Daylight Factor (overcast sky) versus Daylight Availability (clear sky) in Computer-based Daylighting Simulations

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Abstract

Daylighting software is an important component towards creating accurate simulations for sustainable design. Ecotect has been widely used by designers and consultants for its quick and simple analysis in the early design phases. It has many advantages, but only provides two sky conditions: CIE overcast and uniform skies. Using the overcast sky conditions might give feedback that is not useful in some cases. Even worse, naïve users might not understand the implications of using overcast sky conditions when testing simple building rotations on a site and assume that the building orientation does not matter for daylighting. Three different software programs (AGI32, Ecotect, and 3ds Max Design) were tested with four different cases under CIE clear and overcast sky conditions. This study shows how different the results were from three programs and also discusses some issues that software users should be aware of when they do daylighting analysis.

Keywords: Daylight Factors, Daylight Availability, Daylighting Simulation, Sustainable Design

1. Introduction

As energy efficiency and sustainability become increasingly important issues in the field of architecture, daylighting is recognized as a key strategy in reducing the energy consumption by reducing the amount of electrical lighting in a building. In addition to reducing the carbon footprint of buildings, daylighting is known to have positive effects on human health and productivity. Consequently, energy standards and green building rating systems have strongly recommended that designers incorporate daylighting strategies into building design. However, this recommendation is all too frequently ignored due to the complexity of daylighting design and to concerns of the potential for thermal and visual discomfort caused by excessive sunlight penetrations and glare.

Many daylighting analysis methods have been developed and used by students, designers, and consultants. From physical modeling to computer-based simulations, analysis methods are used to predict the performance of daylighting systems before a building is completed. Using these methods, quantifiable values such as illuminance levels can be measured or calculated. However, it is not easy to get accurate, predictable, or often even matching values between techniques due to the multitude of variables, including sky selection.

The digital simulated representation of the sky is one of the most important factors in daylighting calculations. It is critical for accurate analysis, and software users must understand the implications of their selection when choosing between different sky representations. When a physical model is built and tested outside to measure illuminance levels inside the model, the light levels will be quite varied due to different sky conditions.
such as clear sky, overcast sky, and partly cloudy sky conditions. This also applies to computer-based calculations. For designers making design decisions for daylighting systems, this factor should be fully understood and controlled for more accurate calculations. Without accurate sky conditions, predicting daylighting availability is not possible to achieve precisely. Currently, the most widely utilized sky conditions are CIE overcast and clear sky conditions, and the choice of which to use depends on the building’s location. These two sky conditions are typically used in software simulations; however, they are often not the best indicator for specific locations. Other research has been done for establishing better models, for example, the work done for Hong Kong in determining prevalence of sunshine and cloud cover and its implication for energy efficient design [1].

For this study, three different software programs were tested under CIE clear and overcast sky conditions, and the simulation results were plotted on visualized charts to compare different data sets. In order to understand the results better, a clear distinction needs to be made between daylight factor and daylight availability and how the CIE clear and overcast skies are generally defined.

1.1. Daylight Factor vs. Daylight Availability

- Daylight factor is the ratio between indoor illuminance and outdoor illuminance. It can be measured for a specific point or for an average of a space. The following formula shows how to calculate daylight factor from illuminance levels [2].

  \[ DF = 100 \times \frac{Ein}{Eext} \]

  Where

  Ein: indoor illuminance level and Eext: outdoor illuminance level

  By definition, daylight factor should be calculated only under the CIE overcast sky condition. This is critical for the understanding of the final simulation results. An overcast sky does not take into account the direct light entering a space, so rotating a building to face different directions (for example, north, south, east, west) will not significantly change the calculations. Daylight factor is most useful for locations such as London that might have the overcast sky as their primary condition, but even there a more nuanced calculation might be more appropriate.

- Daylight availability is similar to daylight factor, in that it is the ratio between indoor and outdoor illuminance levels. However, daylight availability is calculated under the actual sky conditions, which also includes clear and intermediate skies. Thus, it is assumed to represent better for sunny climate conditions such as Los Angeles.

1.2. CIE Clear sky vs. CIE Overcast Sky

Although the sky is changing every minute of a day, typically average sky conditions are used for daylighting calculations. Different models of virtual skies have been developed by the CIE and others. CIE has mathematically developed 15 different sky conditions, two of which are shown in Figure 1 [3]. Among these sky conditions, overcast and clear skies have been widely used in daylighting simulations all over the world.

