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A SIMPLE COST-BENEFIT ESTIMATION FOR DAYLIGHTING DESIGN AND ANALYSIS DURING THE DESIGN PROCESS

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ABSTRACT

The increasing market demand for early design analysis has created a need for simulation-based decision making tools to evaluate the cost implications of daylight improvements. This study investigates the implications of a tool-based analysis approach for offices, the most typical commercial building type in the United States (US), with respect to internal gains and energy use. Prototype single zone daylight and thermal models were created based on ASHRAE 90.1-2007 climates in the United States and envelope parameters to provide results parallel to industry standards. Daylight analysis is used to evaluate fenestration parameters in cardinal orientations. The results are linked into a thermal analysis engine as schedules for shading and electric lighting use which reduces both end-use electrical consumption and peak cooling demand with related air distribution system size adjustments, amounting to \$11-\$56/m^2, per daylight improvement type, averaged across climate zones.

INTRODUCTION

Daylight analysis is often offered as a contractual add on service from consultants and engineers in efforts to earn 1-2 points for LEED accreditation (U.S. Green Building Council, 2009). The LEED NC 2009 IEQ Credit 8.1, Daylight and Views–Daylight credit requires a workplane illuminance of 269 lux in 75% of all regularly occupied spaces. Providing the service in this capacity is rather costly, commonly ranging from \$1.50-\$3.00/m^2 of building area. Such consulting also has a low probability of success in achieving LEED points as only buildings designed with single-loaded corridors can readily achieve the requirements. Thusly, there is a reasonable desire to investigate the economic benefits of daylighting beyond the LEED rating system in order to create better, more efficient buildings.

Daylight analysis during the design process can be used to evaluate fenestration parameters and architectural massing which reduces both end-use electrical consumption and peak cooling demand. The high costs cited earlier, however, deter many design teams from early design analysis, when form is still fluid. When waiting until the project design is set, daylight evaluation for LEED costs roughly the same, yet at this point improvements often cannot be made. This paper specifically targets the design development phase of a building project for that reason.

We investigate the capacity of daylight analysis and design to improve energy use relative to life-cycle costs and initial cost savings associated with peak load reductions. First, economic metrics are defined which are used in the evaluation of several daylighting improvements for each of the eight US ASHRAE climate zones. Next, methods of investigating typical energy use reductions for simplified perimeter energy and daylight models are discussed. This dual analysis results in a daylight and energy evaluation methodology which is being implemented into a spreadsheet tool for use in client presentations and consultations.

METHODOLOGY

Energy cost rates, first costs, and the cost of design improvements are correlated with building simulation results from simple single-zone perimeter energy models. In this study, these models are established for the four cardinal directions of North, South, East and West in each of the eight US ASHRAE climate zones. By combining the cost data with iterative simulations for varying combinations of daylighting design improvements, the cost savings of climate-dependant daylighting design improvements are estimated.

Economic Metrics

The evaluation of daylighting strategies is dependent on a number of economic considerations, including improvement capital costs, resulting capital cost reductions and reduced energy costs during building operation. Calculated costs are provided as a function of unit floor area to serve as multipliers applied by design teams to individual projects. This metric is referred to as ‘cost intensity’ and has units of \$/m^2.

Energy costs native to regions representing each climate zone are shown in Table 1 using \$/kWh rates for electricity and \$/Therm for natural gas consumption. These rates range from \$0.08-\$0.15/kWh and \$0.78-\$1.12/Therm between zones. Electric rates are applied to cooling and artificial lighting simulation results for energy use, while natural gas rates are applied to heating energy-use.

Table 1
U.S. E.I.A. Average Retail Price of Electricity and Natural Gas to Commercial Customers

ASHRAE Climate Zone	Cost per Unit Energy	
	Electricity ($/kWh)	Natural Gas ($/Therm)
1	$ 0.0996	$ 1.0918
2	$ 0.0885	$ 0.8279
3	$ 0.0968	$ 1.1156
4	$ 0.1162	$ 1.0238
5	$ 0.0808	$ 0.9011
6	$ 0.0808	$ 0.7795
7	$ 0.0808	$ 0.7795
8	$ 0.1469	$ 0.8960

Costs for individual daylight improvements are based on published U.S. national average construction data, primarily from the *RS Means CostWorks* database and *Cost of LEED: A Report on Cost Expectations to Meet LEED-NC 2009* (RS Means Company, 2011; Building Green LLC, 2010). Table 2 contains unit capital costs for evaluated daylight improvements.

