

COMPARISON OF RESULTS FROM THE DAYLIGHTING SIMULATION OF A SIDE-LIT CLASSROOM USING DAYSIM WITH ACTUAL MEASURED ANNUAL ILLUMINANCES

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ABSTRACT

This paper compares the results from the daylighting simulation of a classroom at Northern Guilford Middle School in Greensboro, North Carolina, with the actual measured illuminance levels from the school. The daylight modeling program DAYSIM was used in conjunction with an EPW weather file to perform annual daylighting simulations. Actual illuminance measurements were taken inside the classrooms over a year using photometric sensors and data-loggers.

The simulated average daily illuminance is compared with the corresponding measured value for a sunny and cloudy day for all the months except February, August and December. The average daily variation for sunny and cloudy days is 18 fc and 9 fc respectively. The simulation correctly models the decaying illuminance levels with increasing distance from the daylighting glazing. This paper also proposes that in modeling a day-lit space using EnergyPlus weather files and DAYSIM, the modeler must focus on accurately modeling only average daily or monthly illuminances and not illuminances at a specific time of the day during the year.

1. INTRODUCTION

There have been a number of studies on the validation of DAYSIM (1). It is one of the most validated modeling programs available (1). Many daylighting designers use DAYSIM to model their systems' behavior. However, most of the times the validation of the model occurs by matching it with only a single point in time. The year-round illuminance data available from the research performed at Northern Guilford Middle School has presented a unique opportunity to compare the DAYSIM model with actual measured values over an entire year.

The Northern Guilford design features a translucent interior light-shelf that serves to diffuse and distribute light inside the classroom. An average annual illuminance of about 79 fc is provided for nine months of the year. The major challenge in the modeling process was to model the curved translucent light-shelf. Due to the lack of expensive equipment required to measure the optical properties of the light-shelf, a trial and error method was adopted to arrive at the results.

Another challenge faced by modelers is the inability to measure the exact optical properties of translucent daylighting elements (requiring expensive measuring equipment). While this may be important in the validation of the software (in this case DAYSIM) it may not be critical in the validation of a daylighting system. This paper attempts to show that a fairly complete picture of the daylighting performance can be obtained by focusing on accurately modeling average daily or monthly illuminances, instead of trying to match the model closely with the performance at any single point in time.

2. DESCRIPTION OF TYPICAL NORTHERN GUILFORD MIDDLE SCHOOL CLASSROOM

Northern Guilford Middle School (NGMS) was designed with the intent of maximizing the solar potential available on site. The 140,000 square foot school has classrooms divided into three wings and is described further below.

2.1 Description of Daylighting Design

All day-lit classrooms at NGMS have side-daylighting with high clerestories on the south side. All wings are single-

storied and have classrooms on both sides of a central corridor (Figure 1). The three wings are oriented on the east-west axis with each wing having an orientation 10 degrees . The south-side classrooms have a 1'-6" curved exterior light-shelf to reflect light into the classroom. Blinds on the view windows were kept closed throughout all the testing and data collection. Figure 2 shows a typical classroom wing.



Fig. 1: South and north-side classrooms from a wing at Northern Guilford Middle School

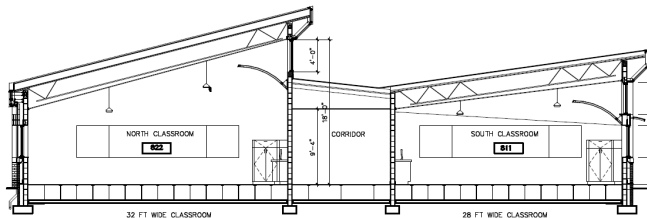


Fig. 2: Typical classroom wing section

The south-side classroom was modeled for this research. Typical classrooms are featured with varying amounts of cabinetry and computer stations positioned at different locations, but these were not included in the model.

To create an area with low natural light (less than 25 fc) inside the day-lit classroom that allows teachers to use projectors and other visual aids, an architectural 'soffit' was introduced (Figure 3) (2).

2.2 Interior Light-shelf

The daylighting design of NGMS incorporates a unique element in the form of a curved interior light-shelf made from translucent acrylic panels attached on an aluminum frame (Figure 3).

