Scientific Applications Using Radiance - Fribourg, Switzerland, September 30, October 1, 2002

Parametric Study of Daylighting Strategies with Consideration of Glare Problems

Case Study: IGES Research Center in Zushi

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The present study focuses on the daylighting design strategies adopted in the IGES Research Center building, in particular considering the incidence of glare problems in the usability of daylight. A parametric approach has been applied to compare the efficiency of these strategies. The Radiance software was used to calculate glare factors and illuminance levels. A control program was developed which used climatic data to calculate electricity consumptions for each working hour in a year, assuming a continuous dimming control. The aim of the study is to evaluate as accurately as possible, the efficiency of design decisions in a particular case, considering lighting energy consumption and visual comfort.

1 Introduction

The energy used in lighting systems is usually more than 30% of the total electricity consumption in a commercial building. This is especially relevant if we consider the increment in electricity consumption rates in the last decades. Values of 200 kWh/m^2 per year are not uncommon in new office buildings, and lighting requirements can be as high as 100 kWh/m^2 per year [1].

Consequently, lighting saving measures are considered important energy saving factors in the global performance of buildings. Moreover, lighting systems are major sources of internal heat gains, which usually determine the sizing and therefore the initial cost of air-conditioning plants. Reducing the energy consumption for lighting will thus reduce as well the consumption of the air-conditioning system.

The use of daylighting to replace partially artificial lighting is considered one of the most efficient measures for lighting saving due to the high efficacy of daylight. However, when assessing the

performance of daylighting systems, special care should be taken to consider the effects of glare in reducing the usability of natural light [2].

This study attempts the definition of a procedure to assess the incidence of glare in the daylighting performance of a building, which could in turn influence design decisions.

2 Building description

The IGES Research Center is located in Zushi, Kanagawa prefecture, about 50km southwest from Tokyo. It is a new building completed in March 2002, accommodating several facilities for the Institute for Global Environmental Strategies, including research rooms, a library, conference rooms, as well as support services including cafeteria, lodging rooms for scholars, etc.

It was designed as an example of environmentally responsive architecture and therefore includes several strategies for the efficient use of energy, such as cogeneration system, solar panels, light shelves, natural ventilation, airflow windows, etc.

The morphology of the building presents three main volumes: a curved three-story wing that accommodates the main functions (research areas, library, etc.), a conical volume for the main conference room, and a glazed atrium that connects the former and acts as reception and service area (figs. 1-3).

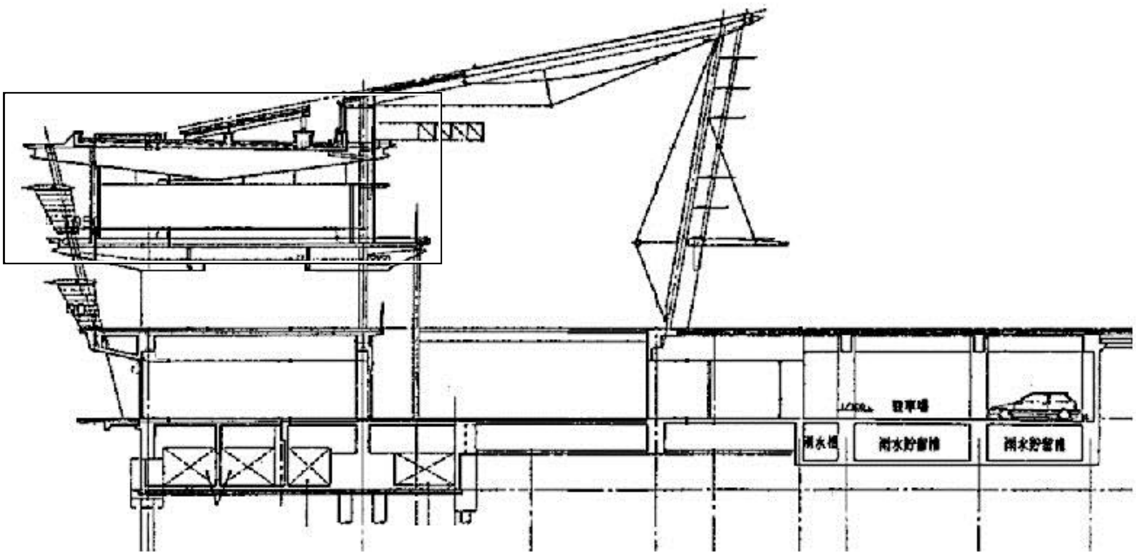


Fig. 1. N-S Section through west wing and atrium.

The present study centers on the research rooms (kenkyushitsu) in the third floor of the west wing. The location of the building, having direct visuals to the mount Fuji across the bay, determined the design of a complete glazed façade in the west direction. This forced the adoption of several protective strategies to avoid overheating as well as glare problems.

The openings are double-glazed, forming an airflow window system. The air between the two

panes is extracted to minimize heat transmission. In this space there are adjustable blinds for controlling glare and direct solar radiation. In this way, heat gains from radiation can be evacuated rapidly by the airflow windows. The inner pane has a section of 50cm at the top, made of translucent glass. This is to help in reducing glare problems by providing a more distributed light source. Additionally, the ceiling has been tilted to make the ceiling surface brighter and improve the penetration of natural light.

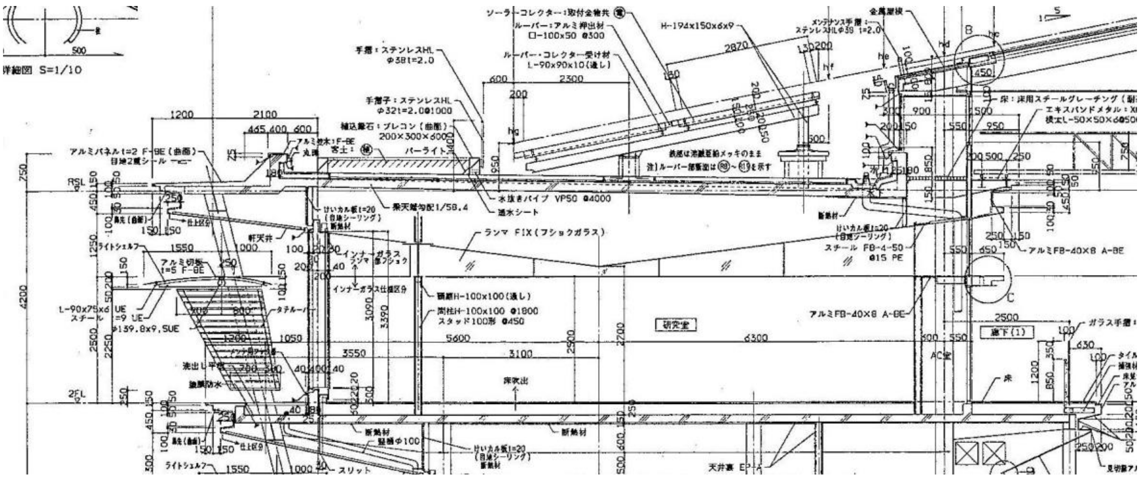


Fig. 2. Detail of the research rooms in the second floor.

On the outside, three devices help in the control of solar incidence. The overhang above the window projects more than 3m, providing considerable shading. A light-shelf is located in front of the window to redirect the light from the sky to the ceiling, compensating partially for the light loss due to the overhang, and also shading partially the façade from direct sun light. Finally, vertical louvers are placed at thirds of the total room width for extra protection, especially from low sunlight in the evenings.

The other three walls of the research rooms are glazed above 2.5m. This improves the distribution of natural light and increases the daylight penetration, in particular from the atrium side.

The particularities of the site and the requirements of the use make this building a significant study case, showing the interaction of opposing needs: for protection from and admission of natural light.

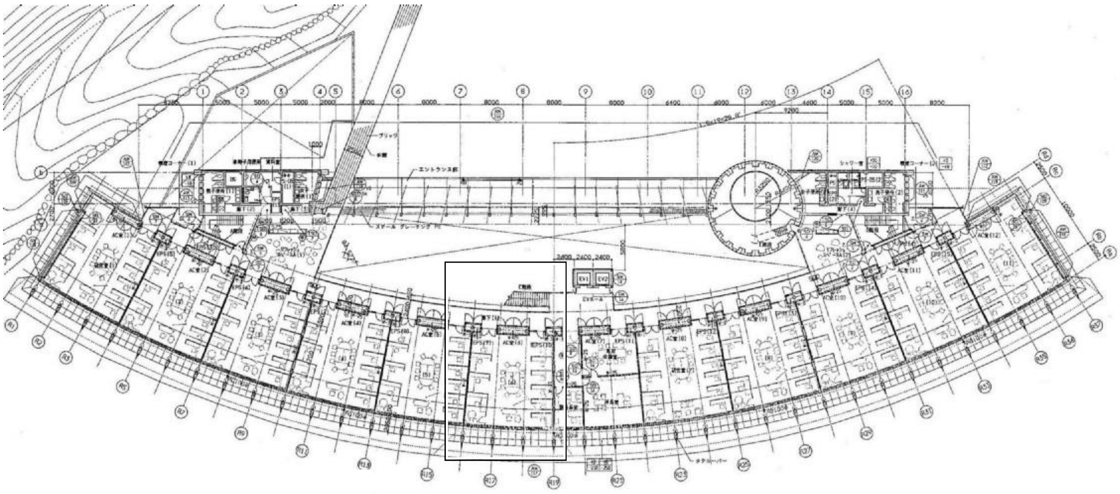


Fig 3. Second floor plan

3 Methodology

To evaluate the different daylighting strategies, a parametric approach was used by applying the same assessment procedure to different instances of the building. This procedure consisted in a triple set of simulations repeated for each operating hour during one year. Several modules of Radiance were used [4]. The first simulation calculated the incidence of glare for an observer situated in the center of the room, near the window. In accordance to these results, the situation of the window's blinds was changed. Each section of blinds was considered independently, but only two positions (open, closed) were simulated.

