights are ignored by the standard because they are offset by lighting energy savings. This daylighting credit is only allowed for skylights that meet a number of other criteria set by the standard. The principal criteria for skylights are that the lighting within the daylit area must be controlled to insure the lighting energy savings, and that the skylights must make up less than a prescribed percentage of the overall roof area. The maximum roof area for skylights is set by the standard for a range of climate conditions and lighting power densities.

Roof monitors and clerestories are not allowed the same daylighting credit as skylights in the standard. The added glazing for these daylighting measures must be included in the wall fenestration calculation. Thus the potential energy savings associated with these daylighting measures are ignored by the standard.

5.2 Method{ TC "5.2 Method" \l 2 }

Computer simulations were used to model the thermal performance of the retail building with added daylighting measures. The TRNSYS models were modified to include thermal characteristics of the skylights and sawtooth roof monitors. TRNSYS was also used to calculate the incident radiation on the skylights and monitors, and to simulate the hourly control of lighting devices in the building. The computer simulation was otherwise unchanged from the building envelope analysis and used the same building design and TMY weather input data.

5.2.1 Toplighting Models - Skylights & Monitors{ TC "5.2.1 Toplighting Models - Skylights & Monitors" \l 3 }

The daylighting models were based on the lumen method for toplighting recommended by the Illuminating Engineering Society (IES, 1993). The method assumes a uniform distribution of skylights or monitors across the ceiling. Equation 5.1 was used to determine the average horizontal illuminance on the workplane:

$$E_i = E_{xh} \cdot \tau \cdot CU \cdot \frac{A_s}{A_w} \tag{5.1}$$

where:

E_i = average incident illuminance on the workplane from skylights

E_{xh} = horizontal exterior illuminance on the skylights

A_s = gross projected horizontal area of all the skylights

A_w = area of the workplane

τ = net transmittance of the skylights

CU = coefficient of utilization

The coefficient of utilization for the skylights and roof monitors was based on IES values. A CU of 0.55 was used for the skylights, and a value of 0.589 was assumed for the sawtooth roof monitors. The transmittances were based on values from the ASHRAE Fundamentals (ASHRAE, 1993). The skylights were assumed to be translucent, with a visible daylight transmittance of 0.52. The monitors were assumed to have low emissivity (low-E), double-pane windows with a visible daylight transmittance of 0.76.

Only the store's ambient lighting was included in the analysis. Because the building is a retail store, it has a large number of spot lights to accent merchandise. Although these lamps are incandescent, and make up a large portion of the lighting load, it was assumed that they could not be replaced by daylighting.

The lumen method was also used to calculate a base level of illuminance for the two types of ambient lighting in the space. Two general areas of the store were lit by different sources. The largest part of the store was lit by fluorescent lamps, with an average illuminance of 280 lx (26 footcandles). A smaller portion of the store was lit with metal halide lamps at an average illuminance of 566 lx (53 footcandles).

The illuminance due to daylighting was calculated for each hour of the simulation. For those hours where the illuminance was equal to or greater than the base level of ambient lighting, the ambient light fixtures were assumed to be off. For hours where the daylighting did not provide the base level of illumination, continuous dimming was assumed. The ambient lighting was assumed to be on at a level that would make up the difference between the light provided by the daylighting and the base level of ambient lighting in the store.

The building model was also modified to reflect the changes in building envelope resulting from the addition of skylights or roof monitors. The skylights were assumed to have thermal characteristics given in ASHRAE Fundamental for a standard (not low-E) double glazed skylight with and aluminum frame and a thermal break (U-value = 1.02 Btu/hr-sf-F). The roof monitors were assumed to have the double pane, low-E coated windows with aluminum frames and thermal breaks. The overall thermal heat transfer for these windows was also based on ASHRAE tables (U-value = 0.40 Btu/hr-sf-F).

The building model was also designed to reflect the interactive nature of lighting energy savings with heating and cooling loads. The internal loads in the space were modeled as being dependent on the lighting, so that when the lights were off the internal loads in the space were decreased by the amount of the power of the lamps. In this way the cooling load benefits and the heating load penalties associated with added daylighting could be modeled.

Both north and south facing monitors were tested to determine the best orientation. Having south-facing monitors increased the lighting savings, but caused increases in both the cooling energy use and peak loads. Without the cooling energy and peak load savings, the monitors failed to be cost-effective in any locations. A north orientation, however, provided sufficient light, cooling energy and peak load savings. Therefore, north-facing monitors were assumed throughout the remainder of the analysis.

5.2.2 Economic Analysis{ TC "5.2.2 Economic Analysis" \l 3 }

The same method was used to determine the cost effectiveness of daylighting options as was used to compare the building envelope measures in Chapter 4. The life-cycle savings of the daylighting measures were compared using the building as it was constructed as a base case. The same general economic assumptions, such as discount rates, tax rates, inflation rates, etc., and the same utility and cooling equipment cost assumptions were made.