TABLE 1: CLASSROOM CHARACTERISTICS

Side of Corridor	South
Dimensions, w x d, ft	28'-8" x 28'
Area, ft ²	803 ft ²
Daylight Glazing Type	Clear, insulated
Transmittance	80%
Area, ft ²	75.1 ft ²
Exterior light-shelf	Aluminum, 2'
Ceiling Reflectance	90%
Wall Reflectance	60%
Floor Reflectance	35%
Overhang	45°
View Windows	2 nos. , South-facing

The interior light-shelf was specially designed and manufactured for this school, the frame being constructed out of 2.5" hollow aluminum tubes with a white, powder coated finish, and white acrylic panels having a transmittance of 20% acting as a perfect diffuser of beam sunlight (3).

The light-shelf is mounted on pivots on the wall just below the daylighting glazing. The pivots allow the light-shelf to be lowered so that it can be easily cleaned. It has a curvature of radius 6 feet and it runs the entire length of the daylighting window. It serves two purposes: first to diffuse all direct light and prevent glare, and second to improve light levels at the back of the classroom by bouncing some of the light falling on it on to the ceiling. A 45° overhang above the daylighting glazing is provided on all daylighting glazing to stop direct sunlight from striking the glazing (and the interior light-shelf) in the summer, while still letting in direct light in the winter (Figure 2). This design enables passive solar gain in the winter while reducing summer cooling loads, representing sound passive solar design.

3. DESCRIPTION OF EQUIPMENT SETUP FOR DATA COLLECTION

3.1 Equipment Selection

Photometric light sensors and data loggers from LI-COR Biosciences were selected for indoor data collection. For outdoor solar radiation measurement, Onset Computer Corporation's HOBO weather station was selected. The LI-210 Photometric sensor is constructed with a filtered silicon

photodiode contained in a fully cosine-corrected sensor head. This sensor has a spectral response that falls within $\pm 5\%$ of the CIE Standard Observer Curve (4). This curve is a measure of the spectral response of the average human eye (LI-COR).



Fig. 3: Interior light-shelf in a classroom

LI-1400 Data Loggers were purchased to record data from sensors in the classroom. Each data logger has five channels that can be used with the photometric sensors. A calibration multiplier must be applied to the current reading from each sensor before the reading is logged by the data-logger. To record external solar radiation data, Onset Computer Corporation's HOBO Micro Station, a four-channel weather-proof data logger along with a silicon pyranometer smart sensor, was used (5). The pyranometer sensor uses a silicon photodiode to measure the solar radiation in Watts per square meter. Even though a silicon photodiode is not the ideal type of sensor for solar measurements, with proper calibration and careful mounting, the results are adequate for the purposes of this work.

To mount the pyranometer sensor, a simple weather station stand was constructed with two bracket arms, one of which was used to fix the sensor such that it faced directly upwards (Figure 4). The sensor was then connected to a data-logger, also mounted on the stand. It was transported to the roof and was set up with weights holding it down against the elements.



Fig. 4: Weather station positioned on the roof

3.2 Data-logger Setup

For the purpose of this study, a sampling period of thirty seconds and a logging period of five minutes are selected. Thus, for this work, readings are sampled every thirty seconds and those ten readings are then averaged and logged every five minutes. The data logger on the weather station uses the same sampling and logging interval as the data logger for the classroom. This allows direct comparison between exterior solar conditions and interior illuminance.

3.3 Sensor Setup

The main characteristics of the daylighting in the classroom that needed to be measured are the front to back illuminance gradient, the east to west gradient and obviously the light levels at different parts in the classroom. To this effect, a sensor grid using 5 sensors, all of which could conveniently be connected to a single data logger, was created. Three sensors are positioned in a row from the front of the classroom to the back and the remaining two are placed symmetrically opposite to each other to the east and the west. The above explanation becomes clear from Figure 5, which shows a typical sensor layout for a south-side classroom with the soffit on the west side. Each sensor is five feet away from the adjacent wall or soffit. The sensors are placed on student desks within the classroom, at a height 2.5 feet. Each sensor is leveled using three leveling screws provided in the sensor bracket.