The new description of the room was then used in a second simulation to obtain illuminance levels under eight hypothetical sensors associated to eight pairs of lamps. These levels were considered to control the artificial lighting output to compensate natural light and provide the minimum requirement of 600 lux (this is the usual design illuminance in Japan). Finally, the illuminance levels of artificial lighting were converted into energy consumptions by means of the illuminance efficacy and the coefficient of utilization of the lamp (fig. 4) [3].

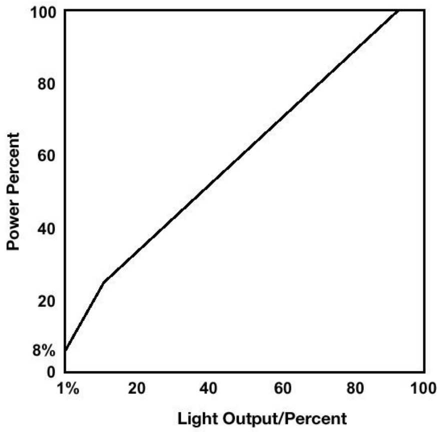


Fig. 4. Relation between power input and light output

The systematic modification in the design of the building allows the comparison of the relative performances of each design strategy. Since the building's main façade was oriented towards the west, high incidence of glare is expected. Because of this, one extra model was included for reference, being the same as the complete building, but oriented to the south.

3.1 Models of the building

As stated above, each model changed one aspect of the building by suppressing one strategy at a time. By comparing the performance with and without such strategy, its contribution to the total performance of the building can be obtained. Five different models were studied (fig. 5): 1 - Base case (complete), 2 - Without light shelf, 3 - Without louvers, 4 - With flat ceiling, 5 - Oriented to south.

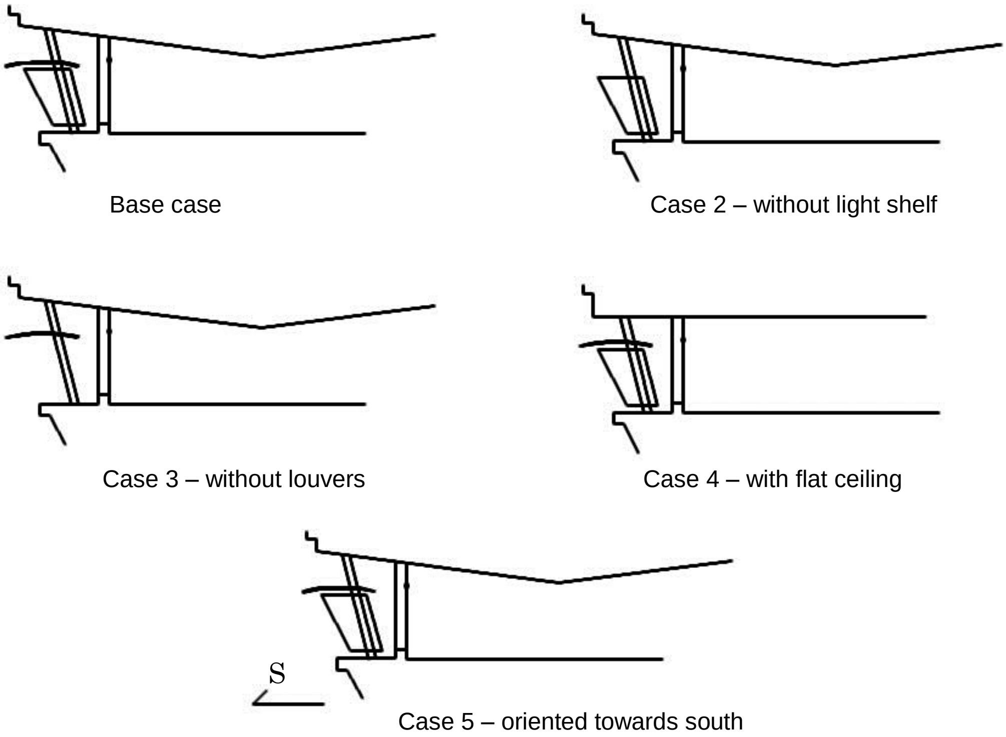


Fig. 5. Scheme of cases studied

3.2 Control program

The Radiance modules were controlled by an iterative program written in Perl and which used system calls to execute the Radiance components [4]. The set of simulations carried out for each hour is outlined in figure 6.

Firstly, the sky condition was determined from climatic data. This determinated the input values to use in the Gensky program. From the sky models available within Radiance, three were used:

standard overcast, intermediate with sun and clear with sun. To determine the sky model, a relation between direct and diffuse illuminances was adopted. The efficacy was calculated by using a modification of the Perez model [App. E].

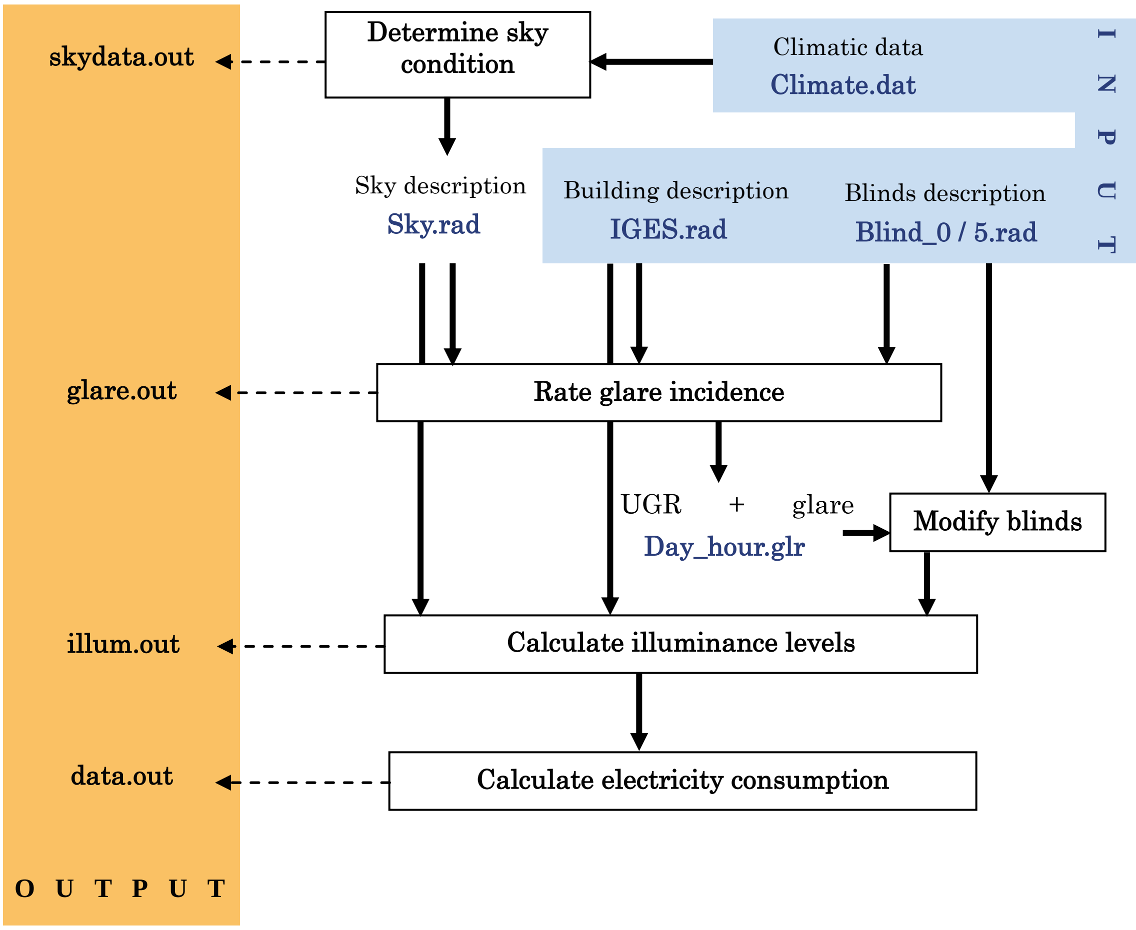


Fig. 6. Control program diagram

Once the sky condition was determined, the program used Findglare to calculate the glare incidence under such conditions. The Unified Glare Rating was calculated from the observer's position looking to the window and for the angles correspondent to the different sections. The results of glare calculations were then interpreted to find the direction of glare sources that required protection. When the glare rating was above the limit value, the sources were individualized and the angle of glare was verified. This determined the position of the six different blind sections, according to user's control (fig. 7). Since this control is not automatic, a delay was considered. Therefore, blinds were closed as soon as it was required, but they got opened again only one hour after the absence of glare was verified.

The glare routine was verified for each hour with possibilities of glare problems (glare hour), this was determined previously with simulations for every hour at different days in the year. It was

found that glare is produced during the morning hours even if the view direction is to the west. This is due to the direct sunlight entering the room from the opposite windows and reflecting in the main window. Since there is no movable protection device for this situation, glare hours were considered only during the afternoons (with the exception of the case 5 which has southern orientation).

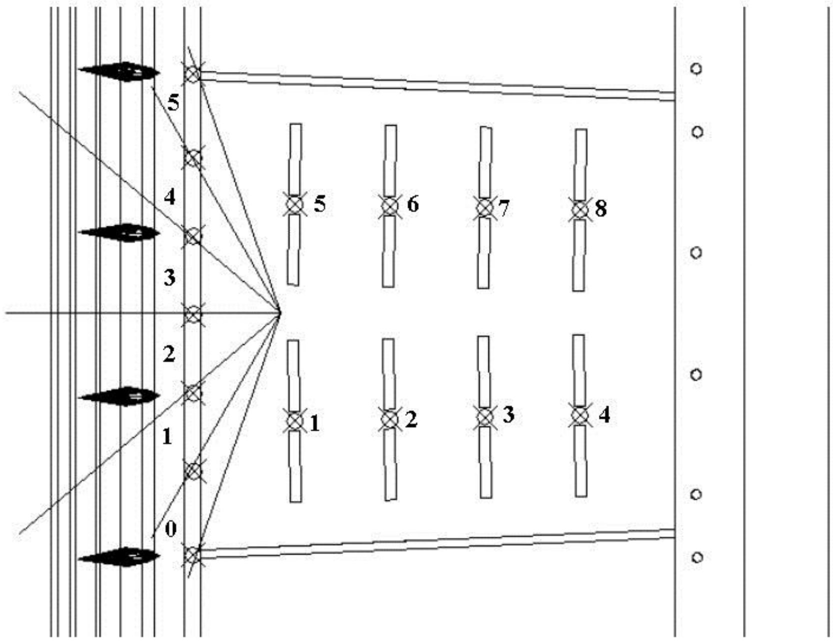


Fig 7. Window sections and position of sensors

4 Results

4.1 Base case

This is the complete model of the building. The results from this case will be taken as a parameter to compare the different variations. Figure 8 shows the incidence of glare on each section of the window according to the total number of hours in a year when the blinds of that section need to be closed. The results are consistent with what it is expected from the geometry of the building. The vertical louvers give more protection to the lateral sections of the window. Also the sun path in the west direction, crossing the window angle of view from upper left to lower right determines a higher incidence of glare in the left central sections.