Testing the cost effectiveness of daylighting options also required cost estimates for skylights and roof monitors. The price of skylights from Means Building Construction Cost Data (Means, 1994) was $17.85 per square foot for double glazed, plastic roof domes including material, installation, overhead and profit. The cost used for roof monitors was an estimate from Michael Nicklas, AIA, an architect with much experience with daylighting construction in commercial buildings (Nicklas, 1995). He cited a range of costs for roof monitors from $35 to $63 per square foot of vertical glazing area. These estimates were based on actual costs for projects he has designed. For this thesis, the midpoint of these estimates, $49 per square foot, was used.

Adding daylighting measures to the retail building would also require adding photosensing controls, dimmable ballasts and wiring. The total cost of the hardware and installation was estimated from Means Electrical Cost Data (Means, 1994). A total project cost of $3300 was assumed based on the costs of photosensing controls and the incremental costs of dimmable ballasts.

5.3 Results{ TC "5.3 Results" \l 2 }

The retail building model, modified to include the daylighting measures, was simulated for a variety of scenarios and a range of skylight and monitor configurations. The amount of glazed area was varied from 0.5 to 4.5% for both skylights and monitors for each of five locations. The model was used to develop estimates for the heating, cooling and peak load impacts of adding the daylighting measures. The results of the models for Madison, Wisconsin, were also tested for sensitivity with respect to key variables in the economic analysis.

5.3.1 Skylights{ TC "5.3.1 Skylights" \l 3 }

A life-cycle cost analysis was performed on the results of the building model with skylights. The results of the analysis for each of the five locations tested are shown in Figures 5.2 through 5.6 below. The life-cycle costs are shown per unit area of building floor area so that the results may be compared more easily with other buildings. In these figures, the life-cycle savings is plotted as a function of the percent of roof area used for skylights. The base case in each is a the building as it was constructed, with no skylights. The base case is assumed to have a life-cycle savings of zero.

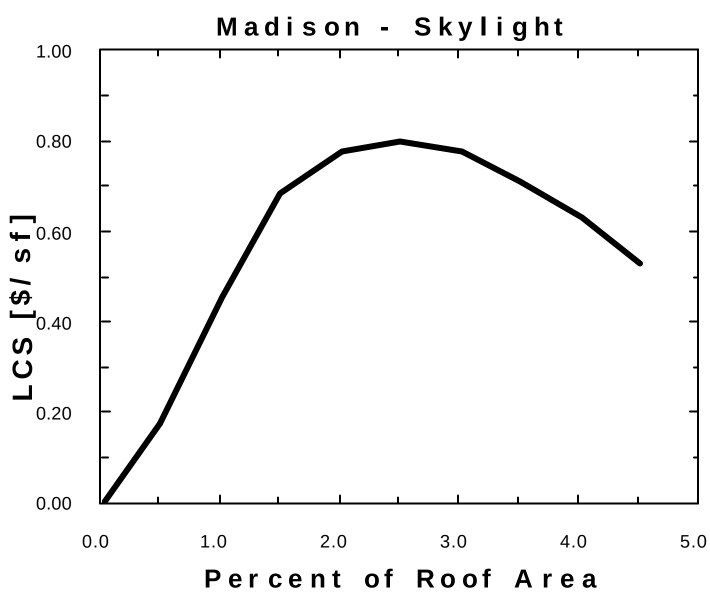

Figure 5.2 Life-cycle costs of skylights - Madison, Wisconsin;{ TC "Figure 5.2 Life-cycle costs of skylights - Madison, Wisconsin;" \l 5 }

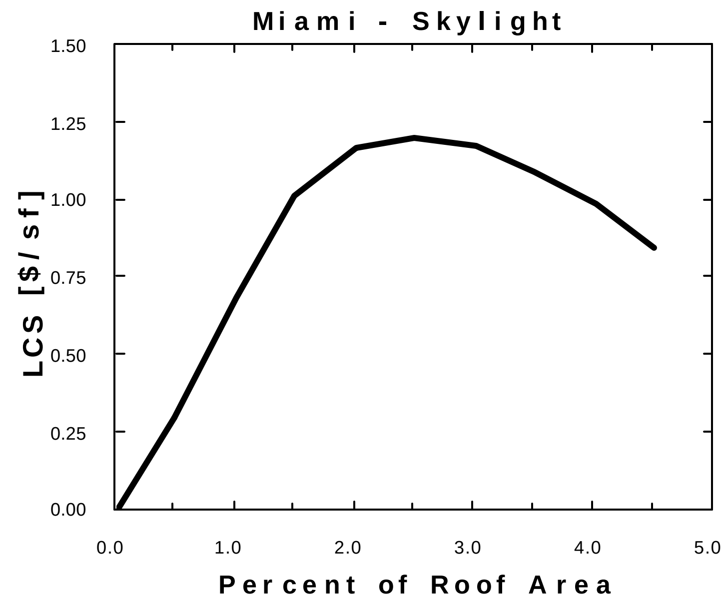

Figure 5.3 Life-cycle costs of skylights - Miami, Florida;{ TC "Figure 5.3 Life-cycle costs of skylights - Miami, Florida;" \l 5 }