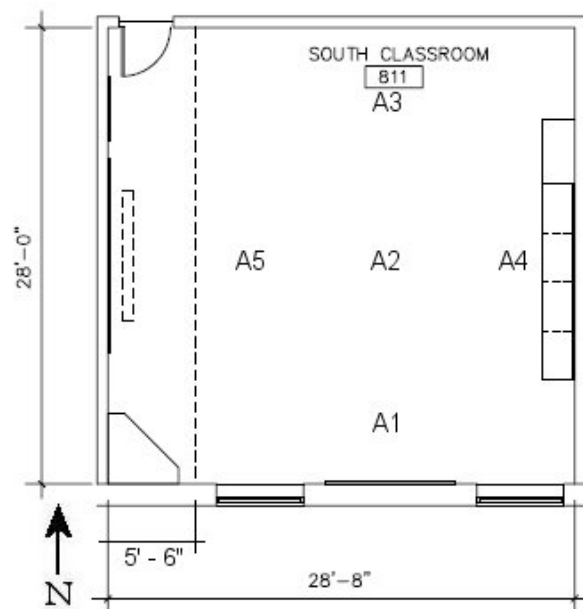


Fig. 5: Sensor layout in the classroom

4. DAYSIM MODELING OF THE CLASSROOM

The daylight simulation program, DAYSIM, was used to perform the simulation of a typical classroom (6, 7). A 3-dimensional model was constructed that included the contribution of the grass and wing reflectance from in front of the classroom glazing (Figure 6). As the performance at the front of the classroom is highly sensitive to the position of the light-shelf, the geometry of the light-shelf and its position with respect to the glazing is carefully replicated.

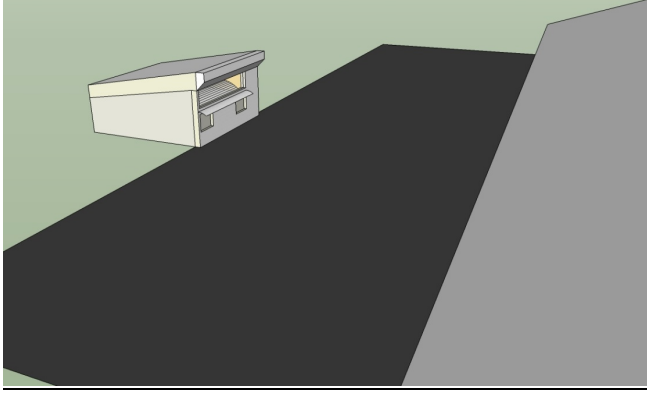


Fig. 6: SketchUp model of the classroom showing opposite wing

4.1 Modeling Parameters

The surface reflectances of the walls, the soffit, the ceiling and the floor were measured using a MINOLTA luminance meter. The grass in front of the classroom is estimated to have a reflectance of 0.29 (8). Important classroom characteristics such as the surface reflectances, glazing properties and the interior light-shelf properties are listed in Table 2.

For this study, sensor locations were defined such that they matched the locations of the sensors in the actual classroom. The weather file selected for the simulation is for Greensboro, NC, where the school is located. A five minute time-step was chosen for the simulation. The Radiance parameters chosen for this simulation are given in Table 3. A recommended medium level accuracy is chosen, as the model does not have any dynamic shading elements.

4.2 Modeling the Interior Light-shelf

Modeling the curved interior translucent light-shelf is complex and it was done primarily through the iterative comparison of the simulation results with the measured values. Previous studies of modeling translucent panels also served as a starting point for modeling the light-shelf (6). Adjusting the specularly of the light-shelf resulted in a

change in the front to back illuminance distribution. The light-shelf is assumed to perfectly smooth. It is also assumed to be a perfect diffuser and so the transmitted specularly is zero.