Table 2
Capital construction costs pertaining to selected types of daylight improvements

Capital Cost	Unit Cost ($/Unit of Measure)	Cost Intensity ($/m^2 of floor area)
Exterior shading devices	$807/m^2 of material	Varies by Climate $15-$250/m^2
Improved glazing	$75/m^2 of material	$10/m^2
Daylight dimming ballast (3x)	$250/ballast	$23/m^2
Air distribution system	$215/m^2 of floor area	Varies by Climate $129-$215/m^2

Estimating Energy Reduction per Climate Zone

Once a cost model for a series of potential building upgrades has been constructed, the energy savings and comfort benefits of those upgrades have yet to be determined. Relative assumptions are made about energy savings through the use of coupled daylight and energy models compared to a standard baseline case. The decision to use a separate daylighting model was made because such models consider volumetric geometry and employ modern algorithms which are most representative of reality. (Ward, 1994; US Department of Energy (USDOE) 2010; Ramos and Ghisi, 2010; Jakubiec and Reinhart, 2011).

The energy simulations herein are performed using EnergyPlus (USDOE, 2010). EnergyPlus is a validated energy-modelling tool that models heating, cooling, lighting and ventilation energy use.

All daylight simulations utilized this paper are performed with DAYSIM, a validated raytracing software which uses a daylight coefficient method to predict hour-by-hour point illumination annually (Reinhart and Walkenhorst, 2001). The benefits of DAYSIM are that it can simulate complex building geometries with external obstructions accurately; that it uses the Perez sky distribution paired with typical meteorological year (TMY) data to realistically simulate direct and diffuse sky components; and that it generates hourly electric lighting and window shading (venetian blinds) schedules based on detailed simulation results and expected occupant behavior (Reinhart, 2004).

EnergyPlus utilizes the same TMY weather files for the consideration of climate in energy simulations as does DAYSIM. Thusly, we use the shading and lighting schedules generated by DAYSIM as schedule inputs into the energy analysis of EnergyPlus while sharing the same occupancy schedule between the two programs.

As daylighting strategies will typically affect perimeter zones more strongly than interior zones, a single-zone perimeter model was constructed for analysis in each climate zone. The building is an internally load dominated office building with an occupant density of 1person/10m^2, 4.0W/m^2 equipment load and 10.74W/m^2 lighting load occupied between 9AM-5PM on weekdays. The material components for the daylighting and energy models were determined based on ASHRAE standard 90.1 2007, and are detailed in Table 3 below. For glazing properties, visual transmittance was correlated in each program. All ceilings and floors in the energy model are considered to be adiabatic as if the model is part of a larger multi-story building.

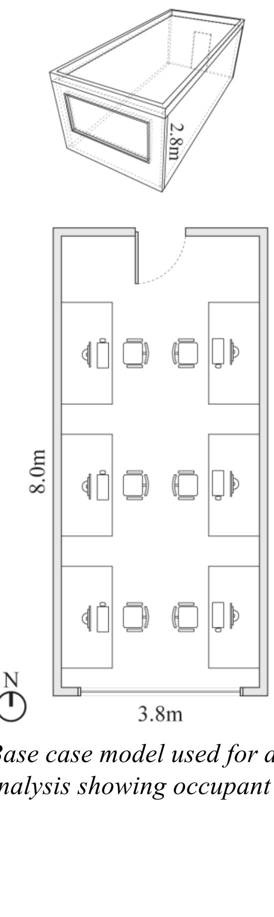

Figure 1 Base case model used for daylight and energy analysis showing occupant locations.