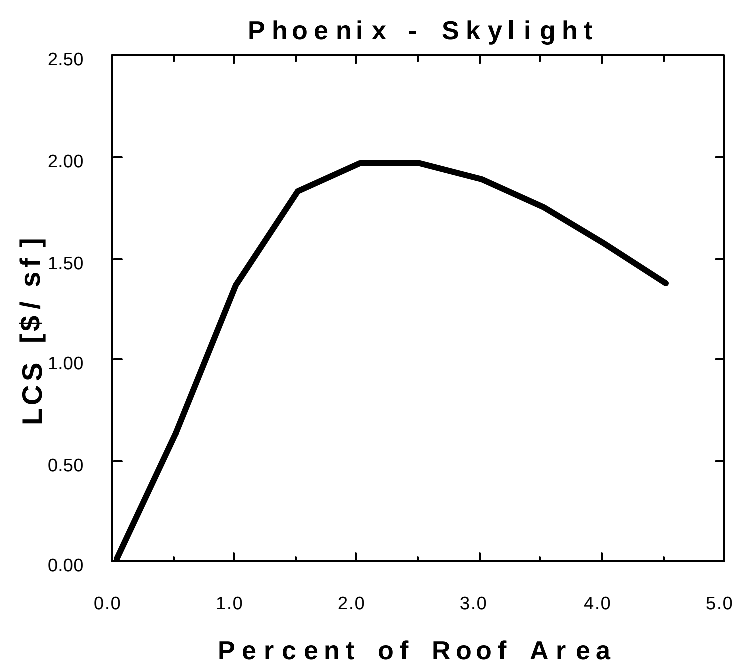

Figure 5.4 Life-cycle costs of skylights - Phoenix, Arizona;{ TC "Figure 5.4 Life-cycle costs of skylights - Phoenix, Arizona;" \l 5 }

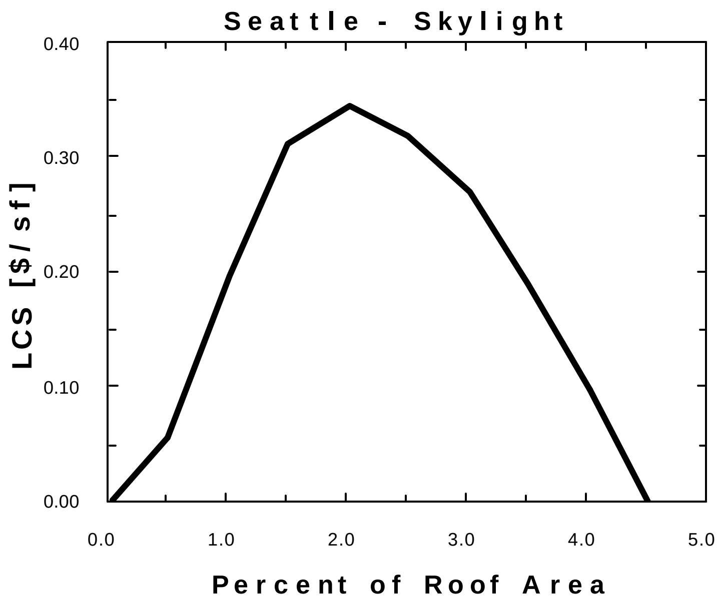

Figure 5.5 Life-cycle costs of skylights - Seattle, Washington;{ TC "Figure 5.5 Life-cycle costs of skylights - Seattle, Washington;" \l 5 }

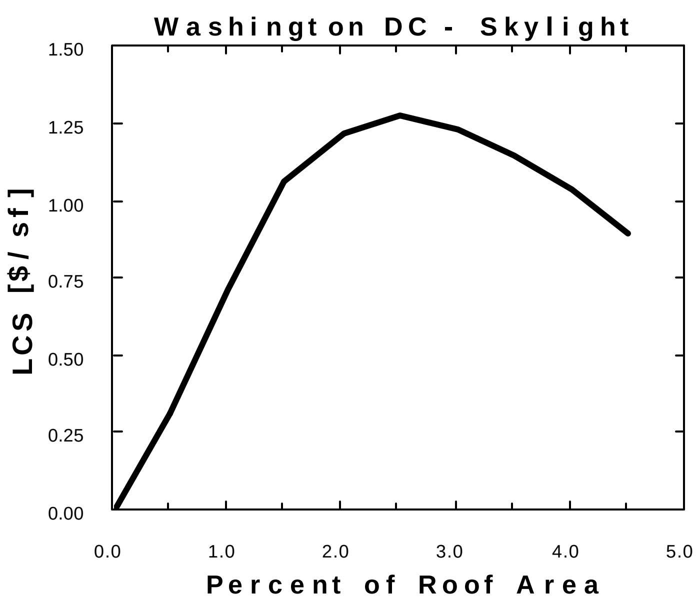

Figure 5.6 Life-cycle costs of skylights - Washington, DC;{ TC "Figure 5.6 Life-cycle costs of skylights - Washington, DC;" \l 5 }

The curves demonstrate the effects of two competing effects on life-cycle savings. As the skylight area is increased, the initial cost of installing the skylights is increased. Greater skylight area also increases the energy savings that result from turning off lights. The maximum life cycle savings represents the point at which the best balance between initial costs and operating savings is achieved.