The total lighting consumption in a year was 1077.5 kWh for one room, with a total of 2755 blind-hours closed[1].

[1] By "blind-hour" it is meant the unit of one blind section closed during one hour. Two blind sections closed during one hour, for example, will be the same as one blind section closed for two hours.

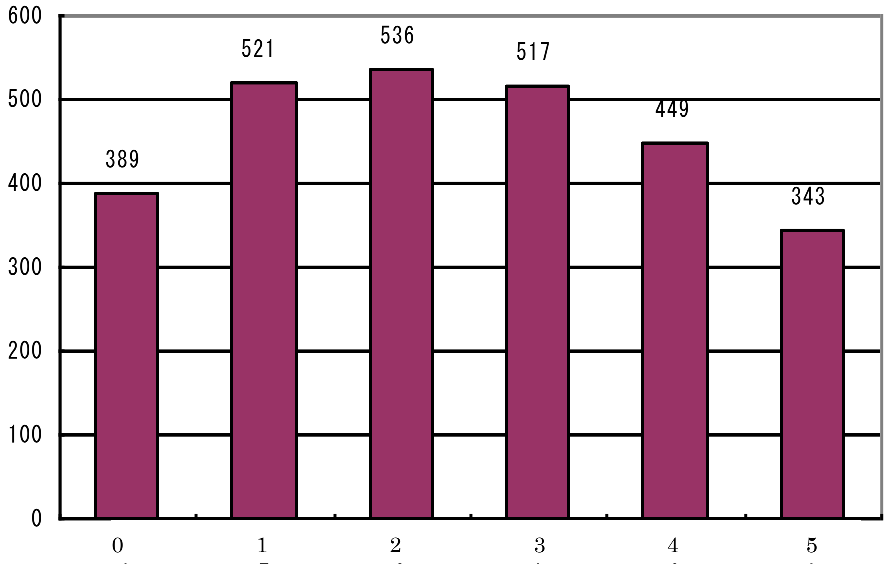


Fig. 8. Number of hours with closed blinds due to glare for each section.

Figure 9 shows the daily consumptions during a year. It can be observed that lower rates are obtained in summer due to higher illuminance levels. Also the relationship between glare rate and energy consumption is apparent. The need to close blinds clearly conditions the availability of daylight within the room.

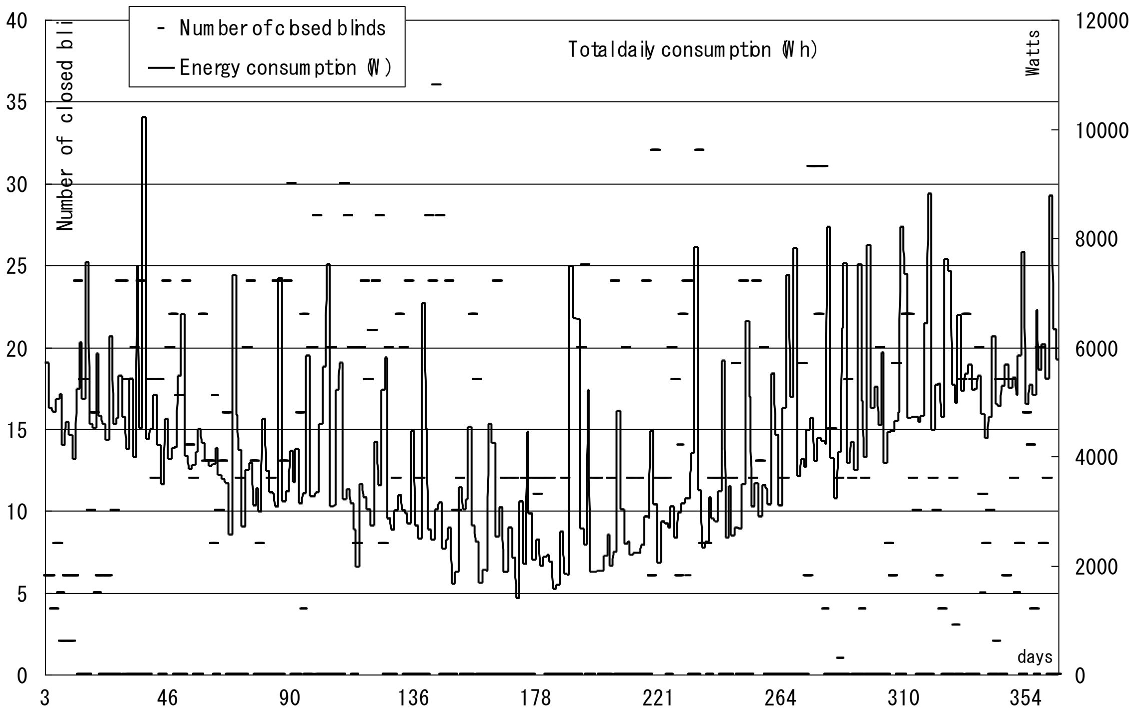


Fig. 9. Daily consumptions, base case

4.2 Variations of the base case

After repeating the same procedure for the four different variations of the building, the results were compared taking the first case as comparative base.

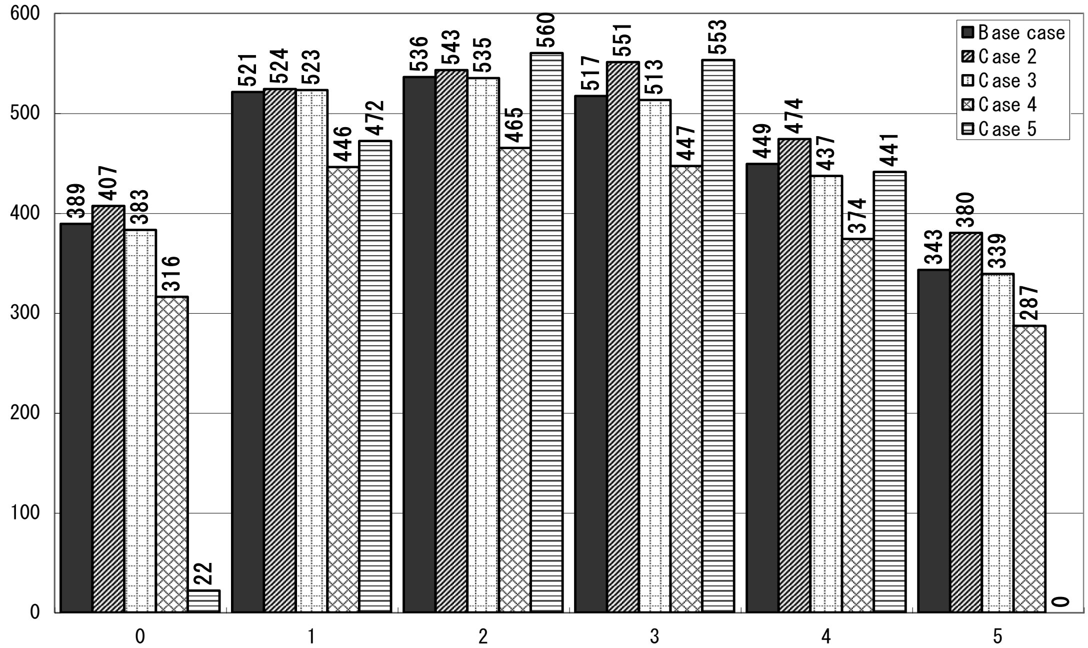


Fig. 10. Comparison of glare incidences for 5 cases

A comparison of glare incidences is shown on figure 10. Case 2 presented higher incidences of glare especially in the extremes of the window, because of the absence of light shelf.

Case 3 has only minor differences with the base case, showing that the louvers have little incidence in the glare performance. In some cases the building without louvers performed better than with them. This is probably due to reflection glare caused by the louvers. It should be said however that this result is design dependent and that a different number of louvers with a different reflectance, would have a very different performance.

Case 4 shows lower values in all the window sections. This is because a flat ceiling also implies a lower border of the overhang, resulting in higher protection. Finally, case 5 presents much lower values, especially for extreme angles, where the louvers give in this case a better protection due to the change in orientation.

4.3 Energy consumptions

When comparing the glare results with the energy consumptions obtained, the relationship between them can be observed as well as the performance relative to the base case. Figures 11 to 14 show these relationships using the data resulting from the difference between each case's results and the base case results.

In Case 2 (Fig. 11) it can be seen that the higher glare increments are in summer, in coincidence with the grater sunlight availability. The annual energy consumption was 1084.3 kWh, which represents an increase of 0.6%, and there was a total of 2879 hours of closed blinds.

