DAYLIGHTING OPTIMIZATION IN SMART FAÇADE SYSTEMS

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ABSTRACT

As part of the application of optimal control to smart façade systems (SFS) with motorized Venetian blinds inside the glass enclosed cavity, we investigate the rapid determination of daylighting quantity and quality obtainable from these systems.

This paper proposes a set of daylight performance indicators to assess smart façades or similar systems, and discusses real-time daylighting optmization.

INTRODUCTION

Since the 1950's onwards, the theory of daylighting propagation through blind systems has been extensively studied. Early studies (Parmelee et al [1952, 1953], Nicol [1966]) have been focused on studying parametric characteristics by using simple analytical methods.

In the 1990s, due to the awareness of potential benefits of the blind systems in 'smart' facades and the implacability of complex theoretical models, many researchers shifted to experimental studies, resulting in the establishment of luminous transmittance curves for a discrete set of azimuth and louver angles (DiBartolomeo [1997], Lee [1995, 1998], Breitenbach [2001]). In works done by DiBartolomeo (1997) and Lee (1995, 1998), the lighting energy consumption and peak cooling load were measured when sky conditions and stationary louver angles (set at 0°, 15°, and 45°) were recorded. A more comprehensive experimental study done by Breitenbach (2001) also resulted in the establishment of luminous transmittance curves as a function of a discrete set of azimuth and louver angles.

These experimental studies were aimed at generating a full set of data points, or sometimes a simplified model (based on such a set), for incorporation into the thermal simulation programs. What is lacking thus far is a comprehensive procedure to determine quantitative and qualitative luminous characteristics of blind systems at any time in a given condition, e.g. the luminous intensity distribution, total lumens entering the space, window surface luminance, total area of over-lit surface in the space, etc.

More recently, owing to fast proliferation of computing power, physically-based programs (RADIANCE, LIGHTSCAPE) and computing-intensive techniques (ray tracing, radiosity) have been applied to simulate advanced daylighting systems such as blinds, prismatic reflectors, light shelves and complex shaped internal spaces (Moeck 1998). But, because of prohibitively long simulation times, these techniques are usually not suited to be incorporated in on-line real-time optimal control systems that require instantaneous prediction of indoor daylight distribution.

For these reasons, this study applies pre-simulations with RADIANCE for a typical, rectangular, office space that has a south facing smart façade, and results are consequently analyzed and processed to generate a simple algorithm to predict indoor daylight distribution. It is then described how such an algorithm is employed in real-time computation for optimal control actions.

DAYLIGHTING SIMULATION MODEL

In order to keep the number of variables within bounds, the daylighting prediction model was developed for a specific reference office space and an attached reference façade system.

The reference office to be used for daylighting simulations is shown in Figure 1: it is a rectangular space of 3m high, 4m wide and 6m deep. The south facing smart façade unit is 2.8m high and 3.8m wide. The window sill is 0.2m. The reflectance of ceiling, wall, floor and exterior ground is 0.8, 0.5, 0.2, and 0.2, respectively. These reflectance values are generally accepted as recommended by IESNA (2001) for office design.

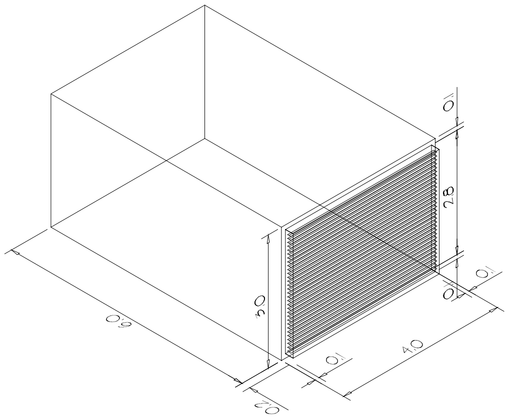


Figure 1 Daylighting simulation model

The Smart Façade Demo Unit (SFDU) installed at Georgia Tech was selected as a reference smart façade system. This unit was developed for experimental testing of optimal control studies related to energy, daylighting, visual comfort and thermal comfort, as shown in Figure 2. The Unit consists of an exterior glazing, an interior low-e glazing, a motorized rotating louver, an air cavity, and electronically controlled ventilation dampers at the top and bottom of each glass layer. The louver slats are 8.75cm wide and have the reflectance of 0.5.