Adding skylight area had two competing effects on the peak load. For small areas, skylights caused reductions in peak loads due to lighting energy savings. However, as the area of the skylights was increased, the added solar heat gains caused peak cooling loads to increase. In most cases the optimal amount of skylight area was slightly more than the amount that resulted in the lowest peak cooling load. In Madison, Seattle, and Washington DC, the addition of the optimal level of skylights to the building caused demand reductions in cooling equipment. In Phoenix and Miami however, skylight area of any amount caused the peak cooling load of the building to increase. The skylights still provided economic benefit in these locations, even though peak loads were increased.

The results of the analysis indicate that skylights are cost effective at each of the locations and provide life-cycle savings ranging from $0.35 to $2 per square foot of building area. In each case the optimal size for the skylights was from 2 to 2.5% of the roof area of the building.

The sensitivity of the analysis was tested using the Madison results. Figure 5.7 below shows how changes in the assumptions of key variables in the analysis would have effected the optimal skylight area. Each point on the graph represents the optimal skylight area for a given set of assumptions. The center point of the graph, where each of the lines cross represents the optimal skylight area for the base case assumptions in the analysis. In the base case the optimal skylight area was 2.6% of the roof area. Each line shows how the optimal skylight area would have changed in response to a change in one of the assumptions, with all the other values held constant. The variables examined in the sensitivity analysis are shown at the right in the figure and were varied over a range of ±100%. The values in parenthesis are the base case assumptions for each variable.

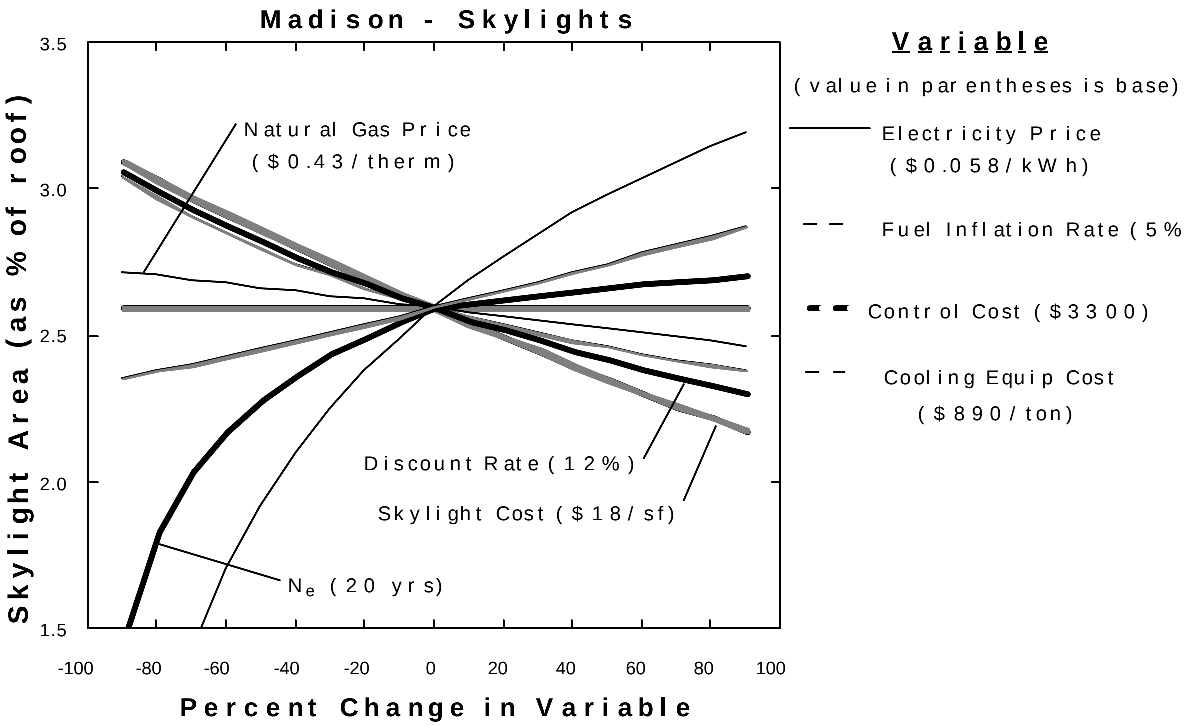

Figure 5.7 Sensitivity analysis of skylights - Madison, Wisconsin{ TC "Figure 5.7 Sensitivity analysis of skylights - Madison, Wisconsin" \l 5 }

The analysis was most sensitive to the cost of electricity assumed in the analysis. At high electricity prices the optimal skylight area would be increased because the value of lighting savings would be greater. At low electricity prices the optimal amount of skylight area is less because the value of the lighting energy savings is decreased. Large changes in all the other variables cause only slight changes in the optimal amount of skylight area for the building.

The optimal amount of skylight area found for the building was checked against the building envelope portion of Standard 90.1. In each case the optimal area was found to be less than the maximum amount of skylight area allowed by the code. The skylights did, however, exceed the maximum U-value set by the standard for the daylight credit. In fact, none of the skylights listed in the fenestration data would have passed the criteria for thermal performance in Madison. Therefore, the skylights assumed in the analysis would not have been eligible for the daylight credit. The U-value requirements of the credit would seem to be too stringent if skylights that have an overall energy and cost-saving impact on the building are not eligible for the daylight credit.