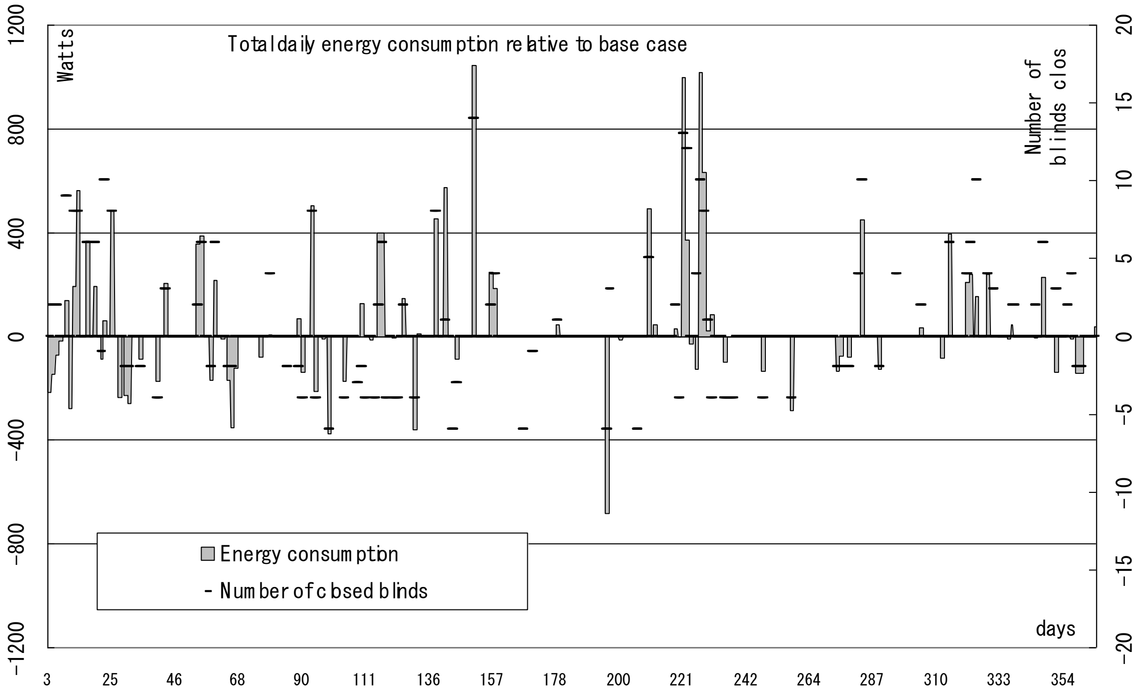


Fig. 11. Energy consumption and glare rates for Case 2

Case 3 shows little variation with respect to the base case (fig. 12). In this case the energy consumption was 1074.7 kWh, and the glare incidence was of 2730 blind-hours closed.

In Case 4 (fig. 13) although the more protection also reduces the daylight penetration, the lower glare rates compensate that effect to get lower energy consumptions in the total (see also fig. 15). The annual consumption was 1050.1 kWh (2.5% less than the base case), with a total of 2335 blind-hours closed. This suggests a very consistent relationship between glare factors and daylight availability that can affect energy consumption rates even more than geometrical constraints.

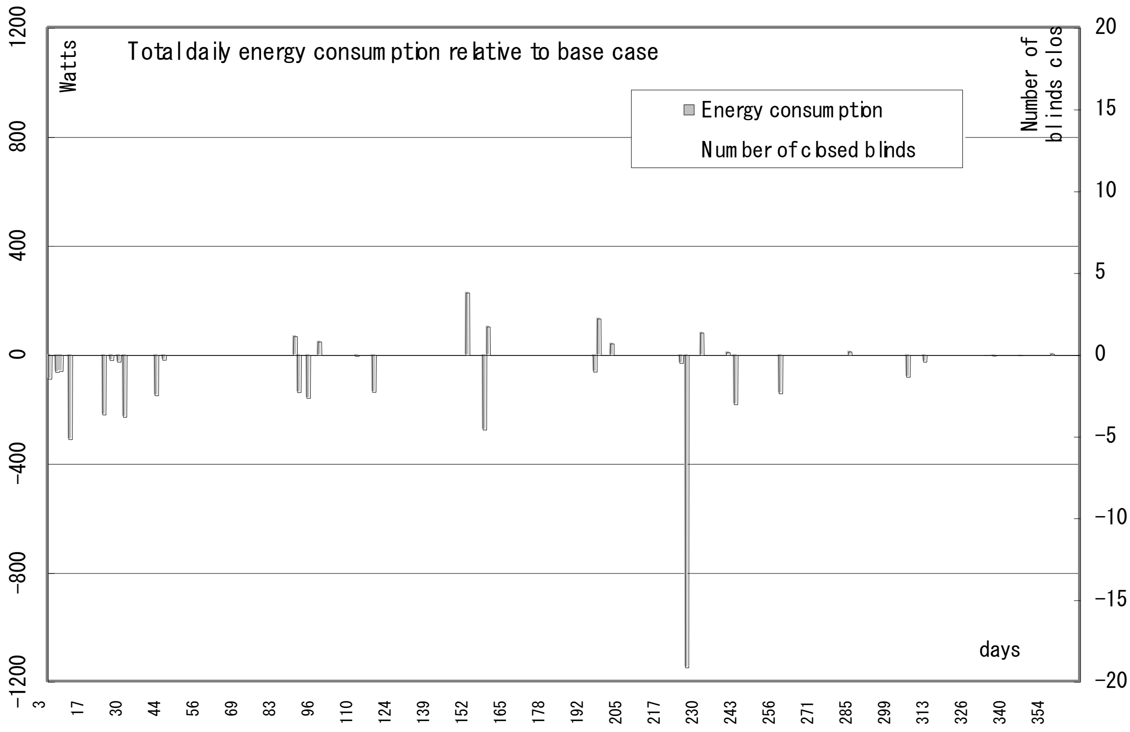


Fig. 12. Energy consumption and glare rates for Case 3

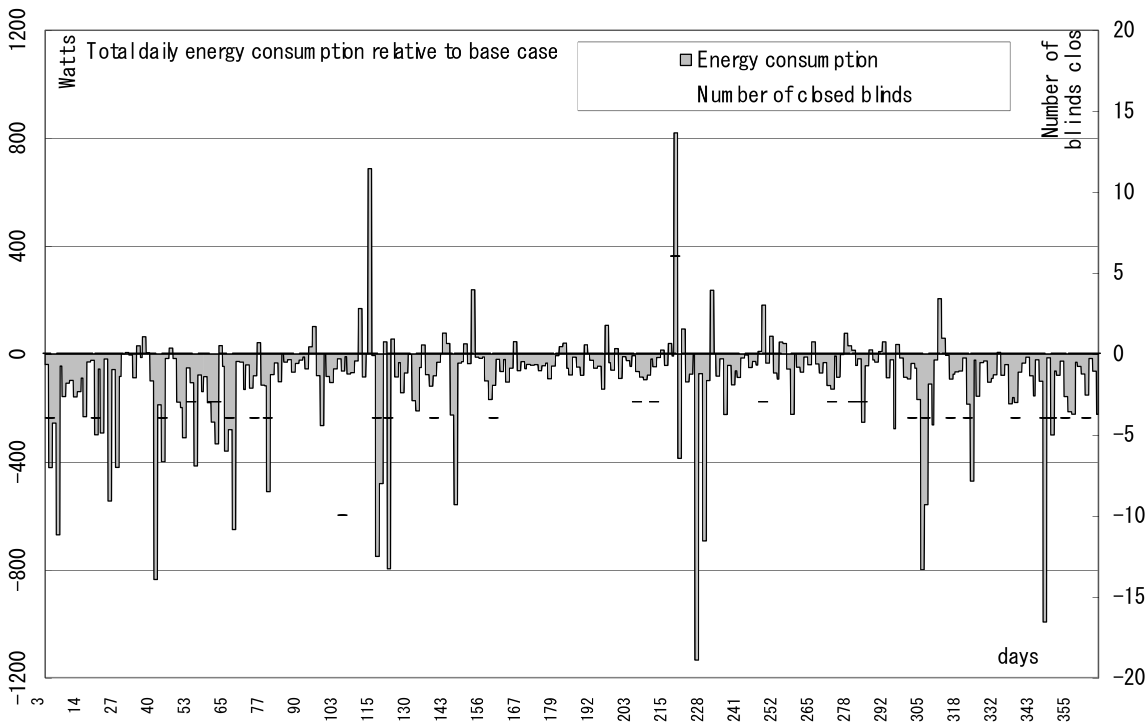


Fig. 13. Energy consumption and glare rates for Case 4

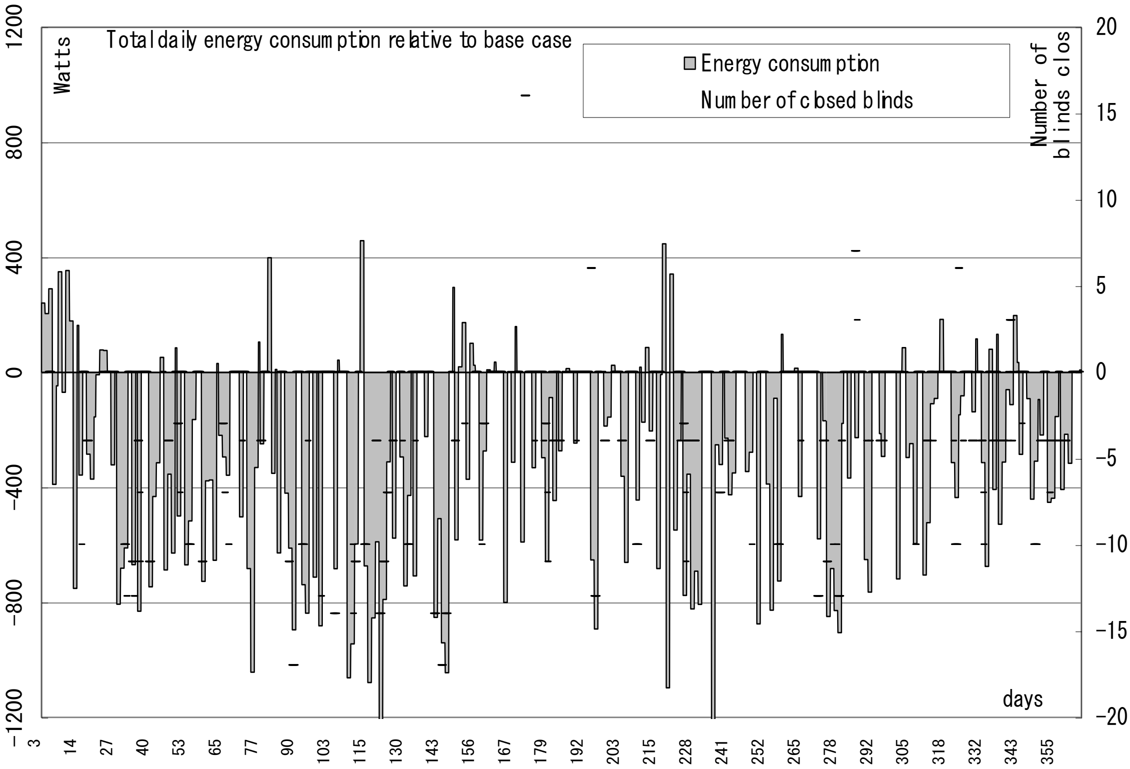


Fig. 14. Energy consumption and glare rates for Case 5

Case 5 (fig. 14) shows the improvement in the overall performance due to a change in orientation. Although glare rates are sometimes higher than in the base case, the energy consumptions are almost always lower, which shows a better use of daylight corresponding with a better orientation.