Figure 2 Smart façade system installed in the College of Architecture Building, Georgia Institute of Technology, Atlanta, GA, U.S.A.

DAYLIGHTING PERFORMANCE CRITERIA

Visual performance is defined by the Illuminating Engineering Society of North America (IESNA) as the quantitative requirement for performing a visual task, taking into consideration speed and accuracy. It is also a measure of how well one can perform a visual task. This visual performance primarily depends on the following qualitative and quantitative criteria tabulated in Table 1.

Table 1 Current visual criteria

	Recommended Values	References
Task Illuminance	General offices, 500 (Lx)	CIBSE (1997)
	Performance of visual tasks of medium contrast or small size, 500-750-1000 (Lx)	IESNA (2001)
	Tasks with medium visual requirements, e.g., medium machining, offices, control rooms 300-500-750	CIE (1986)
Luminance Ratio*	Between windows and adjacent surfaces 40:1	VELDS (2000)
	Anywhere within the normal field of view 40:1	Stein (2000)
Uniformity**	For the whole room, the ratio of the minimum and average illuminance ≥0.8	CIE (1988), CIBSE (1994)
Daylighting Glare Index	Just acceptable degree: DGI ≤ 16	Hopkinson (1972)
Visual Comfort Probability	VCP ≥ 70	IESNA (2001)

* *The ratio between the minimum and maximum luminance within the field of view of the observer.*

** *The ratio between the minimum and maximum illuminance or between the minimum and average illuminance at a work plane.*

Before attempting to apply the above-mentioned criteria to the smart façade system, the following facts should be considered:

- *Luminance ratio*: The way daylight impacts the louvers results in horizontal, dark and bright striped luminance distribution cast on the interior glazing of the façade. The configuration (shape, pattern, brightness) of these horizontal stripes varies not only with user's eye position but also with all reflections, transmissions and absorptions induced by the louver angle. With this in mind, the luminance ratio between the stripes, which vary in brightness, and adjacent surfaces (wall, ceiling, and floor) is difficult to assess.
- *Daylighting Glare Index (DGI)*: Since the daylighting glare index is obtained from experiments with uniform light sources, it is not yet clear whether DGI can be used to represent the degree of discomfort glare in situations with a non-uniform luminance distribution on the window surface such as the case addressed here (Velds, 2001).
- *Visual Comfort Probability (VCP)*: Visual comfort probability has been developed for

small electric light sources, and thus not applicable to large windows.

Following Moeck's (1998) study, the averaged luminance of a window surface is proposed instead of the luminance ratio, daylighting glare index and visual comfort probability. This is likely to be the most appropriate until general indices for the glare sensation of this particular system are developed. The luminance of the window surface should be the underlying basis for daylighting glare computations. Currently, there is no clear-cut standard for limiting luminance on window surface but IESNA RP-1 (1993) limits the luminance of any room surface to 850 cd/m2. Assuming a perfectly diffuse surface with reflectance of 0.8, this corresponds to an illuminance of 3340 Lx. In this study, the value (850 cd/m2) suggested by IESNA is applied.

In summary, the following visual comfort criteria to describe the daylight quality and quantity for smart façade systems are selected:

- Daylit task illuminance at the work plane
- Uniformity
- Luminance of window surface

Beside the above-mentioned three visual comfort criteria, the following two should also be of concern for daylighting optimization in smart façade systems.

- Daylighting autonomy: the ability to illuminate the task with only daylighting.
- Outward visibility: direct view to the outside for a worker at his workstation.

By providing enough daylight for the perimeter zone, not only electric lighting but also cooling demand can be reduced. In this study, the daylighting autonomy is evaluated based on the daylit illuminance of the work plane at 3m distance from the window. The threshold value of illuminance can vary according to the task category. In this study, 500 lux is selected as recommended for general office work.