The window to wall ratio (WWR) is fixed at a standard 40% of the façade area, and the depth of the modeled perimeter zone is 8m as shown in Figure 1. Four cardinal orientations were tested; however, for the purposes of this paper, only the South-facing data and results are presented for the sake of brevity.

Table 3
Base case material parameters used in energy simulations per ASHRAE zone

ASHRAE Climate Zone	Exterior Walls U-Value (W/m^2K)	Glazing SHGC (%)	Glazing U-Value (W/m^2K)	Glazing TVis (%)
1	0.70	0.25	5.17	0.08
2	0.70	0.25	4.03	0.16
3	0.48	0.25	4.03	0.16
4	0.36	0.34	4.26	0.29
5	0.36	0.34	3.64	0.29
6	0.36	0.34	3.64	0.29
7	0.36	0.44	3.12	0.65
8	0.36	0.44	3.12	0.65

A city was selected from each ASHRAE climate zone to consider the effects of climate on the appropriateness of daylighting design for different physical locations: 1 Miami, FL; 2 Houston, TX; 3 Atlanta, GA; 4 Baltimore, MD; 5 Chicago, IL; 6 Minneapolis, MN; 7 Duluth, MN; and 8 Fairbanks, AK. Electric lighting and blind schedules were generated for each zone model using DAYSIM. Blinds are opened by a conscientious (active) user seated near the window each day in the morning and at a noon lunch break. If any user experiences direct sunlight on their desk, the blinds are lowered until the end of the lunch break or until the next morning (Reinhart, 2004). Electric lighting is on a continuous dimming system based on perfect knowledge of workplane illuminance with a ballast factor of 20% when the lights are on. Reduced natural lighting levels during periods when blinds are closed are accounted for by the DAYSIM dimming model. These schedules are used as inputs into EnergyPlus energy simulations (An and Mason, 2010).

Several daylighting improvements were considered in various combinations to represent potential energy savings from simple design modifications,

- Continuous dimming of electric lights is considered for all upgrades; however, the base case model has electric lighting turned on during all occupied hours.
- Improved visual transmittance of glazing is zone dependant such that zones 1, 2 and 3 have a TVis = 0.29; for zones 4, 5 and 6, TVis = 0.4; and for zones 7 and 8, TVis = 0.70. ASHRAE 90.1 thermal performance data from Table 3 is maintained in all cases.
- Static shading is modelled as a series of horizontal louvers sized for the peak cooling hour in the base case model using the familiar equation for the horizontal projection D, D=height window x cos ϕ / sinθ ϕ D= height × cosº⁄sin□ where □ is the azimuth and □ is the altitude of the sun at peak cooling.

From these simple renovations and including the baseline model, five daylighting and energy models are generated for each ASHRAE climate zone,

A. Baseline model – lights always on during occupied hours.
B. Default glazing.
C. Default glazing with fixed external shading.
D. Improved glazing.
E. Improved glazing with fixed external shading.

An example of the methodology for developing these schedules can be illustrated in the case of ASHRAE Zone 4, Baltimore MD. A falsecolor plot of the hourly annual cooling loads is shown in Figure 3. The peak cooling load based on the typical meteorological year (TMY) weather data is found on September 4th at 13:00. Using the earlier equation for the horizontal shading projection considering louvers spaced vertically at 0.2m height, the horizontal projection is found to be 0.13m as seen graphically in Figure 2. The resulting Daylight Autonomy (DA) for a 500 lx minimum illuminance level is displayed in Figure 4. Daylight autonomy is defined as the percentage of occupied hours in the year where a minimum illuminance is met by daylight alone (Reinhart, 2004). As the minimum illuminance at each occupant location is used to generate electric lighting schedules for each hour in the year, DA is a reasonable representation of the amount of electric lighting necessary and the daylit quality of a space.