Figure 15 shows the annual total values for glare and energy consumption relative to the base case for each variation case. It can be pointed out that the proportion is not constant. However, glare is indeed a determinant factor of the energy consumption rate. It appears to determine the tendency in electricity consumption, to which other factors might add effect (case 5) or counteract to rest effect (case 4) but the tendency of the glare incidence is always confirmed.

To compare the ability of each strategy to distribute daylight, another set of calculations was executed without considering the effects of glare. This way, the illuminance results are determined only by the building geometry.

In figure 16 can be seen that Although Case 4 (with horizontal ceiling) has lower values near the window, it distributes the light deeper in the room having higher values away from the window. This shows that although the tilted ceiling permits more light to enter the room, the horizontal variation combined more efficiently with the light shelf in redirecting the daylight.

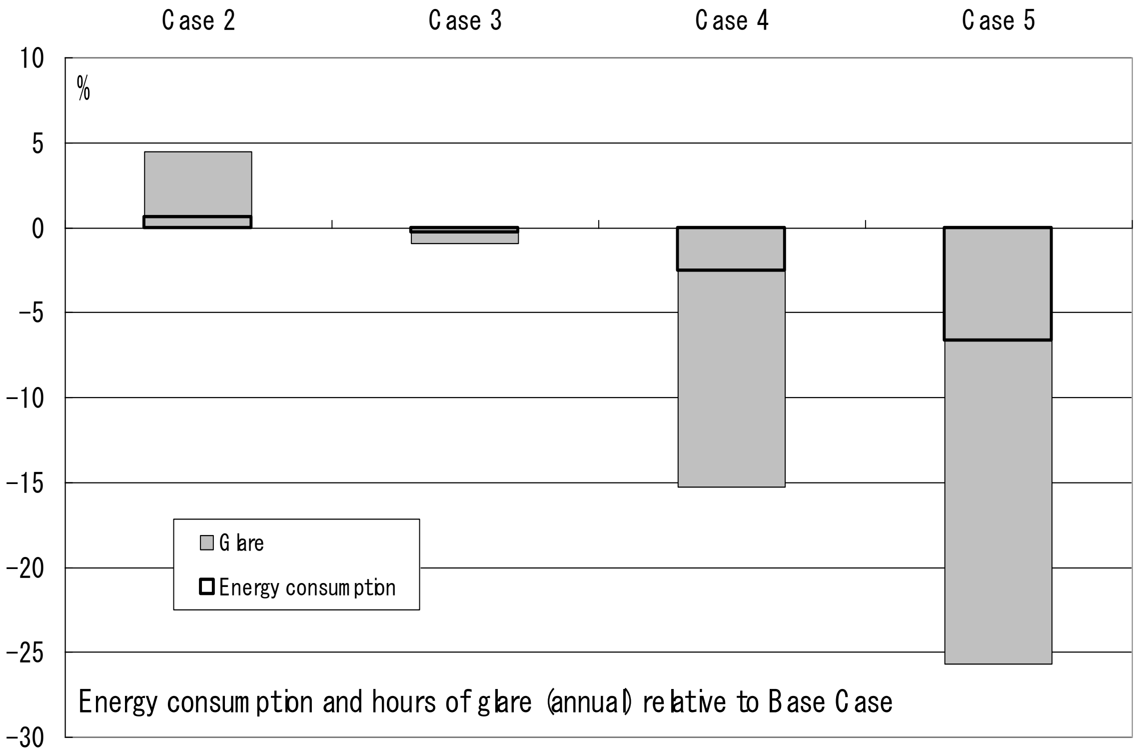


Fig. 15. Energy consumptions and glare rates relative to Base case

Case 2 (without light shelf) shows higher results near the window but almost equal in points 3 and 4, showing that the light shelf can lower the values where they can be excessive without affecting the results in the darker parts of the room, demonstrating the efficiency of the light shelf to redirect light.

Case 3 shows little or no difference with the base case. When the glare is not considered, the louvers have no effect in the daylighting performance of the building.

Finally, case 5 has much higher values near the window, but they become lower much sooner than in other cases. This is probably due to the fact that the aperture in the wall opposite to the main window (facing the east in the base case) receives much less light when oriented towards the south.

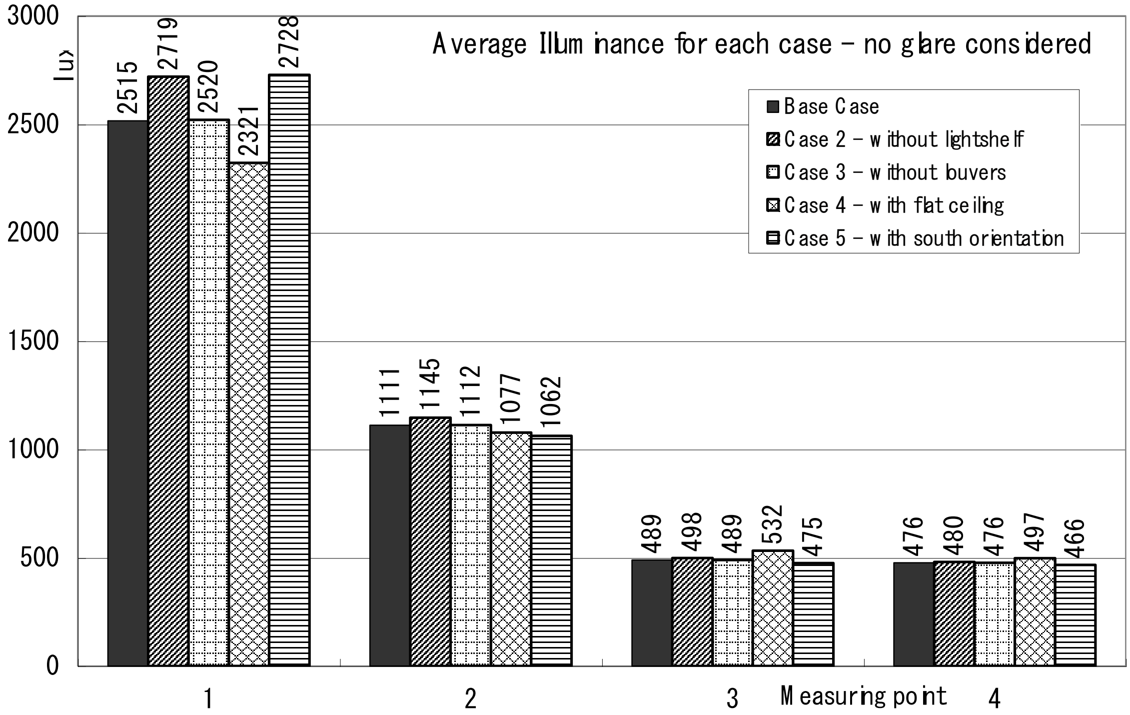


Fig. 16. Annual average of illuminance in four measuring points

5 Conclusions

A method to estimate the incidence of glare in the lighting energy consumption of a building was presented. The results showed sometimes to be counterintuitive and prove that in particular cases general design solutions might not be optimal.

The main inconveniences found during this study were related to the long times needed for the calculations, as well as the computer resources that had to be employed. Each year-round run for a certain model of the building produced the four output files, but also additional files for glare calculations (two for each glare hour) and several pictures that were used to verify the normal behavior of the simulations. A typical set of simulations was completed every 36 to 40 hours, which made very difficult to test small variations to prove some assumptions. Louvers, for instance, could have been tested with different reflectances to test the reflected glare incidence for different models.

Glare discomfort proved to be an important factor when protection devices controlled by occupants can generate higher demands of artificial light. The variation of the glare rates was always related to a variation of the energy consumption. However, this is obviously within a certain range, since beyond a certain limit, the increase in glare protection will have little positive effect while reducing the daylight availability. Further research could concentrate in one aspect (e.g. the length of the overhang) to find the relationship between glare protection and energy consumption. This way, optimal values could be found.

About the specific results for this building, they show some aspects of the design variations studied. The light shelf has some protective effect without reducing the daylight levels inside the room. Also, it was showed that the horizontal ceiling redirects the light from the light shelf further into the rear part of the room, although in this particular case this is not crucial due to the double-sided daylighting.

The horizontal ceiling showed a better performance due to the better protection and probably because of the redirection effect mentioned above.

It has to be indicated, however, that these results are dependant on several factors assumed within the simulations. Further research should include the comparison of this methodology with real conditions where differences are expected, especially with respect to the assumptions regarding the behavior of occupants.

References

[1] Aronsson, S., Nilsson, P., *Learning from experiences with Energy Efficient Lighting in Commercial Buildings*, CADDET Analyses Series No. 6, May 1991.

[2] Foster, M., Oreszczyn, T., *Occupant control of passive systems: the use of Venetian blinds*, Building and Environment 36 (2001) 149-155.

[3] Kaufman, J., *IES lighting handbook*, Illuminating Engineering Society of North America, New York, 2000.

[4] Ward, G., *RADIANCE Reference Manual*, Lawrence Berkeley National Laboratory, Berkeley, 1999.