There is no general standard for outward visibility through the gap between louver slats. Usually, the slat width corresponds approximately to the slat distance such that it can perfectly exclude solar radiation when it is set at –90˚ or +90˚. When the louver slat angle is ±45˚, it can totally block a horizontal view normal to the window surface. In this study, ±45˚ is selected as the threshold value for viewing of the outside through the openings between the louver slats.

CALCULATION OF DAYLIGHTING PERFORMANCE CRITERIA

Daylit task illuminance at the work plane: A total of 11 virtual illuminance sensors are located at the center line of the space to determine the task illuminance on the work plane. The 11 points are located at 0.7m above the floor and spaced at a 0.5m interval starting from the surface of the interior glazing as shown in Figure 3. The calculated illuminance values are averaged, as shown in Equation (1).

$$E_{avg} = \frac{\sum_{i=1}^{11} E_i}{11} \quad (1)$$

Uniformity: Once the illuminance is calculated, uniformity is determined. The uniformity U can be defined as the ratio of the minimum and average illuminance as shown in Equation (2).

$$U = \frac{E_{min}}{E_{avg}} \quad (2)$$

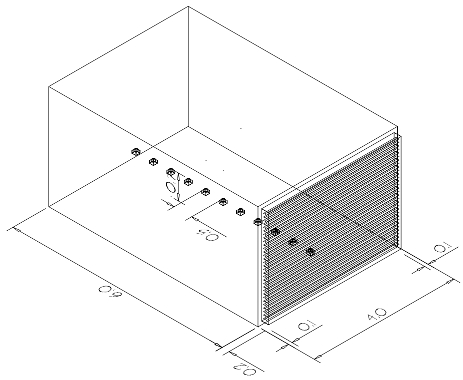


Figure 3 Calculation of task illuminance and uniformity on the work plane

The window luminance, taken as the underlying basis of glare sensation, depends on a user's viewing direction and position. Three typical viewing cases exist:

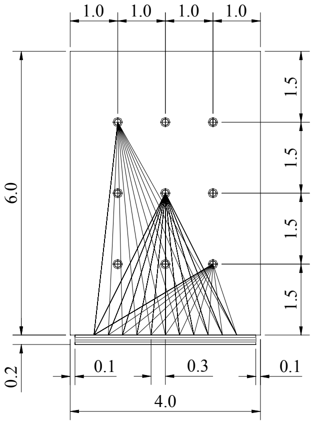
- Case 1: Looking directly at a window, in a standing position
- Case 2: Looking directly at a window, in a seated position
- Case 3: Looking at the task, in a seated position

Looking directly at a window in a standing position is the worst case for glare sensation. Looking directly at the aperture while seated provides information about the typical glare to expect in a room. Looking at the task while seated usually occurs with a narrow field of view, leading to very little possibility of glare sensation (Robbins 1986). For our optimization study, Case 1, the worst case, is chosen.

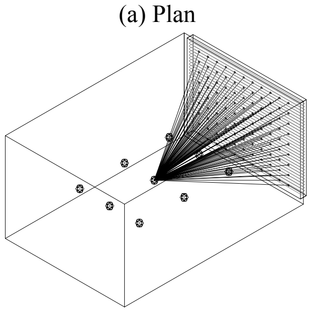
The window luminance values are determined from 9 different positions shown in Figure 4. From each position, luminance values at 99 (11 by 9) points on the window surface are calculated. The points on the window are spaced at 0.3m interval vertically and horizontally as shown in Figure 4 (a) and (b). The total of 891 (99 points × 9 viewer positions) calculated luminance values is averaged:

$$L_{avg} = \frac{\sum_{p=1}^{9}\sum_{i=1}^{99} L_{i,p}}{891} \quad (3)$$

where L_{avg} is the average luminance of the window surface and p represents position 1 to 9.



(a) Plan



(b) Axonometric

Figure 4 Calculation of the window Luminance

DAYLIGHTING SIMULATION

Daylighting simulation cases are made for the three key seasonal days of the year: Jun. 22nd, Sep. 22nd and Dec. 22nd, whereas on each day the following CIE sky conditions are selected: clear, intermediate, and overcast.