5.3.2 Monitors{ TC "5.3.2 Monitors" \l 3 }

A life-cycle cost analysis was performed on the results of the building model with sawtooth roof monitors. The results of the analysis for four locations are shown in Figures 5.8 through 5.11 below. The life-cycle analysis is omitted for Seattle because, given the cost assumptions stated previously, no case was found where the roof monitors would be cost effective there. This is due partly to the typically overcast conditions in Seattle and partly to the low cost of electricity.

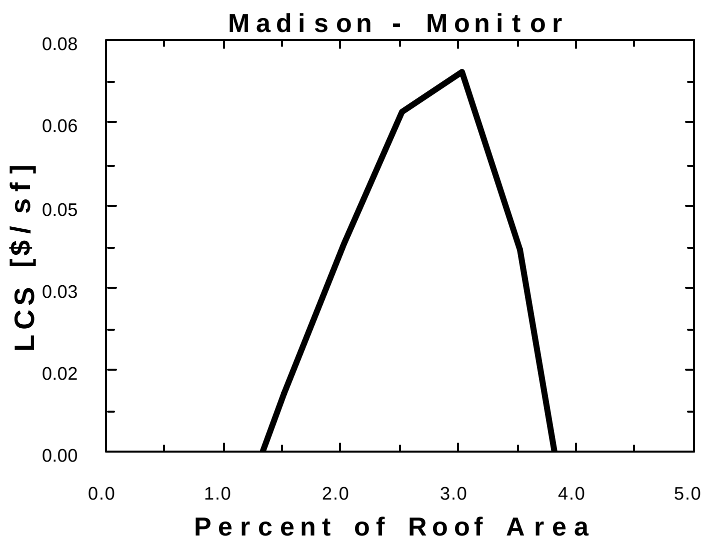

Figure 5.8 Life-cycle costs of monitors - Madison, Wisconsin;{ TC "Figure 5.8 Life-cycle costs of monitors - Madison, Wisconsin;" \l 5 }

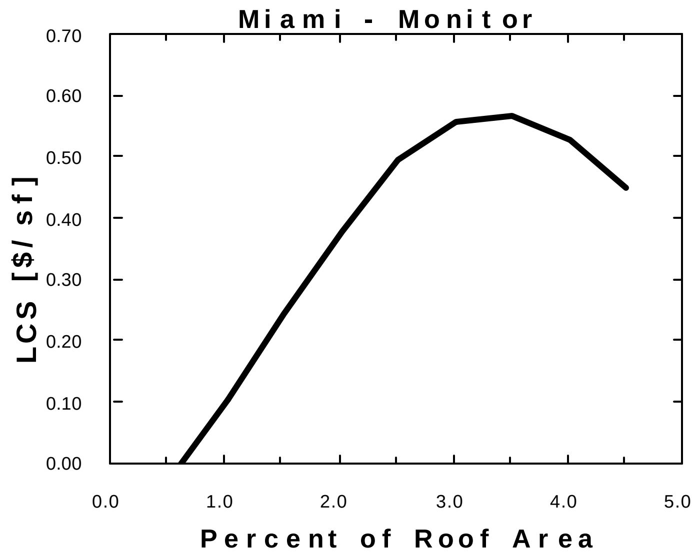

Figure 5.9 Life-cycle costs of monitors - Miami, Florida;{ TC "Figure 5.9 Life-cycle costs of monitors - Miami, Florida;" \l 5 }

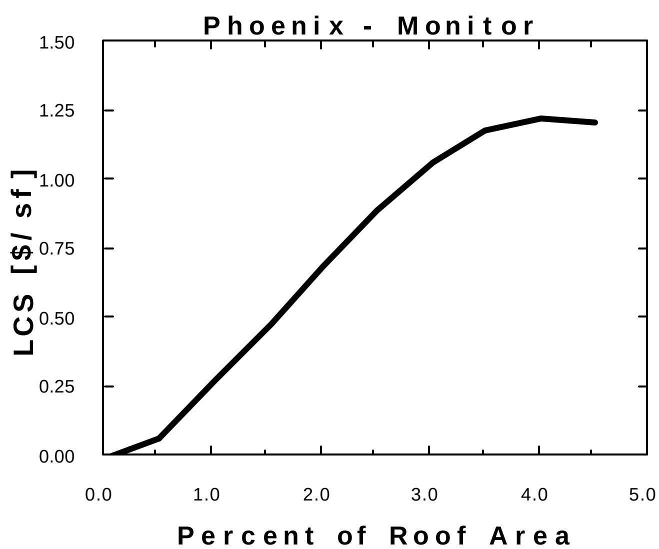

Figure 5.10 Life-cycle costs of monitors - Phoenix, Arizona;{ TC "Figure 5.10 Life-cycle costs of monitors - Phoenix, Arizona;" \l 5 }