Appendix A – Transcription of the control program

```
#################################################################
# iges.pl control file for year round calculation with Radiance
#                 by Santiago Torres 01/12/17
#################################################################

### VARIABLES
$day=0; $month=1; $day_m=0;
$blnk="_";
@limsup=(90,60,40,0,-40,-60);
@liminf=(60,40,0,-40,-60,-90);

### file header printing
open (OUT, ">>data.out") or die "cannot open data.out 0 $!";
print OUT "¥nday¥tdate¥thour¥tIll dir¥tIll dif¥tEffic¥tIrrad dir¥tIrrad dif";
print OUT "¥tsky type¥tglare¥t¥tIllum(lx)¥t¥t¥t¥t¥t¥t¥t¥tConsumption (W)¥n";
close OUT ;

open (CLIMOUT, ">>skydata.out") or die "cannot open skydata.out $!";
print CLIMOUT "¥nday¥thour¥tsin_alt¥tsky_irr¥tbm_irr¥tabs_hum";
print CLIMOUT "¥tdir_irr¥tglb_irr¥talt¥tz¥tep¥tm¥text_irr¥tdel";
print CLIMOUT "¥tdp¥tlw¥tc_a¥tc_b¥tc_c¥tc_d¥teffic¥tsky_illum";
print CLIMOUT "¥tdir_illum¥tglb_illum¥trad_sky¥trad_dir¥tsky_frac";
close CLIMOUT ;


### MAIN LOOP STARTS
open (CLIMATE, "<climate.dat") or die "cannot open climate.dat $!";
for $data (<CLIMATE>) {

  ### DAILY SETUP
  ### the length of the climate file line determines whether it is a new day header
  if (length($data)<10){

    ### start with blinds up - each value represents on section of the window
    ### glare1 registers the glare incidence in the present hour
    ### glare2 keeps the values from the past hour to simulate user`s delay
    @glare1 = (0, 0, 0, 0, 0, 0); @glare2 = (0, 0, 0, 0, 0, 0);

    ### day, month and hour
    $hour=0; $day++;
    $day_m=substr($data, 2, 2); $month=substr($data, 0, 2);
```

```
  ### day of the week (0=holiday, 1=sunday)
  $week=substr($data, 4, 1);

  ### last working hour (14:00 on Saturday or else 20:00) (first=8am)
  if    ($week>=2 and $week <= 6)  {$last_hour = 20;}
  elsif ($week == 7)               {$last_hour = 14;}
  else                             {$last_hour =  0;}
  print "¥n$day¥t$month/$day_m";
}
### END DAILY SETUP

### HOURLY ROUTINE
if (length($data)>10){
  $hour++;

  ### WORKING HOUR ROUTINE
  if ($hour>=8 and $hour<$last_hour) {

        ### HOURLY SETUP
        #glare2=glare last hour; glare1=glare this hour
        @glare2=@glare1; @glare1=(0, 0 ,0 ,0 ,0 ,0);

        print "¥n$hour¥t";

        ### GENSKY
        ### determines the sky luminance distribution from climatic data

        ### climate data
        # $irrad_cld/sun=horiz irradiance (efficacy=179, Radiance data)
        # $sky_frac=quotient between sky and direct irradiance

        # measured data #

        $sin_alt=substr($data, 16, 3)/1000;   #altitude sine
        $sky_irr=substr($data, 10, 3);        #difuse irradiance (kcal/h)
        $sky_irr*=1.163;                      #conversion ->(W)
        $bm_irr=substr($data, 7, 3);          #beam [normal] irrad (kcal/h)
        $bm_irr*=1.163;                       #->(W)
        $abs_hum=substr($data, 4, 3);         #absolute humidity
        $abs_hum*=0.1;                        #->(g/kg')

        # calculated data #

        $dir_irr=$bm_irr*$sin_alt;            #horiz direct irradiance
        $glb_irr=$sky_irr+$dir_irr;           #global irrad=sky+beam
```

```
$alt=atan2($sin_alt,(sqrt(1-$sin_alt*$sin_alt))); #solar altitude (radians)
$z=(1.570795-$alt);  #zenith angle (radians)

# $ep=sky clearness
if ($sky_irr!=0) {
  $ep=((($sky_irr+$bm_irr)/$sky_irr)+1.041*($z**3))/(1+1.041*($z**3));
} else {$ep=0;}

# $m=optical air mass
$m=($sin_alt+0.50572*(($alt*180/3.14159+6.07995)**(-1.6364)))**(-1);

# $ext_irr=extraterrestrial irradiance
$ext_irr=1353*(1+0.033*cos(0.0172024*$day))*$sin_alt;

# $del=optical transparency of cloud cover
if ($ext_irr!=0){
   $del=$sky_irr*$m/$ext_irr;
} else {$del=0;}

# $dp=dew point temperature
if (($abs_hum>1) and ($abs_hum<35)){
   $ln=log(0.001*$abs_hum);
   $dp=90.93743+$ln*(16.98006+$ln*(-0.7905916+$ln*(-0.2411693+$ln*(-0.01389958)
)))+0.80452911*abs($ln+5.5801499);
} else {die "no dew point temperature";}

# $lw=atmospheric precipitable water content
$lw=exp(0.07*$dp-0.075);

# a-d=Perez coeff depending on $ep, @up &@low=upper and lower $ep bounds
@up=(1.065,1.23,1.5,1.95,2.8,4.5,6.2,500);
@low=(1,1.065,1.23,1.5,1.95,2.8,4.5,6.2);
@a=(96.6251,107.5371,98.7277,92.721,86.7266,88.3516,78.624,99.6452);
@b=(-0.4703,0.7866,0.6972,0.5591,0.9763,1.3891,1.4699,1.8569);
@c=(11.501,1.7899,4.4046,8.3579,7.1033,6.0641,4.9305,-4.4555);
@d=(-9.1555,-1.892,-6.9483,-8.3063,-10.9361,-7.5967,-11.3703,-3.1465);

for $i (0..7) {
   if (($ep>=$low[$i]) and ($ep<$up[$i])){
         $c_a=$a[$i]; $c_b=$b[$i]; $c_c=$c[$i]; $c_d=$d[$i];
   }
}

# $effic=global luminous efficacy
# if the sun is below the hortizon, $del=0 and log($del)->inf
# in that case the average value of 133 is used
```

```
        if ($del!=0) {
           $effic=1.35*$c_a+0.8*$c_b*$lw+0.5*$c_c*cos($z)+0.5*$c_d*log($del);
        } else {
           $effic=133;
        }

        $sky_illum=$sky_irr*$effic;#sky illuminance
        $dir_illum=$dir_irr*$effic;#direct illuminance
        $glb_illum=$glb_irr*$effic;#global illuminance

        $rad_sky=$sky_illum/179; #difuse irradiance for input in Radiance
        $rad_dir=$dir_illum/179; #idem for direct irradiance

        # $sky_frac = relation of sky irrad to beam irrad
        if ($bm_irr!=0) {$sky_frac=$sky_irr/$bm_irr;} else {$sky_frac=0;}

        # $sky=sky model  +s sunny sky [CIE standard clear + sun]
        #                 +i intermediate [CIE intermediate + sun]
        #                 -c cloudy [CIE standard overcast]

        if ($alt>0.0873) {
           if ($bm_irr<$sky_irr)  {$sky="-c";}
           elsif ($sky_frac>.35)  {$sky="+s";}
           else                   {$sky="+i";}
        } else                    {$sky="+s";}

        open (OUT, ">>data.out") or die "cannot open data.out 1 $!";
        print OUT "¥n$day¥t$month/$day_m¥t$hour¥t$dir_illum¥t$sky_illum";
        print OUT "¥t$effic¥t$rad_sky¥t$rad_dir¥ts: $sky";
        close OUT ;

        open (CLIMOUT, ">>skydata.out") or die "cannot open skydata.out $!";
        print CLIMOUT "¥n$day¥t$hour¥t$sin_alt¥t$sky_irr¥t$bm_irr¥t$abs_hum";
        print CLIMOUT "¥t$dir_irr¥t$glb_irr¥t$alt¥t$z¥t$ep¥t$m¥t$ext_irr¥t$del";
        print CLIMOUT "¥t$dp¥t$lw¥t$c_a¥t$c_b¥t$c_c¥t$c_d¥t$effic¥t$sky_illum";
        print CLIMOUT "¥t$dir_illum¥t$glb_illum¥t$rad_sky¥t$rad_dir¥t$sky_frac";
        close CLIMOUT ;

        #generate sky description
        system ("gensky $month $day_m $hour $sky -B $rad_sky -R $rad_dir -a 35.6 -o -139.5
-m -135 > sky.rad");


        ### FINDGLARE
        # find glare sources, calculate glare comfort rating
        # $findglare_param = parameters for findglare
```

```
        # once a month register glare views (rpict)
        # first possibility of glare at $first_glare depending on $day

        if   ($day<70) {$first_glare=13;}
        elsif ($day<162){$first_glare=14;}
        elsif ($day<202){$first_glare=15;}
        elsif ($day<264){$first_glare=14;}
        else          {$first_glare=13;}

        if   ($day<45) {$last_glare=17;}
        elsif ($day<108){$last_glare=18;}
        elsif ($day<240){$last_glare=19;}
        elsif ($day<279){$last_glare=18;}
        else              {$last_glare=17;}

        unless ($hour<$first_glare or $hour>$last_glare or $sky eq "-c") {
           $findglare_param="sky.rad iges.rad";

           ### add blinds to description according to last hour
           for $i (0..5) {
                if ($glare2[$i]==1) {$findglare_param.=" blind$i.rad";}
           }

           ### oconv creates the scene description to be used by Radiance modules
           system ("oconv $findglare_param > findglare.oct");

           ### findglare detects glare sources and background illumination
           if (($day_m==23 and $month==1) or ($day_m==24 and $month>=2 and $month<=5) or
($day_m==28 and $month>5 and $month <=8) or ($day_m==20 and $month>8)) {
                system ("rpict -vth -vp 2 5.8 1.5 -vd -1 0 0 -vh 180 -vv 180 -av 1 1 1
findglare.oct > g$day$blnk$hour.pic");
                system ("findglare -p g$day$blnk$hour.pic -t 6000 -ga 10-70:10
findglare.oct > glare$day$blnk$hour.glr");
           } else {
                system ("findglare -vp 2 5.8 1.5 -vd -1 0 0 -t 6000 -ga 10-70:10 -av .1 .1 .1
findglare.oct > glare$day$blnk$hour.glr");
           }

           ### glarendx calculates the glare rating values
           system ("glarendx -t ugr glare$day$blnk$hour.glr > g$day$blnk$hour.gle");

           ### GLARENDX RESULTS EVALUATION
           # the view directions with glare problems are identified
           # @limsup=(90,60,40,0,-40,-60);
           # @liminf=(60,40,0,-40,-60,-90);
           open (GLRENDX, "<g$day$blnk$hour.gle") or die "err gle $!";
```