Under clear and intermediate sky conditions, 436 daylighting simulations are conducted. The louver angle changes in 10° intervals from the solar altitude (β) like β, $\beta\pm10°$, $\beta\pm20°$, and so on. The simulation cases are designed in a way to avoid redundant information. For example, the simulation cases after 12 p.m. are not made since 10 a.m. and 2 p.m. times are close mirror reflections of each other for the south facing smart facade unit.

Under overcast sky condition, only 90 cases are simulated at 10:00 A.M. and 12:00 P.M. by incrementing the louver angle in 10° intervals.

The results from a total of 526 (436 + 90) simulations are then interpolated.

DAYLIGHTING OPTIMIZATION

An overall "daylighting performance" can be formulated in a cost function as follows:

$$J = \int_{t_1}^{t_2} \begin{bmatrix} r_1 pf_1\left(E_{avg}\right) + r_2 pf_2\left(U\right) + r_3\, pf_3\left(L_{avg}\right) \\ + r_4 pf_4\left(\varphi\right) + r_5 pf_5\left(DA\right)^2 \end{bmatrix} dt \quad (4)$$

where J is the cost function during a sampling time, r_i are the relative weighting factors, pf_i are the square penalty functions, φ is the louver slat angle, and DA is the daylighting autonomy. A positive louver angle (φ) (degrees from horizontal position) permits building occupants a view of the sky, while a negative louver angle permits a view of the ground.

The daylighting optimization can be achieved by determining the optimal louver slat angle defined is that angle that minimizes the cost function:

$$\begin{aligned} &\min J\left(\varphi\right) \\ &s.t.:\ -90° \le \varphi \le 90° \end{aligned} \quad (5)$$

In order to solve for this nonlinear constrained optimization problem, the 'FMINCON', one of the MATLAB optimization routines is employed. This routine can be effectively used for problems which cannot be solved analytically, and it can search an optimal solution fast enough for real-time optimization.

In contrast to maximizing energy performance (the more saved, the better), more daylighting does not always mean better visual performance. For this reason, the square penalty functions (pf_i) are introduced in Equation (4).

As indicated before, the illuminance of 3340 Lx (equivalent to 850cd/m2) is selected as the maximum average illuminance for avoidance of glare in VDT environments (IESNA RP-1 1993). For the threshold value of minimum illuminance, 500 Lx is selected in general offices (CIBSE 1997). Thus, any illuminance less than 500 Lx or greater than 3340 Lx is penalized, and this is formulated as shown in Equation (6).

$$pf_1\left(E_{avg}\right) = \begin{cases} \left(E_{avg} - 500\right)^2 & if\ E_{avg} < 500 \text{ Lx} \\ 0 & if\ 500 \le E_{avg} \le 3340 \text{ Lx} \\ \left(E_{avg} - 3340\right)^2 & if\ E_{avg} > 3340 \text{ Lx} \end{cases} \quad (6)$$

In a similar way, the penalty functions pf_2, pf_3, pf_4 and pf_5 are generated as follows.

$$pf_2(U) = \begin{cases} (U-80)^2 & if\ U \le 80\% \\ 0 & if\ U > 80\% \end{cases} \quad (7)$$

$$pf_3(L_{avg}) = \begin{cases} 0 & if\ L_{avg} \le 850\ \text{cd/m}^2 \\ (L_{avg}-850)^2 & if\ L_{avg} > 850\ \text{cd/m}^2 \end{cases} \quad (8)$$

$$pf_4(\varphi) = \begin{cases} 0 & if\ |\varphi| \le 45° \\ (|\varphi|-45)^2 & if\ |\varphi| > 45° \end{cases} \quad (9)$$

$$pf_5(DA) = \begin{cases} 0 & if\ E_{y=3m} \ge 500\ \text{Lx} \\ (E_{y=3m}-500)^2 & if\ E_{y=3m} < 500\ \text{Lx} \end{cases} \quad (10)$$

where $E_{y=3m}$ is the the daylit illuminance of a work plane at 3m distance from the window.