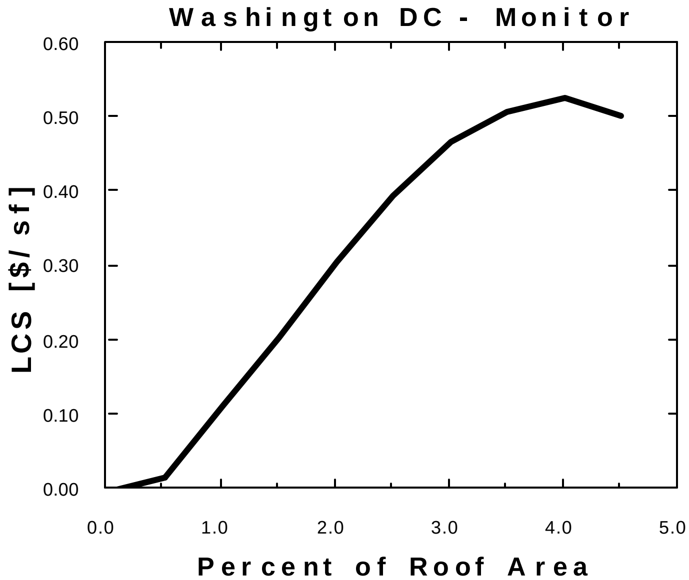

Figure 5.11 Life-cycle costs of monitors - Washington, DC;**{** TC "Figure 5.11 Life-cycle costs of monitors - Washington, DC;" \l 5 **}**

The results show that roof monitors are only marginally cost effective in Madison. In the other three cities, however, the roof monitors show significant cost savings. In Miami, Phoenix and Washington DC, the optimal glazing area for monitors was found to be from 3.5 to 4% of the gross ceiling area of the building.

A sensitivity analysis was conducted on the results for roof monitors in Madison. The results of the sensitivity analysis are shown below in Figure 5.12.

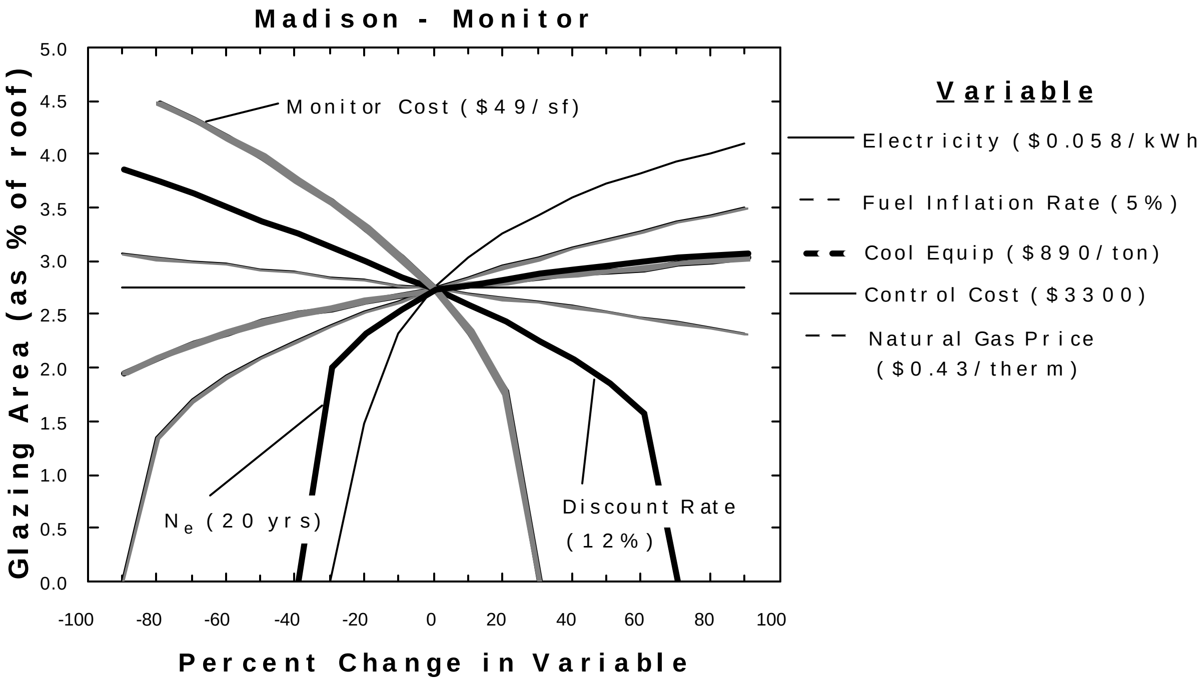

Figure 5.12 Sensitivity analysis of monitors - Madison, Wisconsin{ TC "Figure 5.12 Sensitivity analysis of monitors - Madison, Wisconsin" \l 5 }

As the monitors were only marginally cost-effective in Madison, the results showed a great deal of sensitivity with respect to several assumptions in the analysis. The greatest change in optimal glazing area was seen for changes in the assumptions for roof monitor cost, electricity rate, and N_e, the period of the economic analysis. Either a decrease in the electricity cost of 20%, a decrease in the value of N_e of 30%, or an increase in the monitor cost of 20% would cause the roof monitors to be no longer cost effective in Madison (the optimal glazing area would be zero). The sensitivity analysis was repeated for Washington DC to verify that the same variables were important to the analysis in a scenario were the monitors showed greater cost effectiveness. Figure 5.13 below shows the results of this sensitivity analysis.