TABLE 2: MATERIAL PROPERTIES FOR DAYSIM

Non-Specular, Opaque Surface Reflectances	
Ceiling	0.9
Walls	0.6
Floor	0.28
Soffit	0.86
Grass	0.29
Overhang	0.6
White Membrane Roof	0.9
Exterior Light-shelf	0.7
Glazing Properties	
Material type	Glass
Red, blue, green transmissivity	0.76
Interior Light-shelf Properties	
Material type	Translucent
Specularity	0.019
Roughness	0
Transmissivity	0.61
Transmitted specularly	0

TABLE 3: RADIANCE PARAMETERS

ambient bounces	5
ambient division	1500
ambient sampling	100
ambient accuracy	0.1
ambient resolution	300
direct threshold	0
direct sampling	0

For the transmissivity, different values were tried and each time the results were compared with the actual readings. While the value of 0.61 appears to be high, it is found that this works best with the current model. The availability of extensive year-round data enabled the iterative testing and improvement of the simulation response.

5. RESULTS

5.1 Methodology for Comparison of Measured and Modeled Illuminances

To compare illuminance levels between the modeled and measured data on a particular day, the corresponding solar radiation resource available on that day must be matched. Data was collected from the school by setting up equipment on weekends and holidays when the classrooms would be unoccupied, whereas the radiation data was collected continuously throughout the year by the weather station on the roof. Thus, solar radiation data can be used from only those days when equipment was setup in the classrooms. From the weather file, sunny and cloudy days were selected such that they were as close to the days of the month during which actual data was collected, as well as having minimum hourly variation from the measured solar radiation.

Next, classroom illuminance data from the simulation for the selected days was compared with the actual measured light levels. Due to the inherent variation in the measured solar radiation and the solar radiation data obtained from the weather file, the validation of the model becomes difficult. However, assuming that the surfaces and geometries have been modeled correctly, the error introduced by the weather file can be accounted for in the results. The comparison is, therefore, made only for average illuminance levels for an entire day rather than comparing hourly illuminance values.

5.2 Solar Radiation Data Comparison

The solar radiation data obtained from the weather file for Greensboro, NC is compared with the actual radiation data for the selected sunny and cloudy days. For the months of September and October, no cloudy days occurred when data was being collected. Also, it was not possible to setup equipment at the school in the months of February and August.

The following observations can be made from the table above:

- (1) For sunny days, the measured average solar radiation is greater than the modeled values for all the months. For cloudy days, the radiation data does not show any trend.
- (2) The annual average radiation available for the selected days is similar for the measured and modeled data sets.

It is important to note here that, the days selected from the weather file for comparison represent the best approximation of the actual radiation data obtained from the site.

TABLE 4: SUNNY AND CLOUDY DAY AVERAGE SOLAR RADIATION

Month	Sunny		Cloudy	
	Measured	Modeled	Measured	Modeled
	(W/m ²)		(W/m ²)	
Jan	336	326	56	85
Mar	500	457	60	138
Apr	670	617	219	205
May	692	652	348	226
Jun	715	648	118	283
Jul	633	592	248	209
Sep	566	513	--	--
Oct	460	432	--	--
Nov	306	291	70	58
Annual Average	542	503	160	172

5.3 Comparison of Interior Illuminances

Table 5 and table 6 show the average daily illuminance in the classroom for sunny and cloudy days respectively. The illuminance values are an average of the five sensor points taken from 8 AM to 4 PM, the typical school operating hours.

TABLE 5: COMPARISON OF AVERAGE DAILY ILLUMINANCES ON SUNNY DAYS

Month	Sunny		Absolute Variation
	Measured	Modeled	
	fc		fc
Jan	174	150	24
Mar	100	102	2
Apr	32	51	19
May	33	44	11
Jun	27	47	20
Jul	31	45	14
Sep	40	61	21
Oct	100	93	7
Nov	171	123	48
Annual Average	79	80	18

TABLE 6: COMPARISON OF AVERAGE DAILY ILLUMINANCES ON CLOUDY DAYS

Month	Cloudy		Absolute Variation
	Measured	Modeled	
	fc		fc
Jan	9	15	6
Mar	9	23	14
Apr	27	32	5
May	30	34	4
Jun	14	40	26
Jul	25	31	6
Nov	10	10	0
Annual Average	18	26	9

The results from the above comparison are discussed here:

- (1) The simulation shows an annual foot-candle variation of 18 fc for sunny days and 9 fc for cloudy days. Considering the scale of illuminances and the logarithmic nature of the human eye (reinhardt), this variation can be considered small.
- (2) The maximum absolute foot-candle variation occurs on a sunny day in the month of November and is 48 fc. Apart from this high value, the maximum variation is below 26 footcandles throughout the year.
- (3) The simulation is not able to match the measured illuminances at the two extremes of the response of the system. Thus, the simulated average illuminance does not rise up to 174 fc in January representing the highest average illuminance and nor does it fall up to 27 fc in June, representing the lowest average illuminance.
- (4) The cloudy day performance of the simulation, with an average annual variation of 9 fc, is also reasonable considering the low interior illuminance levels.
- (5) Observing the radiation data for sunny days, it would appear that a corrected average illuminance for each month would result in an increase in the simulated winter and summer illuminances. However, this paper is an exercise in showing how closely the simulation can match measured data using just the original weather data from the EPW file. Therefore, the weather corrected illuminance values are not presented.

5.4 Comparison of Center Sensor Illuminance

The following graphs compare the hourly illuminances on the selected days for January, March and June representing the winter, equinox and summer performance.

For sunny days, the center sensor illuminance profiles for measured and modeled illuminances show similar trends

(Figure 7). Both the curves for the summer performance are flat while those for the winter show a distinct peak near noon. The simulated values for January do not rise up to the measured peaks.

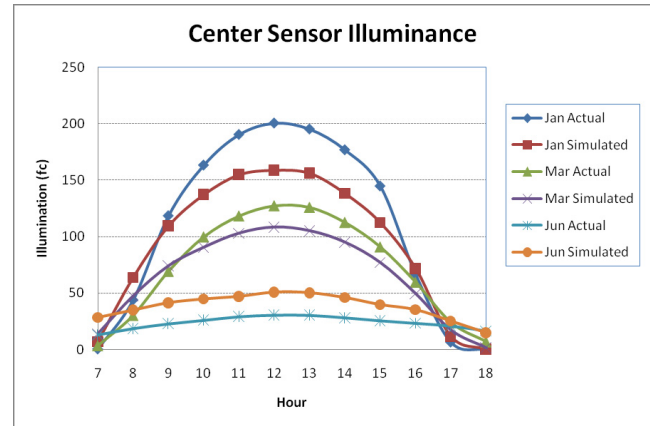


Fig. 7: Comparison of center sensor illuminance on sunny days

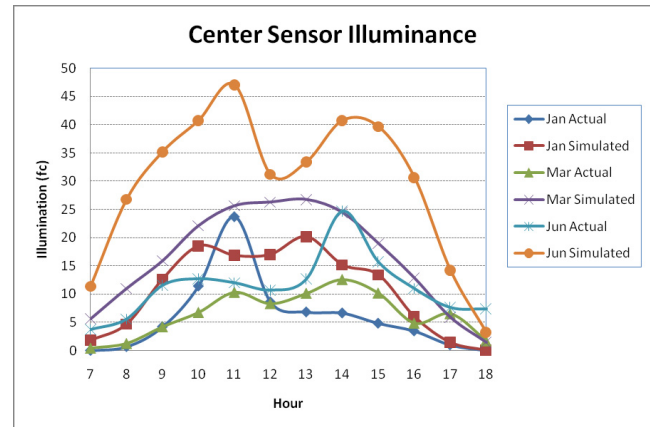


Fig 8: Comparison of center sensor illuminance on cloudy days

From figure 8, it is clear that there are no observable trends in performance apart from the fact that the general illuminance for both the measured and modeled cases remains below 50 fc.

5.5 Comparison of Illuminance Gradients With Changing Distance from Daylighting Glazing

The decrease in illuminance as the distance from the daylighting glazing increases is another important metric that the simulation must be able to model correctly. The following graph (Figure 9) shows the illuminance at three sensor locations in the classroom at 12 Noon at three different times of the year. It can be seen from the graph

below that the simulation is able to correctly model the decaying illuminance level from the front to the back of the classroom at different times during the year.