The option of squaring the penalty functions makes the cost function differentiable, which is required for application of the MATLAB optimization algorithm..

Additionally, the threshold values in penalty functions can be moderated by the occupant. For example, the angle (±45˚) for outward visibility or the 500 Lx for minimum illuminance level can be changed according to the user's preference. The optimization is embedded in an on-line real-time occupant-responsive system that can be accessed through the web interface to enable the occupant's selection of the preferred setting or control modes from any standard browser (Park et al 2003).

DAYLIGHTING OPTIMIZATION RESULTS

Figure 5 shows the daylighting optimization result for a clear winter day (Dec. 22nd) in Atlanta. The average illuminance is between 500 Lx and 3340 Lx all day (Figure 5 (b)). According to Figure 5 (c), it is impossible to keep the uniformity above the desired threshold (≥80%) because the illuminance level rapidly decreases with the increase of the distance from the window surface. But, notice that the uniformity plotted in Figure 5 (c) is only based on the illuminance by daylight. When the rear zone of the space is lit by electric lighting, the resulting uniformity improves. Figure 5(d) shows that the maximum window luminance is 948 cd/m2 and remains beyond the threshold for 53.2% of the occupancy time (9:00 am-6:00 pm). This is because the optimization of the louver slat angle makes a tradeoff among multiple cost elements in Equation (4). In this simulation, all weighting factors (r_i) are set equal to 1. This means that 1 Lx is as important as 1% in the uniformity, 1 cd/m2 in the window luminance, 1° in the outward visibility, and 1 Lx in daylighting autonomy. By changing the weighting factors, the window luminance can be brought back within the comfort range (at the cost of other factors in the cost function).

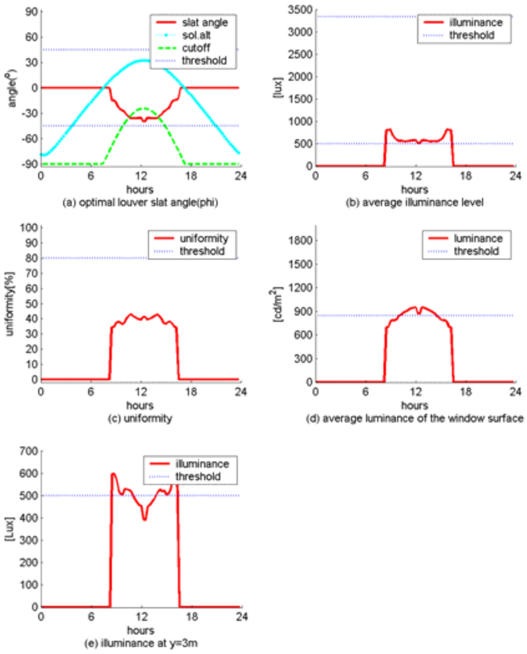


Figure 5 Daylighting optimization for a clear winter day in Atlanta, GA

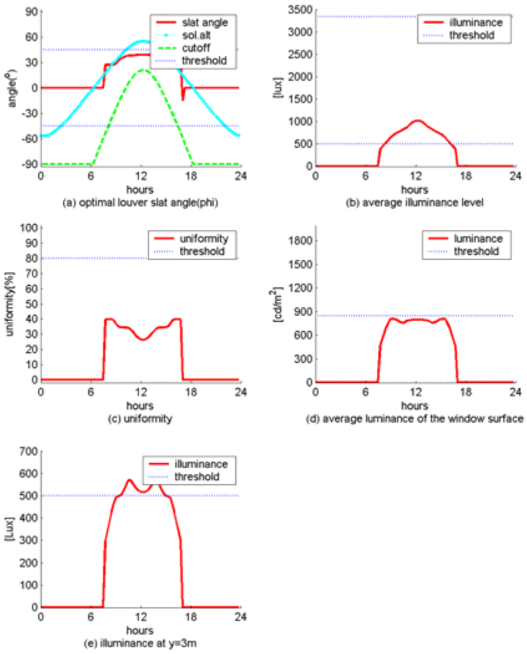


Figure 6 Daylighting optimization for an intermediate fall day in Atlanta, GA

Figure 6 shows the daylighting optimizaiton result for an intermediate sky in the fall season (Sep. 22nd). When the sky is clear, the louver slat angle is towards the ground in order to avoid strong illuminance on the work plane and the overlit window surface (Figure 5(a)). Under the intermediate sky, the louver slat angle is towards the sky to induce more daylight (Figure 6(a), (b)). Uniformity by daylight is always below the desired range of 80% for the entire day. In contrast to that of a clear day, the luminance is always maintained within the comfort range.