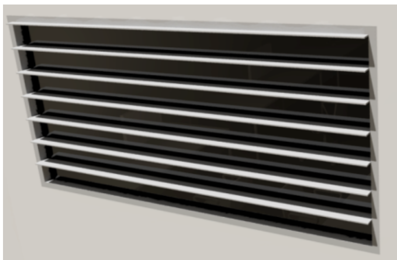

Figure 2 Baltimore case louvers on September 4th, 13:00 (peak cooling load)

RESULTS

Energy Use

The energy results generated for each climate zone using the above methodology are shown in Figure 5 for each South-facing model normalized to an HVAC system with a COP of 4.8 and a heating efficiency of 0.8. These numbers are probably accurate enough to give a relative impression of the effects of sidelit daylighting strategies when presenting initial savings estimates to clients; however, detailed analysis including external obstructions, proper schedules, loads and thermal and visual material properties would be necessary to determine energy savings in the actual design scenario.

For each climate zone, daylighting improvements show a substantial reduction in cumulative annual energy use for lighting, and cooling energy. Lighting energy use intensity (EUI) is reduced in a range from 6% (19.7 kWh/m^2 to 18.5 kWh/m^2, Default glazing, Zone 1 Miami) to 95% (19.7 kWh/m^2 to 7.2 kWh/m^2,static shading with improved glazing, Zone 7 Duluth). Cooling EUI is reduced by up to 95% in the case of Zone 8, Fairbanks with improved glazing (193.5 kWh/m^2 to 8.4 kWh/m^2). It is expected that an increase of heating energy expenditure will occur with a reduction in lighting loads. Heating EUI increases by up to double the baseline in the case of Zone 4, Baltimore with static shading and improved glazing.

Such simulations predict substantial energy savings when considering gross numbers; however, peak loads are also affected by such design decisions. Table 4 further shows the peak loads for each daylighting improvement (B through E) compared against the baseline (A). It can be seen that predicted peak load reductions for cooling are as high as 81% for Zone 8, Fairbanks in the case of improved glazing with fixed shading. Such reductions allow for reduced first costs spent on HVAC systems.

Table 4
Peak heating and cooling loads for daylighting cases

ASHRAE	Peak Cooling Load, Wh/m^2				
Zone	**A**	**B**	**C**	**D**	**E**
1	368.14	364.11	358.38	352.37	345.11
2	407.38	400.30	375.91	325.06	323.33
3	323.14	320.49	317.85	289.36	268.32
4	405.64	384.13	297.87	258.89	247.29
5	423.68	412.97	360.82	324.69	210.66
6	404.70	384.51	368.46	286.85	261.18
7	363.60	329.33	295.06	192.97	187.34
8	350.49	331.73	315.10	84.72	65.74
	Peak Heating Load, Wh/m^2				
	A	**B**	**C**	**D**	**E**
1	8.61	8.51	8.83	9.72	10.00
2	21.59	21.98	21.43	25.55	25.80
3	43.45	45.42	45.55	46.40	46.34
4	53.75	57.99	57.40	58.36	56.77
5	64.65	70.66	69.14	71.06	59.34
6	91.22	90.96	91.25	73.41	61.56
7	87.36	81.43	81.43	53.42	52.04
8	116.00	92.65	95.11	52.66	52.68

A. Baseline, lights always on
B. Default glazing
C. Default glazing with fixed shading
E. Improved glazing
F. Improved glazing with fixed shading

Economic Impact

Energy results are shown in Figure 6 as cost intensities ($/m^2) corresponding with Figure 5 energy use results. A number of factors contribute to the differing gradient of result profiles between energy use and energy cost.

Energy Rates – Table 1 shows climate zones 4 and 8 have the highest electricity rates. This explains Baltimore's higher basecase energy cost than that of Atlanta, and why Fairbanks is higher than Duluth or Minneapolis, despite the climate zone's lower cooling demand. Climate zones 1 and 3 have the highest natural gas rates; however, the low demand for heating in these climate zones negates the higher fuel cost.

'B' and 'C' Cost Offsets – Each daylight improvement strategy provides both cost benefits as well as penalties over basecase 'A' when applied in prescribed bundles 'B' thru 'E'. These relationships are illustrated in Figure 7, looking a single climate zone model, Baltimore. Case 'B,' default glazing, is similar to the basecase 'A,' lights always on, aside from changing lighting controls from all-on to dimming, which incurs a first cost of $23.44/m^2. Air distribution first costs are only reduced by half of that amount, $11.41/ m^2 and operating energy cost is estimated to reduce by $9.93/m^2.