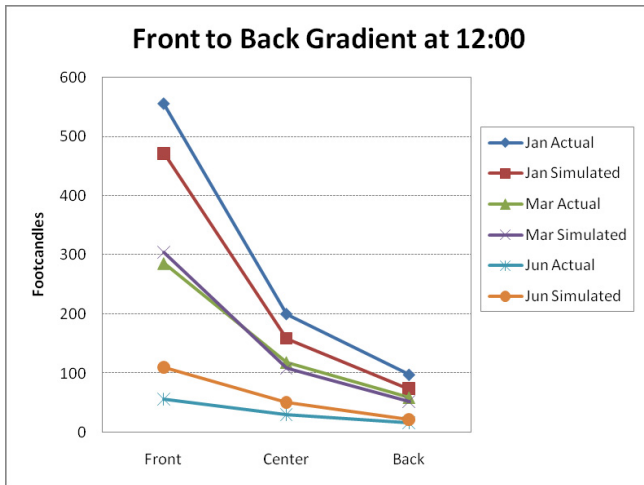


Fig. 9: Comparison of measured and modeled front to back illuminance distribution at 12 Noon on sunny days

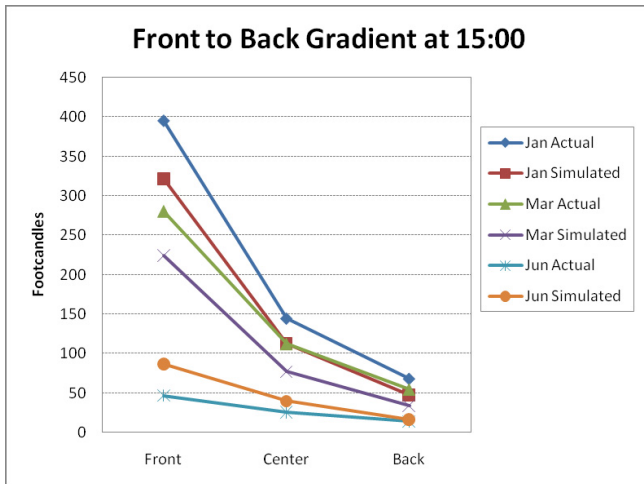


Fig. 10: Comparison of measured and modeled front to back illuminance distribution at 3 PM on sunny days

The variation in the front to back gradient at 3 PM is higher than at 12 Noon (Figure 10). However, this can be attributed to the different levels of solar radiation available at this time in the modeled and measured cases.

While the absolute variation at a sensor location at a particular time may be high, it is not unexpected because of the differences in the radiation data obtained from the weather file. The front to back gradient on cloudy days is much more difficult to predict due to the vast differences in available exterior illuminances and is not expected to match the measured values (Figure 11).

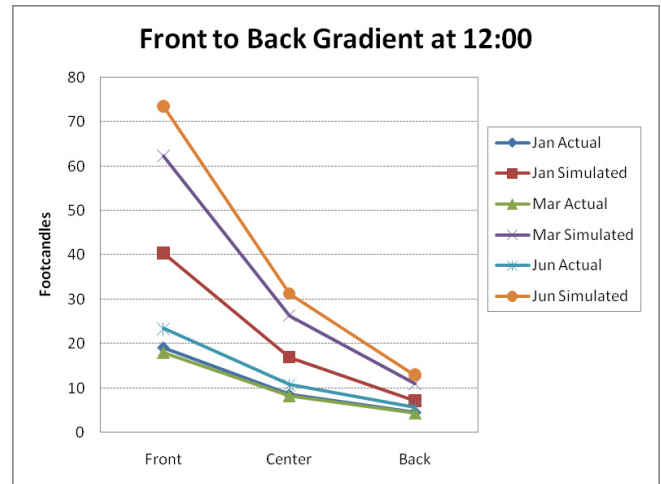


Fig. 11: Comparison of measured and modeled front to back illuminance distribution at 12 Noon on cloudy days

5.6 Comparison of Illuminance Gradients With Changing Distance Parallel to the Daylighting Glazing

This section compares the modeled illuminance gradient along the daylighting glazing going from the east to the west of the classroom. The position of the soffit and the sun in the sky affect the illuminance levels at these sensors.