For want of space, the daylighting optimization for an overcast sky is not included here. but the overall daylighting performance of the smart façade system is discussed in the following section.

PERFORMANCE COMPARISON

To examine the daylighting performance, this smart façade system, (System I), is compared with a manually controlled façade system (System II) having an identical specification as System I, except that optimal control is replaced by manual actions. , These two systems are run for three typical seasonal days (Dec. 22nd, Jun., 22nd, and Sep. 22nd) under the same CIE sky conditions.

As deduced from Vine et al (1998), there is no uniform pattern of decision for the occupant to select the preferred louver slat angle. Thus, for the case of System II, each of the following louver angles, i.e., -60°, -30°, 0°, 30°, and 60° is assumed to be stationary all day. This represents different operation modes of traditional façades. For a better quantitative representation of the system's performance and easy comparison, the following performance indicators are introduced.

Table 2 Performance indicators

Performance Indicators	meaning
PI 1	Average daylight illuminance of the work plane (between 500 and 3340 Lx)
PI 2	% of hours where the average illuminance is in comfort range (between 500 and 3340 Lx)
PI 3	Average uniformity (%)
PI 4	Average luminance of the window surface (cd/m2)
PI 5	% of hours where the average luminance of the window surface is in comfort range (less than 850cd/m2)
PI 6	daylight illuminance of the work plane at 3m distance from the window surface (Lx)
PI 7	% of hours where daylight illuminance of the work plane is in comfort range (greater than 500 Lx)
PI 8	Average of the absolute louver slat angle ($\|\varphi\|$); a measure of "outward visibility performance"

The performance indicators in System II are calculated by averaging results obtained from each of the five louver angle settings, i.e., -60°, -30°, 0°, 30°, and 60°.

System I is compared with System II on the basis of the performance indicators (PIs) shown in Table 3. In comparing each indicator, the following rules are established.

- PI1, PI6: *if* $500 \le PI \le 3340$*, then 1 point is allocated.*
- PI2, PI3, PI5, PI7 : *if* $PI_{sysI} > PI_{sysII}$ *then 1 point is assigned to System I, else 1 point to System II.*
- PI4: *if* $PI4 < 850$ *then 1 point is given*.
- PI8: *if* $PI_{sysI} < PI_{sysII}$ *then 1 point is attributed to System I, else 1 point to System II.*

Based on the above rules, System I performance is exceedingly better than that of System II (40 points to 27 points). Under the intermediate sky condition, the performance difference is larger (15 vs. 9).

Table 4 shows performance aspects of the systems. Especially, System I performs far better in providing a proper amount of daylighting (PI1, PI2) and keeping outward visibility (PI8).

Table 4 Performance aspect comparison

PIs	Performance aspect	System I	System II
PI1	Daylighting Illuminance	5	3
PI2		6	1
PI3	Uniformity	2	7
PI4	Luminance	8	7
PI5		6	6
PI6	Daylighting Autonomy	2	1
PI7		3	1
PI8	Outward Visibility	8	1
		40	**27**

CONCLUSION AND FUTURE WORK

Based on the awareness that real-time daylighting optmization has a great potential for a good interior daylit luminous distribution, a daylighting optimization study has been conducted.

The application of the optimal control to the louver angle is based on the pre-simulations with RADIANCE and is calculated with the constrained nonlinear optimization routine provided by the MATLAB optimization toolbox.

A number of conclusions can be drawn from the obtained results:

- A set of performance criteria is suggested for optimal control of daylighting such as daylit task illuminance at the work plane, uniformity, luminance of the window surface, daylighting autonomy and outward visibility.