'D' and 'E' Cost Offsets – Adding fixed shading sized to meet peak cooling loads increases estimated energy costs reductions by another $12.61/m^2, however the first cost of the measure is a staggering $79.72/m^2. The resulting first cost reduction of $84.03/m^2 for the air distribution system balances the cost equation in the Baltimore climate zone. Climate zones with lower solar angles, however, will require longer shading elements or shorter but multiple shading elements. Fixed shading cost is calculated as $/m^2 of shading material area, which means fixed shading first costs are higher for climates with lower solar altitudes.

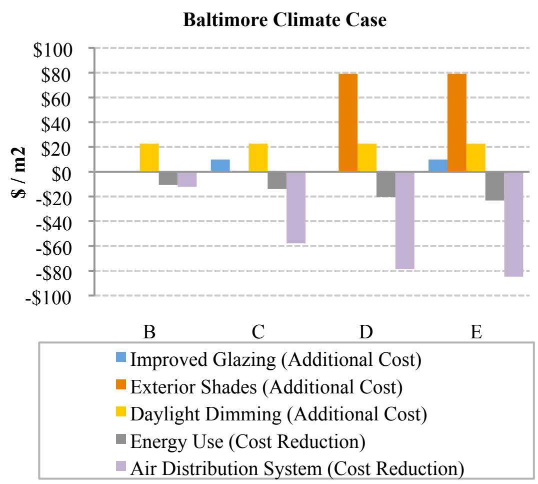

Figure 7 Annual cost intensity for daylighting design improvements and resulting savings and costs ($/m^2)

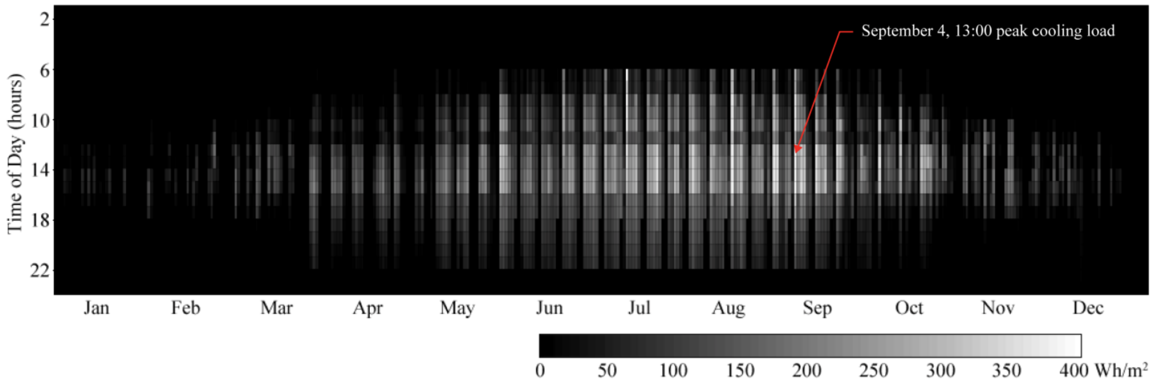

Figure 3 Baltimore base case South-facing zone hourly cooling loads (Wh/m²)