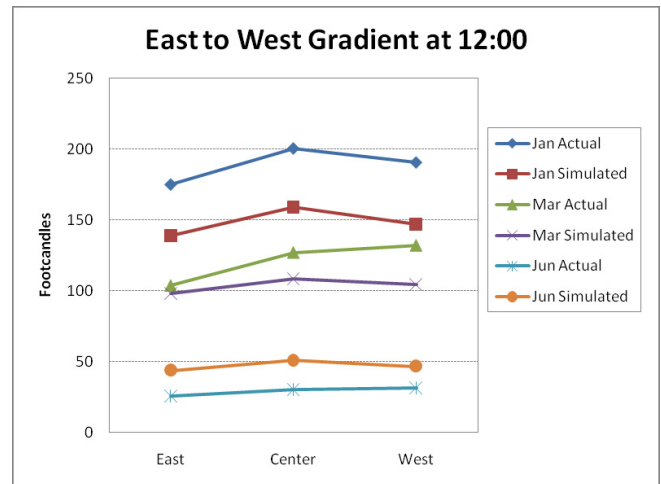


Fig. 12: Comparison of measured and modeled east to west illuminance distribution at 12 Noon on sunny days

The east to west illuminance distribution for January shows a similar trend in both the simulated and measured cases (Figure 12). Again, for the summer, both the simulated and measured curves are flat. In the month of March, the west measured illuminance increases over the center sensor value. However, the simulated west sensor value is slightly lower than the simulated center value.

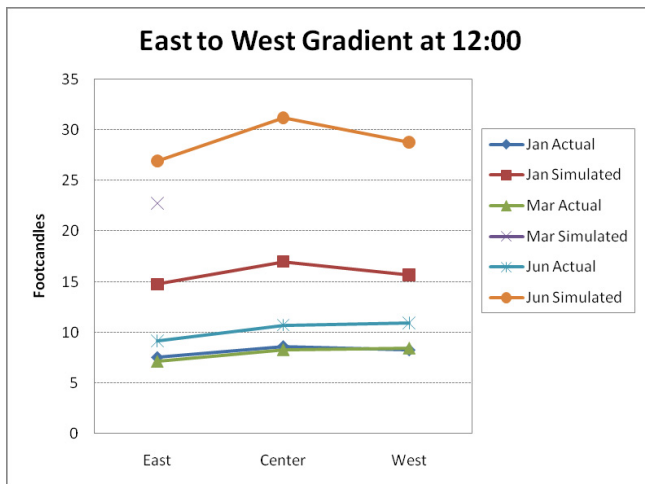


Fig. 13: Comparison of measured and modeled east to west illuminance distribution at 12 Noon on cloudy days

The east to west illuminance gradients for the modeled and measured cases show similar trends, however, the illuminance values are not equal in magnitude (Figure 13).

6. CONCLUSIONS

The goal of this study was to compare the results of the daylighting simulation with the measured values over an entire year. The daylighting simulation could predict reasonably well the average daily illuminance levels in the classroom. The conclusions from this study can be summarized as follows:

- (1) Over the course of the year, the simulation is able to match the measured average illuminance levels for most of the months. However, when the illuminance levels are at their highest or lowest, the response of the simulation is curtailed. Also, the highly unpredictable cloudy day performance is difficult to match without using actual radiation data in the simulation.
- (2) The simulation is able to model the front to back and east to west illuminance gradient in the classroom at different times of the year.
- (3) The curved interior light-shelf in the current daylighting design is a unique translucent element that presents a modeling problem of considerable complexity. It is rare that such daylighting elements will be encountered elsewhere. To model these elements for evaluating their performance in a building environment, it may be sufficient to match just the average daily, monthly or annual illuminance levels.
- (4) This research shows that even without actual direct and diffuse radiation data, it is possible to validate a daylighting simulation using DAYSIM by comparing average illuminance levels for a day or a month. From the daylighting designers' perspective, who simulate their

daylighting designs and want to verify the accuracy of their results, it may be more objective to evaluate average illuminance levels rather than looking at point values in time.

(5) With the limitations imposed by the lack of real solar radiation data, it may not be always possible to validate daylighting models with actual measured values. However, this need not necessarily be a stumbling block in estimating the daylighting performance of the design.

(6) Comparing the trend and average magnitude of illuminances in the model with measured values may be sufficient in most cases for the verification of a daylighting design. Achieving greater accuracy requires an investment in expensive measurement equipment.

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