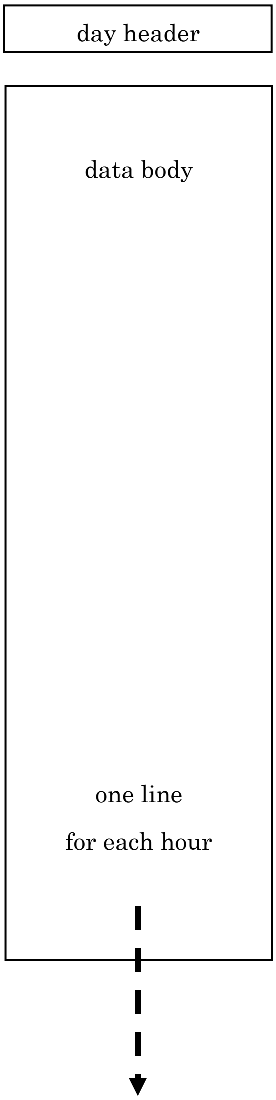
```
for $line (<GLRENDX>) {
      @subline=split(/¥t/,$line);
      $angle=$subline[0];
      $glare_fact=$subline[1];

      # $glare_fact=unified glare rating; 19=max allowed

      if ($glare_fact > 19) {
         for $i (0..5) {
               if ($angle<=$limsup[$i] and $angle>=$liminf[$i]) {
                  $glare1[$i]=1;
               }
         }
      }
}

### GLARE SOURCES CONFIRMATION
# the glare sources are identified to determine the sections
# of window that need to be closed
for $i (0..5) {
      if ($glare1[$i]==1) {
         open (GLARE,"<glare$day$blnk$hour.glr") or die "err glr $!";
         $line=<GLARE>;

         until (substr($line,0,3) eq "BEG") {$line=<GLARE>;}
         $line=<GLARE>;

         until (substr($line,0,3) eq "END") {
               @subline=split(/¥s/, $line);
               $src=atan2 (-$subline[2], -$subline[1])*180/3.14159;
               if ($src<$limsup[$i] and $src>$liminf[$i]){
                  $glare1[$i]=2;
               }
               $line=<GLARE>;
         }
         close GLARE ;
    }
    if ($glare1[$i]==2){$glare1[$i]=1;} else {$glare1[$i]=0;}
}

open (GLROUT, ">>glare.out") or die "cannot open glare $!";
print GLROUT "¥n$day¥t$hour¥ts: $sky¥t$alt¥t@glare1¥t@glare2";
close GLROUT ;
```

```
    open (OUT, ">>data.out") or die "cannot open data.out 2 $!";
    print OUT "¥t@glare1¥t@glare2";
    close OUT ;

} # unless hour => glare hour

### if the hour studied did not have glare results, the columns
# in the output file are left blank
else {
    open (OUT,">>data.out") or die "cannot open data.out3 $!";
    print OUT "¥t¥t";
    close OUT ;
} # else non glare hour

### RILLUM
# calculate illuminances at work plane
# $rillum_param = parameters for rillum
# $x, $y coordinates for photosensors
# once a month register interior views (rpict)

$rillum_param="sky.rad iges.rad";

### add blinds to description according to present and last hour
# this simulates the delay to re-open a blind section
for $i (0..5) {
    if ($glare2[$i]==1 or $glare1[$i]==1) {
         $rillum_param.=" blind$i.rad";
    }
}

open (ILLUM, ">>illum.out") or die "cannot open illum.out 1 $!";
print ILLUM "¥n$day¥ts: $sky¥t$hour¥t$illum";
close ILLUM ;

# generate scene description
system ("oconv $rillum_param > illum.oct");

# strings for output values
$illum_out=""; $df_out=""; $w_out="";

$y=3;
for $a (1..2) {
    $x=2.2;
    for $b (1..4) {
         system ('echo "'."$x $y".' .7 0 0 1" | rillum -ab 1 illum.oct > measure.out');
         open (MEASURE, "measure.out") or die "cannot open measure $!";
```

```
                $measure=<MEASURE>;
                $measure=substr($measure, 0, length($measure)-2);
                if ($glb_illum!=0) {$df=$measure*100/$glb_illum;}
                else {$df="n/a";}
                close MEASURE ;

                ### conversion into electricity consumption
                $need=(600-$measure);
                if ($need>0) {
                   $lm=$need*8.25;
                   if ($lm>560) {
                        $w=(($lm-560)*0.02076)+31;
                   } else {
                        $w=(($lm-56)*0.03373)+9.92;
                   }
                } else {
                   $w=0;
                }

                $illum_out.="¥t$measure";
                $df_out.="¥t$df";
                $w_out.="¥t$w";
                $x+=2.35;
           }
           $y+=5.5;
        }

        open (OUT, ">>data.out") or die "cannot open data.out 4 $!";
        print OUT "¥t$illum_out¥t$w_out";
        close OUT ;

        open(ILLUM, ">>illum.out") or die "cannot open illum.out 2 $!";
        print ILLUM "¥t$illum_out¥t$df_out¥t$w_out";
        close ILLUM ;

        # register interior pictures (rpict) once a month
        if (($day_m==23 and $month==1) or ($day_m==24 and $month>=2 and $month<=5) or
($day_m==28 and $month>5 and $month <=8) or ($day_m==20 and $month>8)) {
           system ("rpict -vp 8 1 1 -vd -1 1 0 -vh 90 -vv 60 -x 512 -y 512 illum.oct >
p$day$blnk$hour.pic");
        }

   } # if 8 >= hour > last hour => working hour
  } # if length $data > 10 => hourly loop
} # for $data => main loop
```

Appendix B – Climate data – TMY file for Tokyo

```
11TOKYO
 1 11
  44 30   0   0 56   0   0    0    0
  40 29   0   0 56   0   0    0    0
  37 28   0   0 62   0   0    0    0
  34 28   0   0 56   0   0    0    0
  32 28   0   0 56   0   0    0    0
  31 28   0   0 50   0   0    0    0
  31 30   0 10 61 15999-870 492
  34 31102 47 73189981-777 629
  40 32426 80 85336941-641 767
  56 34554 88 80443896-450 892
  73 36552 98 75505862-203 979
  90 37481113 70517855    74 997
  99 38281138 76478877 341 939
 105 39261118 83391920 559 828
 106 39142 78 89262964 719 694
 101 38   0 40 70 99995 831 555
  93 38   0   5 57   0   0    0    0
  85 38   0   0 38   0   0    0    0
  82 38   0   0 37   0   0    0    0
   t | H | R |r | Nr |sh|ch | sA |cA
```



t: temperature (0.1 ºC)

H: absolute humidity (0.1 g/kg`)

R: direct solar radiation (kcal/m^{2}h)

r: diffuse solar radiation (kcal/m^{2}h)

Nr: nocturnal radiation (kcal/m^{2}h)

sh, ch: sin, cos of solar altitude (10^{-3})

sA, cA: sin, cos of solar azimut (10^{-3})

Appendix C – Examples of images obtained

Several images were obtained in order to verify the behavior of the systems simulated, in particular the behavior of blinds. Two kinds of pictures were rendered. The first one was a fish eye view that can be also used as input for the glare calculation. This picture has the information about light sources and relative sizes and positions in a field of view of 180 degrees. Therefore, this kind was rendered for each glare hour in one day per month.

The second kind of images is a perspective of the interior that shows the main window with the position of the blinds and the general illumination of the room.

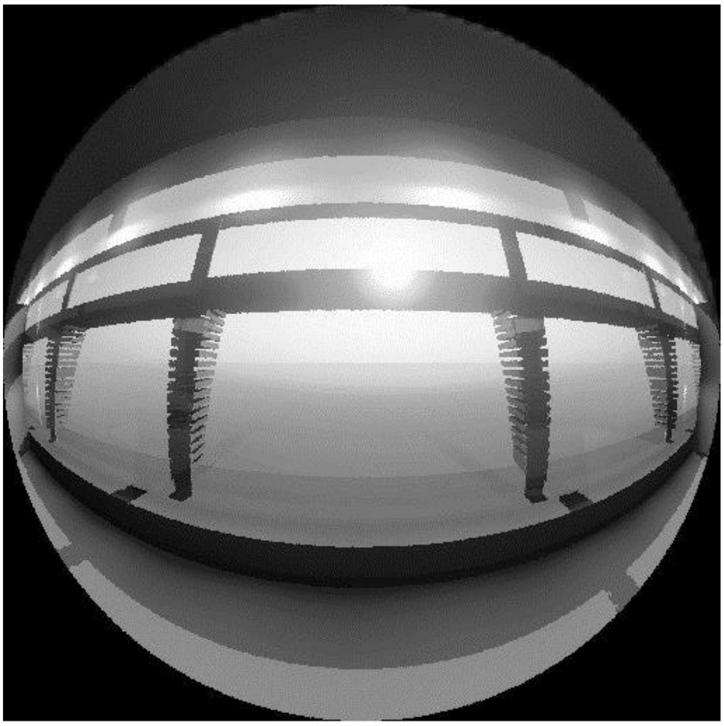


Fig. C.1. Fish eye view (used for glare calculations) for April 24 at 17:00.
Base model

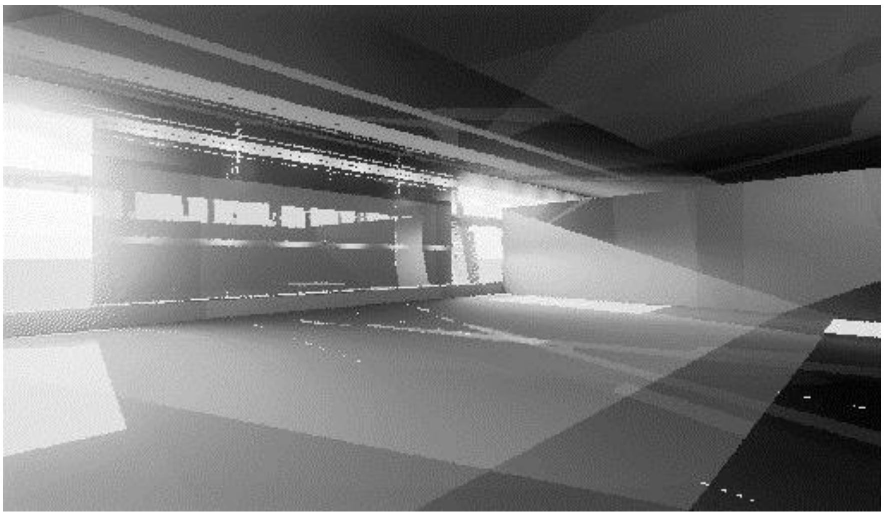


Fig C.2. Interior perspective for the same hour.