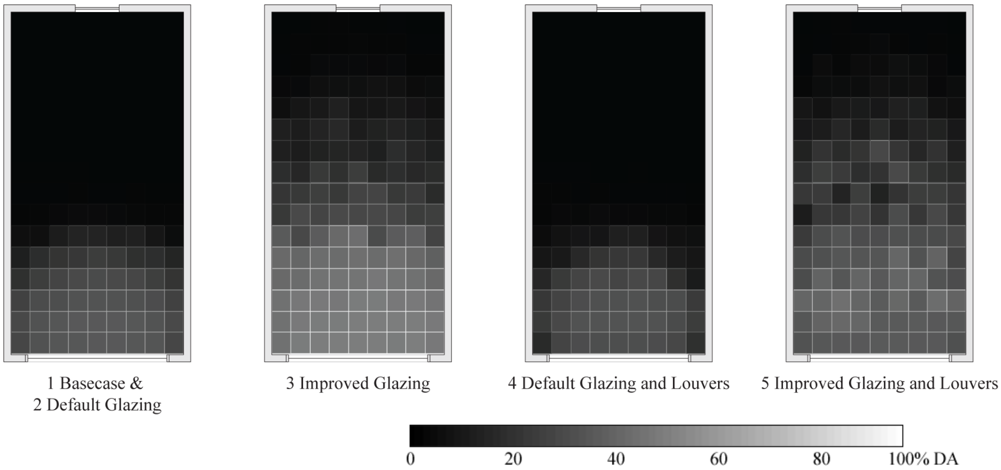

Figure 4 Daylight autonomy (500 lx) for Baltimore South-facing design scenarios considering blind operation

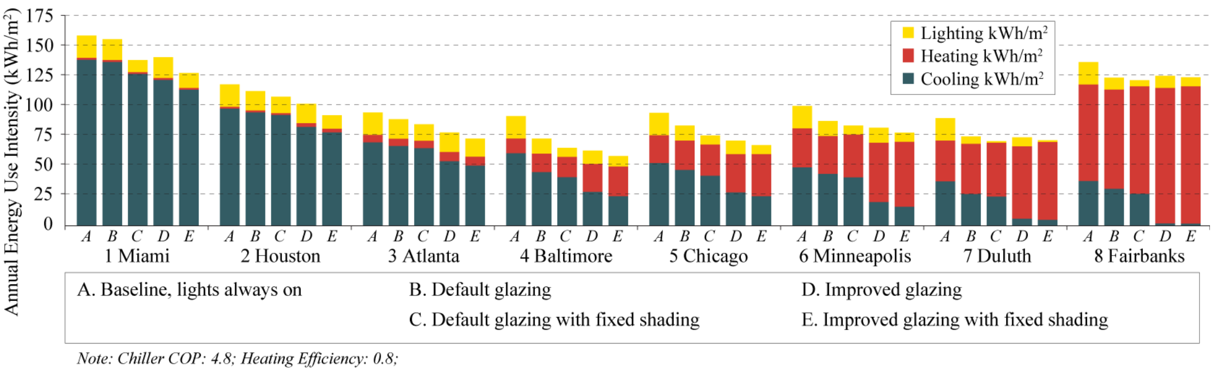

Figure 5 Annual energy use intensity per climate zone and daylighting design improvements (kWh/m²)

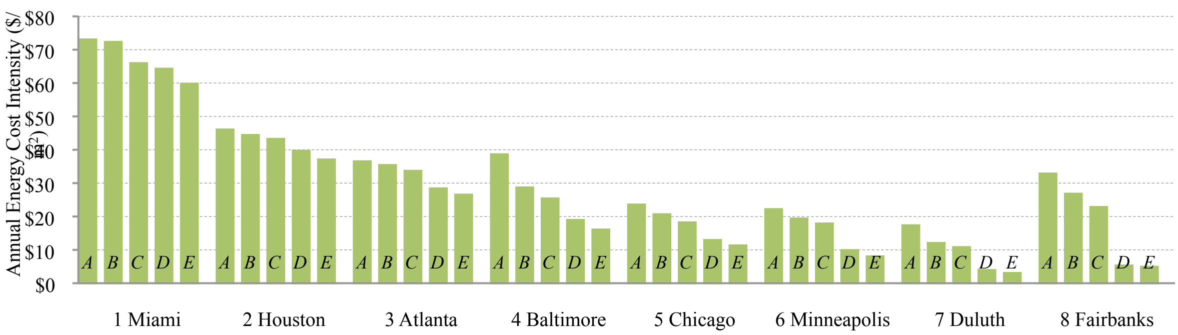

Figure 6 Annual energy cost intensity per climate zone and daylighting design improvements (US$/m²)

Capital Costs – When a building owner/developer performs an investment appraisal, the sum of cash flows determines purchasing power at the present time. Table 4 balances the additional first cost of daylight improvement(s) with resulting first cost reductions to obtain a net capital cost intensity ($/m^2). The net capital cost of 'B' and 'C' averaged across climate zones is $12.19/m^2 while the cost of options 'D' and 'E', is $46.43/m^2. This is because out-of-pocket costs for a high performance glazing product exceeds standard glazing products by a factor of 3. Note that both improved glazing options 'D and E' for climate zone 8 are deemed outliers and were left out of the calculated average cost values.