- A cost function which consists of five cost elements is introduced. The 'FMINCON', one of the MATLAB nonlinear optimization routines, can be effectively used to obtain the optimal control action (e.g., optimal louver slat angle).
- For better representation of the system performance and comparison, performance indicators are introduced. The comparison of smart façade system with a conventional façade with a manually operated louver system confirms that the smart façade system can take advantage of the integrated optimal controls.

Our approach is a (pre-)simulation-based daylighting control of the louver system. Further study may include combinations of other control devices such as occupant presence and photosensor-based electric lighting controls and take energy saving aspects into account.

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Table 3 Performance comparison of System I with System II

	Season	PIs	System I	System II	Points		Season	PIs	System I	System II	Points	
Clear sky	Winter	PI1	742.1	2788.1	1	1	Fall	PI1	561.7	1266.6	1	1
		PI2	100.0	36.9	1	0		PI2	21.6	45.9	0	1
		PI3	36.4	30.2	1	0		PI3	44.3	40.1	1	0
		PI4	822.9	859.9	1	0		PI4	866.7	867.7	0	0
		PI5	46.9	56.3	0	1		PI5	27.0	54.1	0	1
		PI6	520.2	1744.5	1	1		PI6	414.7	463.6	0	0
		PI7	65.6	55.0	1	0		PI7	0.0	30.8	0	1
		PI8	33.3	36.0	1	0		PI8	30.3	36.0	1	0
	Summer	PI1	353.5	289.4	0	0						
		PI2	10.0	0.0	1	0						
		PI3	47.7	51.6	0	1						
		PI4	748.8	538.7	1	1						
		PI5	77.5	80.0	0	1						
		PI6	325.2	248.3	0	0						
		PI7	0.0	0.0	0	0						
		PI8	19.5	36.0	1	0						
	Subtotal				**13**	**10**						
Intermediate sky	Winter	PI1	1349.3	674.0	1	1	Fall	PI1	742.1	469.4	1	0
		PI2	100.0	50.0	1	0		PI2	83.8	32.4	1	0
		PI3	19.7	46.9	0	1		PI3	34.2	51.2	0	1
		PI4	598.8	503.9	1	1		PI4	741.8	515.9	1	1
		PI5	100.0	77.5	1	0		PI5	100.0	70.8	1	0
		PI6	3099.1	468.8	1	0		PI6	487.9	288.5	0	0
		PI7	59.4	20.0	1	0		PI7	56.8	13.5	1	0
		PI8	36.7	36.0	0	1		PI8	34.2	36.0	1	0
	Summer	PI1	344.1	219.3	0	0						
		PI2	0.0	0.0	0	0						
		PI3	41.9	60.8	0	1						
		PI4	399.6	291.7	1	1						
		PI5	100.0	100.0	1	1						
		PI6	278.9	179.6	0	0						
		PI7	0.0	0.0	0	0						
		PI8	26.9	36.0	1	0						
	Subtotal				**15**	**9**						
Overcast sky	Winter	PI1	310.0	190.7	0	0	Fall	PI1	457.8	264.4	0	0
		PI2	0.0	0.0	0	0		PI2	24.3	4.9	1	0
		PI3	40.6	62.8	0	1		PI3	38.8	57.2	0	1
		PI4	295.5	201.5	1	1		PI4	476.2	324.7	1	1
		PI5	100.0	100.0	1	1		PI5	100.0	100.0	1	1
		PI6	251.4	159.4	0	0		PI6	355.2	207.2	0	0
		PI7	0.0	0.0	0	0		PI7	0.0	0.0	0	0
		PI8	30.0	36.0	1	0		PI8	30.0	36.0	1	0
	Summer	PI1	531.2	302.9	1	0						
		PI2	100.0	20.0	1	0						
		PI3	38.2	56.7	0	1						
		PI4	573.8	386.5	1	1						
		PI5	100.0	94.0	1	0						
		PI6	409.7	232.3	0	0						
		PI7	0.0	0.0	0	0						
		PI8	29.5	36.0	1	0						
	Subtotal				**12**	**8**						
Total					**40**	**27**						