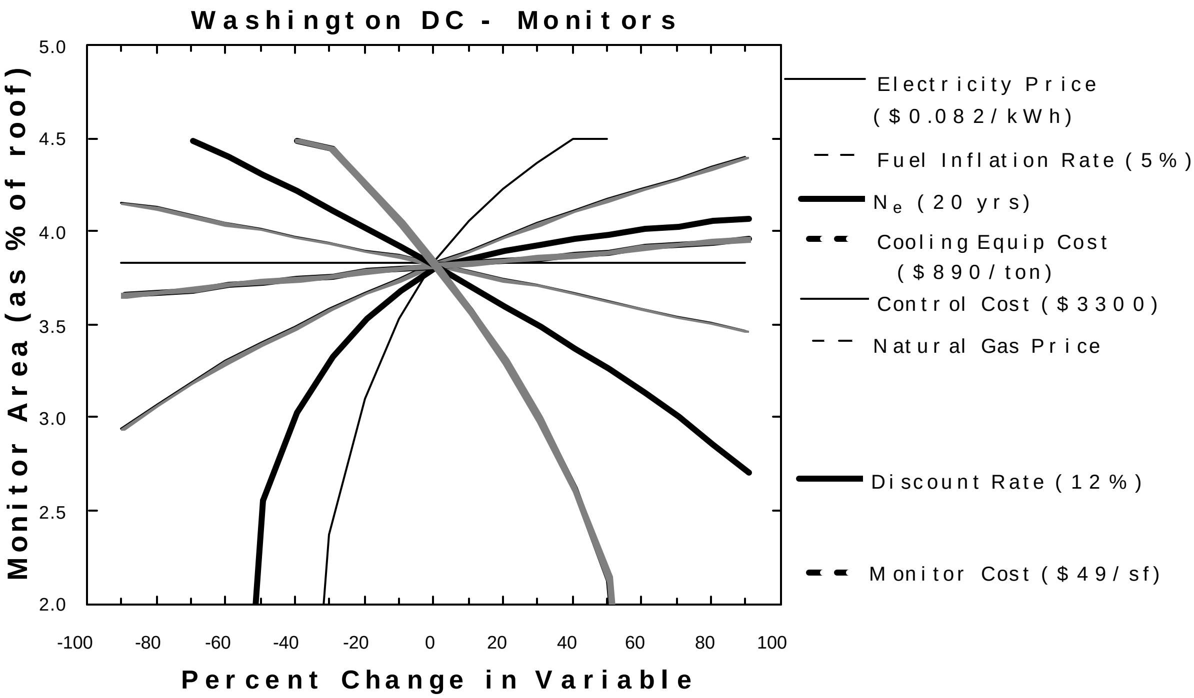

Figure 5.13 Sensitivity analysis of monitors - Washington, DC{ TC "Figure 5.13 Sensitivity analysis of monitors - Washington, DC" \l 5 }

The same assumptions were found to be important to the analysis in Washington DC as were found for Madison. Changes in electricity price, monitor cost, and N_e still caused the greatest change in the resultant optimal monitor area. The optimal area, however, was slightly less sensitive to changes in these variables.

The addition of the roof monitors to the retail building was also checked against the glazing limits set by the envelope portion of ASHRAE Standard 90.1. Roof monitors and clerestories fall under the general limits set on vertical fenestration in buildings. Because the building had very little glass in the original design, the addition of glazing for the monitors would cause no problem in complying with the standard. However, in some buildings, the addition of roof monitors would cause the design to exceed the maximum allowed fenestration.

5.3.3 Summary{ TC "5.3.3 Summary" \l 3 }

The results from the analysis of skylights are summarized below in Table 5.1. The table shows the life-cycle cost savings and simple payback period for the configuration with the lowest life-cycle cost in each city. The table also shows the effect of adding the skylights on the electricity use, natural gas use, and peak cooling loads in the building.

Location	Optimal Area [% of roof]	LCS [$/sf]	Payback [yrs]	Electricity [Δ%]	Natural Gas [Δ%]	Peak Load [Δ%]
Madison	2.5	0.80	2.7	-16%	12%	-4%
Miami	2.5	1.21	2.6	-14%	24%	3%
Phoenix	2.5	1.99	2.0	-15%	47%	5%
Seattle	2.0	0.35	4.0	-12%	16%	-5%
Washington DC	2.5	1.28	2.1	-15%	16%	-1%

Table 5.1 Summary of skylight energy and cost savings;**{** TC "Table 5.1 Summary of skylight energy and cost savings;" \l 6 **}**

The simple payback periods of adding skylights were short, ranging from 2 to 4 years. The cost benefits were achieved in spite of increases in natural gas use. The increases in natural gas use were caused by both increased heat losses through the skylights in winter and by extra energy that was need to replace the heat given off by lighting in winter. Most cities showed cooling load reductions as a result of adding the skylights. Peak loads in some cities, however, were increased by extra solar heat gains caused by the skylights. In each city, however, skylights led to an overall decrease in electricity consumption and overall cost savings to the building owner.

The seemingly large increases in natural gas use in Miami and Phoenix should be put in some perspective. The heating energy use at these locations was much lower than that used at other locations. The large percentage increases, therefore, result from fairly small absolute changes in the natural gas used at these locations.

The results from the analysis of roof monitors are summarized below in Table 5.2. The table shows the life-cycle cost savings and simple payback period for the monitor configuration with the lowest life-cycle cost in each city. The table also shows the effect of adding the monitors on the electricity use, natural gas use, and peak cooling loads in the building. The results for Seattle were omitted because the roof monitors were not found to be cost effective for that location.