Table 4
Net capital cost intensity of daylight design improvements per ASHRAE zone

ASHRAE Climate Zone	Capital Cost (Additional – Resulting Reduction) per Unit Floor Area			
	B. Default glazing	C. Default glazing, fixed shading	D. Improved glazing	E. Improved glazing, fixed shading
1	$21/m^2	$28/m^2	$29/m^2	$36/m^2
2	$20/m^2	$17/m^2	$14/m^2	$24/m^2
3	$22/m^2	$30/m^2	$55/m^2	$52/m^2
4	$12/m^2	(-)$23/m^2	$25/m^2	$30/m^2
5	$18/m^2	$2/m^2	$68/m^2	$43/m^2*
6	$13/m^2	$15/m^2	$73/m^2	$70/m^2
7	$3/m^2	(-)$7/m^2	$60/m^2*	$71/m^2*
8	$12/m^2	$12/m^2	$187/m^2*	$197/m^2*

*Allowable Air Distribution System Cost Reduction limited to 40% over Basecase

Payback Period – Knowledge of project capital and operating budgets will help determine which daylight improvement options meet project financial constraints. For example, if a project is located in climate zone 3 and has a $40/m^2 capital investment budget and an available operating budget which allows for a 10 year payback period, reviewing Tables 4 and 5 would steer the decision towards case 'C' with default glazing and fixed shading. This would provide a $30/m^2 net capital cost and a 5-10 year payback period.

Table 5
Payback period in years for daylight design improvements per ASHRAE zone

ASHRAE Climate Zone	Payback Period in Years			
	B. Default glazing	C. Default glazing, fixed shading	D. Improved glazing	E. Improved glazing, fixed shading
1	Up to 25	0 - 3	0 - 3	0 - 3
2	10 - 15	5 - 10	0 - 3	0 - 3
3	15 - 20	5 - 10	5 - 10	3 - 5
4	0 - 3	0 - 3	0 - 3	0 - 3
5	5 - 10	0 - 3	5 - 10	0 - 3*
6	3 - 5	0 - 3	3 - 5	3 - 5
7	0 - 3	0 - 3	3 - 5*	3 - 5*
8	0 - 3	0 - 3	5 - 10*	5 - 10*

*Allowable Air Distribution System Cost Reduction limited to 40% over Basecase

Beyond Payback – Simple payback often ignores the impact of cash flows that are received following the payback period, though it is those cash flows which determine the profitability of an investment. Table 6 show a cost savings intensity ($/m^2); this is the energy cost reduction which would continue following the payback period. For example, if a project is located in climate zone 3 again, both case 'C' and 'D' in Table 5 offer a 5-10 year payback period. It turns out that default glazing with fixed shading and improved glazing share similar first costs. Table 6, however, provides insight into energy cost savings, following payback, with case 'D' offering $25/m^2 more annual savings per unit floor area than case 'C'.

Table 6
Annual cost savings intensity for daylight design improvements following payback period per ASHRAE zone

ASHRAE Climate Zone	Annual Savings per Unit Floor Area			
	B. Default glazing	C. Default glazing, fixed shading	D. Improved glazing	E. Improved glazing, fixed shading
1	$3/m^2	$13/m^2	$18/m^2	$27/m^2
2	$5/m^2	$20/m^2	$50/m^2	$53/m^2
3	$3/m^2	$6/m^2	$31/m^2	$47/m^2
4	$21/m^2	$70/m^2	$98/m^2	$107/m^2
5	$8/m^2	$37/m^2	$61/m^2	$98/m^2*
6	$14/m^2	$24/m^2	$75/m^2	$91/m^2
7	$26/m^2	$54/m^2	$99/m^2*	$99/m^2*
8	$18/m^2	$32/m^2	$114/m^2*	$114/m^2*

*Allowable Air Distribution System Cost Reduction limited to 40% over Basecase

DISCUSSION

The data presented suggests that daylighting analysis in practice could be well poised to move beyond the realm of LEED credit verification. Daylighting design can have substantial energy use reduction and first cost benefits. In south-facing perimeter zones, the above research suggests payback periods typically less than five years and a mean annual savings of $79.5/m^2 for design case E, improved glazing and fixed external shading.