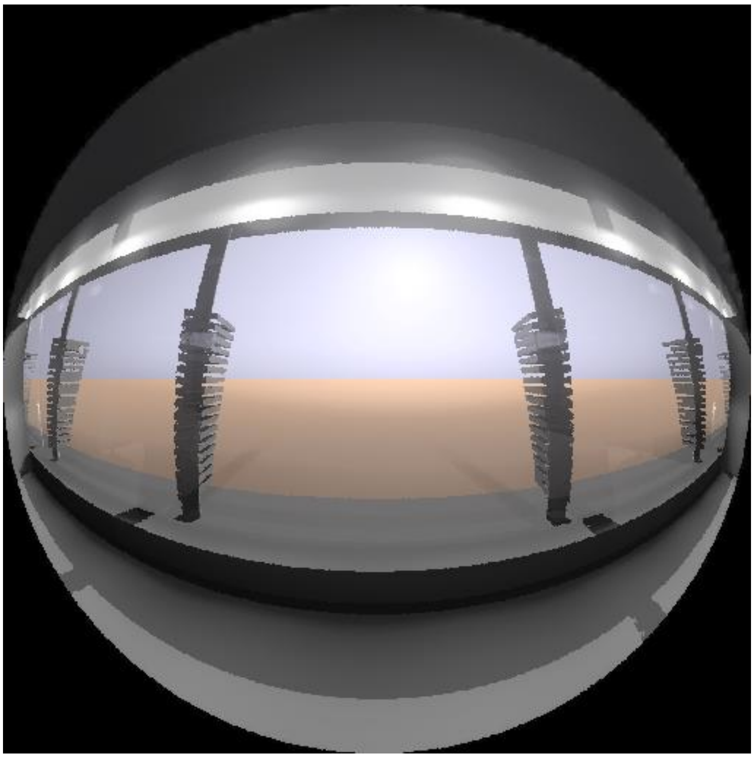


Fig. C.3. Fish eye view for April 24 at 17:00.

Case 2 – without light shelf

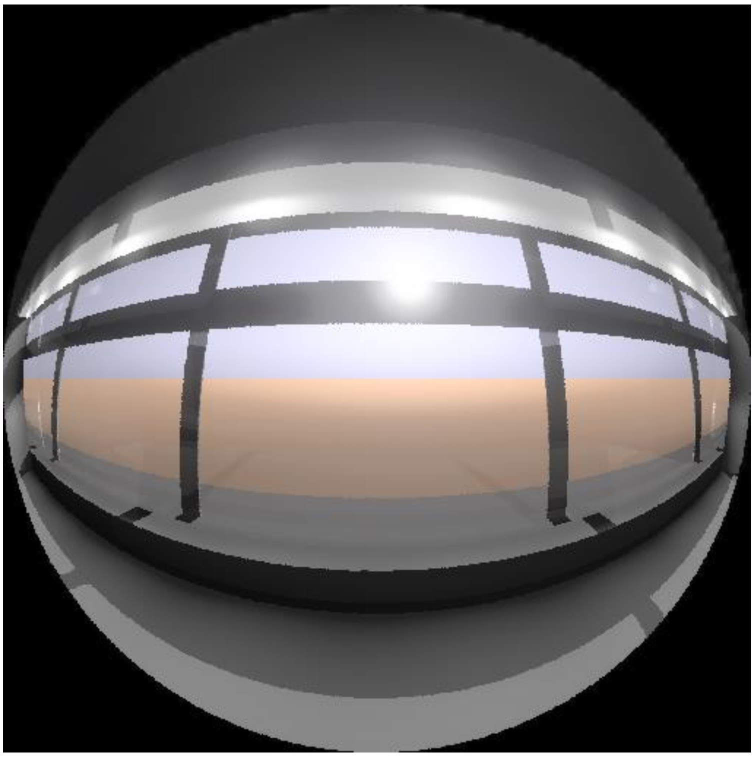


Fig. C.4. Fish eye view for April 24 at 17:00.

Case 3 – without louvers

Appendix D – Calculation of Global Efficacy

To obtain a description of the sky illuminance through the Gensky module of Radiance, illuminance values were necessary in an hourly basis throughout the whole year. However, climatological stations usually record only irradiance values.

In order to use the climate data from the standard meteorological file (TMY[1]) an independent verification was made to determine a method to calculate the daylight efficacy.

The Perez model was implemented, which uses a set of coefficients along with atmospheric values in the following expression [1]:

$$K_G = a_i + b_i\, l_W + c_i \cos z + d_i \ln(\Delta)$$

where K_G is the global efficacy, l_w is the atmospheric precipitable water content, z is the solar zenith angle, Δ is the sky brightness coefficient, and a_i.. d_i are coefficients depending on the sky clearness. Since these coefficients are site dependent, illuminance and irradiance measures from a monitoring station near Tokyo [2] were used to correct the equation. These measures provided simultaneous data for Illuminance and Irradiance, thus allowing the accurate calculation of real efficacy values that were contrasted against theoretical values obtained from the equation.

Figure D.1 shows the results of global horizontal illuminance calculated with the Perez model, against the real measured values. It can be observed that the calculated values are lower than the real ones. To correct this situation, additional coefficients were added in each term of the equation until the results corresponded as close as possible with the measures. The same graphic with corrected values is presented in figure D.2.

Thus, the final equation adopted was modified as follows:

$$K_G = 1.35\, a_i + 0.8\, b_i\, l_W + 0.5\, c_i \cos z + 0.5\, d_i \ln(\Delta)$$

Where the Perez coefficients were maintained and corrected by the new coefficients. The graphic also shows the correspondence between calculated and measured values, with low dispersion in the data.

---

[1] Typical Meteorological Year.

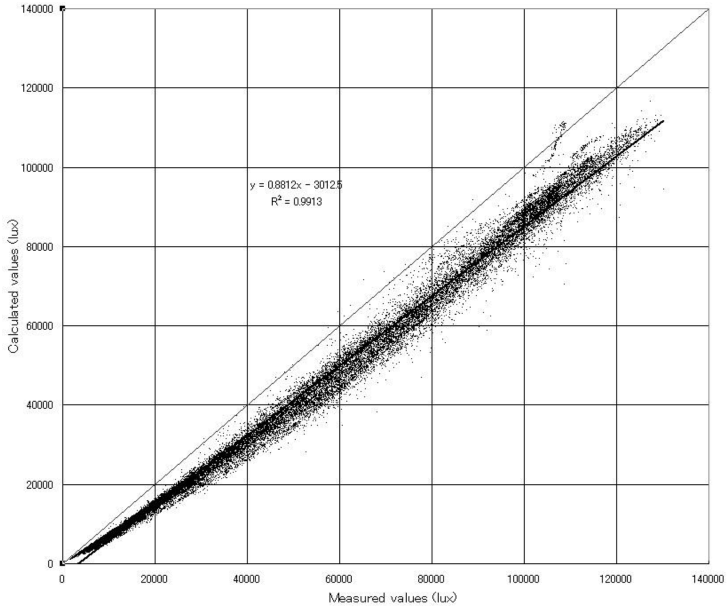


Fig D.1. Results from the calculations against measured values

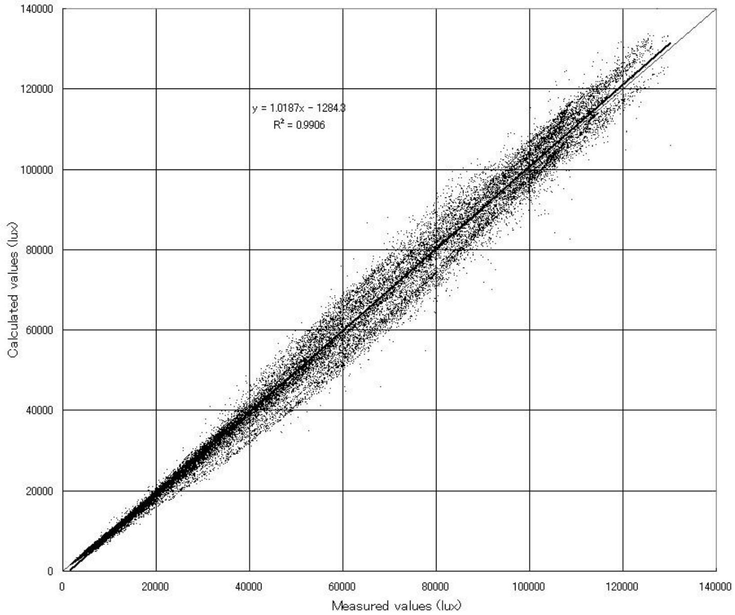


Fig. D.2. The same as in fig. 1 after correcting the values.

References

[1] Muneer, T., *Solar Radiation & Daylight Models for the Energy Efficient Design of Buildings*, Architectural Press, Oxford, 1997.

[2] Data measured at the Kajima Technical Research Institute, Chofu Station, member of the International Daylight Measurement Programme.