Location	Optimal Area [% of roof]	LCS [$/sf]	Payback [yrs]	Electricity [Δ%]	Natural Gas [Δ%]	Peak Load [Δ%]
Madison	3	0.07	9.1	-13%	14%	-12%
Miami	3.5	0.57	6.7	-15%	29%	0%
Phoenix	4.0	1.23	5.2	-15%	58%	1%
Washington DC	4.0	0.52	6.8	-16%	24%	-9%

Table 5.2 Summary of monitor energy and cost savings;**{** TC "Table 5.2 Summary of monitor energy and cost savings;" \l 6 **}**

The roof monitors had lower life-cycle savings and longer payback periods than the skylights. The optimal glazing area for the monitors was larger than that for skylights, and ranged from 3 to 4.0%. Paybacks for the roof monitors ranged from 5.2 to 9.1 years.

The addition of roof monitors resulted in decreased peak cooling loads in Madison and Washington DC, but no change in peak loads in Miami and an increased peak load in Phoenix. The added heat gains in Phoenix is due to solar heat gains through the monitors and additional conductive gains from the added wall and roof area in the sawtooth roof assemblies. However, there is a net decrease in electricity use in all cities.

The cost savings from adding skylights to the retail building were greater than the savings from most of the insulation measures required by ASHRAE Standard 90.1. The overall payback period for adding the required insulation measures to the retail building in Madison was 6.3 years. The payback for skylights was 2.1 years and the payback for adding monitors was 9.1 years.

5.4 Conclusions{ TC "5.4 Conclusions" \l 2 }

Skylights are a cost effective way of adding daylighting to the retail building. Skylights were found to pay for themselves in each of the locations tested in 2 to 3 years. Cooling equipment resizing contributed to the cost savings associated with the skylights in most cities. In Phoenix and Miami, however, skylights were found to increase cooling loads in the building. In all the other cities tested, cooling equipment size could be decreased due to lower internal heat gains from lighting.

The optimal size of skylights was found to 2 to 2.5% of the gross ceiling area of the building. This result was found to be insensitive to most of the assumptions made in the analysis. The assumptions having the greatest effect on the optimal skylight area were the costs of electricity and skylights.

Sawtooth roof monitors were found to be economically viable in only four of the five locations tested. The monitors were not cost effective in Seattle where electricity is cheap and sunny days are less frequent. The monitors were only marginally viable in Madison. The results of the analysis for monitors in Madison were very sensitive with respect to changes in assumptions of electricity price and cost of roof monitors. In Madison, only small changes in these variables made the monitors not cost effective. In Phoenix, Miami and Washington DC, however, the roof monitors offered simple paybacks of five to seven years. In these cities, the analysis was also less sensitive to changes in assumptions.

Although skylights are more cost effective than roof monitors in the retail building, there may be other reasons to recommend roof monitors over skylights in retail building designs. Skylights sometimes cause leaks in flat roofs. Although good installation can prevent leaks, there is some risk of this problem when skylights are installed. Many designers also consider roof monitors to be more aesthetically pleasing than skylights. Monitors offer an unfiltered, unobstructed view to the sky that translucent skylights do not provide. These factors should be weighed with the cost savings involved when deciding to install either skylights or roof monitors.

The cost savings of daylighting measures in the retail building were found to be of the same magnitude as the cost savings from more conventional changes to the building envelope. The daylighting designs tested in this analysis yielded cost savings with paybacks ranging from 1.7 to 9 years. Adding extra insulation to the building, as required to meet all the requirements of ASHRAE Standard 90.1, yielded a payback of 6.3 years.

The primary difference in the energy savings found for daylighting measures compared to insulation measures was in the type of energy saved. Energy savings from added insulation measures resulted primarily in heating energy savings. Because the retail building used natural gas for heat, the energy savings were due to reduced natural gas bills. The energy savings from daylighting measures, however, were due to reduced electricity use. Both reduced lighting loads, and decreased cooling loads contributed to savings on electric bills. The natural gas use of the building was increased by the addition of daylighting measures. Each of the two designs tested added to heating loads because of increased heat losses from fenestration, and decreased internal heat gains from lighting.

Sensitivity analyses were conducted to determine how changes in the model assumptions would effect the results of the daylighting study. The results of the analysis on skylights were less sensitive to changes in economic assumptions than the results for monitors. However, in both cases the same variables were important. The two variables that had the greatest effect on the results were electricity cost and the unit cost of the glazing (the cost of either monitors or skylights per square foot). The variable that least effected the results was the cost of added ballasts and controls for dimming the lighting.

ASHRAE Standard 90.1 allows a daylighting credit for adding skylights in commercial buildings. Roof monitors offer a cost-effective, energy-saving alternative to skylights for adding toplighting in buildings. In the retail building studied in this thesis, the added glazing would not have interfered with the building complying with the standard. However, for some buildings it might. If the standard were modified to include a daylighting credit for roof monitors, building designers would have the option of adding roof monitors and clerestories without being penalized for the extra glazing in the building. The could produce more cost-effective designs.