In effect, this paper addresses the high cost of design-level consulting without a clear evaluation of the benefits of daylighting design. Consulting engineers must communicate this data to both the architect and the owner in order for daylighting design to become commonplace. This could result in a net benefit to all parties. The architect can better market their services as 'sustainable' and in terms of the human comfort effects of proper massing and shading design. The owner will have a building, which costs less and uses less energy. Finally, the consulting engineer benefits from a substantial expansion of billed services on projects which opt for detailed daylighting analysis.

Limitations of the Methodology

The methodology employed in this paper has several limitations which should be discussed relative to its broad applications to design. A basic calculation of potential energy-reduction benefits of designing an office building relative to natural daylighting is performed. A standard perimeter zone is used in the simulations as such zones will be most affected in terms of lighting reduction, thermal loads and occupant behaviour. The utilization of a single perimeter zone however does not include thermal interactions with interior zones and thusly is an abstraction from reality. Thusly, the results presented in this paper should only be interpreted and utilized for perimeter zones. Modelling one typical daylit space per facade probably makes sense in many cases; however, a complete thermal model is necessary to transfer heat and energy synergistically between zones.

The authors also wish to assert that fixed shading consisting of louvers is not the ideal nor only method for daylighting design; however, it serves the intent of this study as an easily reproducible method to account for the position of the sun, reduce climate-specific building loads and reduce occupant discomfort from direct sunlight. Any daylighting design should strive to reduce building thermal loads and improve occupant comfort through the same benchmarks; therefore, the louvered assumption of daylighting design is deemed acceptable for the purposes of this paper.

The average retail fuel prices in Table 1 and the estimated construction costs in Table 2 are intended to serve as 'default' values as one would find in any simulation tool. These prices will vary by market, project and over time.

Cost-Benefit Estimation Tool

A simple 'simple cost-benefit estimation tool' will accompany the publication of this paper in accordance with the preceding simulation data. The estimation tool will provide consulting engineers with the ability to enter custom inputs following 'performance curves' based on the energy models simulations performed for each ASHRAE climate zone in this study. Results calculated by the tool based on custom user inputs will update the cost intensities and payback periods presented in Table 4– Net Capital Cost, Table 5– Payback Period and Table 6–Cost Savings following Payback Period. Spreadsheet tool authors will regularly update the default values used in the spreadsheet tool, either annually or as updated cost data becomes publically available from their respective sources. The purpose of the spreadsheet tool is to take neither the place of detailed simulation nor that of an extensive cost-benefit analysis. The spreadsheet tool will be of value at those points in the design process when important decisions require immediate guidance, in the absence of either waiting time or scope for detailed simulations or extensive cost-benefit analyses.

CONCLUSION

We present a simple framework to evaluate prospective costs and benefits for a standard office building in multiple climates. The intent of this study is to generate discussion and dictate relationships for the development of a spreadsheet tool that will accompany the publication and presentation of the final paper.

Typically, in the initial stages of design, an architectural practice knows information such as the building massing, program, the rough dimensions of the building and how much perimeter area the building form will have. However, it is often not clear if it benefits a specific project to perform detailed daylighting analysis and design. As previously mentioned, such analysis alone costs as much as $3.00/m^2 of building floor area.

By coupling annual daylight illuminance, occupant behaviour and energy models, a detailed daylight analysis was performed which illustrates that considering daylight in the process of designing buildings can have significant operations and first-cost economic savings. While this may seem obvious, more importantly it allows a framework for determining the relative savings by building type, form and climate.

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