- CIE overcast sky

  With completely cloudy sky (100% covered), this sky model has been widely used to calculate daylight factor. Many designers and users have used this model to calculate the worse case scenario. Ecotect software uses this sky model as a default.
• CIE clear sky
CIE clear sky is defined by having less than 30% of clouds covering the sky or no clouds [4]. In either case, the sky is brighter towards the location of the sun, and the sun is visible. Direct sunlight can be considered and calculated inside a building. This model is useful when visual glare and thermal discomfort studies are performed. For predominated sunny climate areas such as Los Angeles and Phoenix, this sky model should be considered in daylighting calculations.

Figure 1. CIE Sky Conditions [5]

2. Methods and Approach
This research topic started by testing a simple room with two different sky conditions and comparing the illuminance levels to verify what assumptions were being made about the sky conditions. The following three programs were used: Ecotect, AGI32, and 3ds Max Design (lighting analysis). Relationships between sky conditions and building orientations have been tested in each software program to compare how the building’s direction affects light levels under each sky condition. After completing the first test, three more cases have been tested with an exterior ground surface and an interior/exterior overhang.

2.1 Computer-based Daylighting Simulation Software
• AGI32
This is popular architectural lighting analysis tool used often by lighting consultants. It uses a full radiosity method for lighting and daylighting calculations but also supports ray tracing rendering images for photo-realistic images. 15 CIE sky conditions are available to choose from, and users can select any of them based on different site conditions. The program requires very long calculation time and creates large file sizes.

• Ecotect
Ecotect uses a geometric version of the split flux method, which is an internationally recognized manual technique [6]. While this software has a relatively short simulation time, its calculation result is not quite as accurate as other methods. As a quick design tool in early design phase, this software has been very popular among the design decision makers. A user can select CIE overcast or uniform sky conditions, but it doesn’t support the clear sky option. This is one weakness of the software. However, it provides a sun shading pattern study tool, which is useful in early design phase. Energy simulation is also available in this program. Weather data can be used for energy simulations, but it does not work with daylighting simulations.
• 3ds Max Design

Newer versions of 3ds Max have incorporated daylighting analysis tool. It uses ray tracing mental ray methods for simulations. With the interoperability between 3ds Max Design and Revit, this software has huge potentials in the lighting and daylighting analysis fields. It gives photorealistic high dynamic range images. It uses CIE, PEREZ sky models, and weather data files for its analysis. Several options are available within the program, including caustics [7].

Table 1. Comparison Chart of Three Software Programs

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<th>AGI32</th>
<th>Ecotect</th>
<th>3ds Max Design</th>
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<td>Ray tracing with split flux method (BRE daylight factor)</td>
<td>Ray-tracing mental ray</td>
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<td>CIE overcast</td>
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<td>Not realistic (needs Radiance for better rendering images)</td>
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2.2 Four Test Cases

Located in Los Angeles (latitude: 34° and longitude: 108°), the virtual test room was 40' long, 20' wide, and 12' high. One of the 20' wide walls was entirely glass with an 89% transmittance value. Light meters were added into the middle of the space with 2 feet on-center spacing at 2.5 feet above the floor. The properties of all the elements are given here: ceiling: 80% reflectance walls: 50% reflectance, floor: 20% reflectance, glass wall: 89% transmittance. This virtual space has been tested with four building orientations (east, west, south, and north) under both CIE overcast and clear skies. From the base case model described above, three additional models were created to test different facade conditions.

Figure 2. Light Meter Locations in Plan View (located at 2.5ft above the floor)
• Case #1
  A simple room was built with one glass wall as described above.

• Case #2
  Same as Case #1 except that an exterior ground surface with 0.1 reflectance value was added in front of the window wall.

• Case #3
  Same as Case #2 except that an exterior overhang was added outside the window wall (overhang is 4’ long, 20’ wide, and 0.5’ high with 0.8 reflectance value).

• Case #4
  Same as Case #2 except that an interior and exterior overhang was added at the window wall (each overhang is 2’ long, 20’ wide, and 0.5’ high with 0.8 reflectance value).

Figures 3 and 4 show rendered images of the east and north oriented cases at 9:00AM under a CIE overcast sky condition. These images are exported from AGI32. In figure 3, the window wall is facing the sun but the direct sunlight is not visible in these images since the sun is completely covered by clouds. The grey color sky in those images represents the fully cloudy sky defined as CIE overcast sky. Natural light coming through the window wall shows smooth patterns in all four cases. Images with east and north orientations shown in figures 3 and 4 are identical in each case. The actual indoor illuminance levels will be compared later, but these images simply explain that the relationship between building orientation and the sun's position are not factors when calculating daylight factor. This is critical for software users to be aware that daylighting performance under the overcast sky cannot be improved by simply changing building orientation.

Figure 3. Section views under CIE overcast sky _ East orientation at 9:00AM
Figure 4. Section views under CIE overcast sky_ North orientation at 9:00AM

Figure 5. Section views under CIE clear sky_ East orientation at 9:00AM
Figure 5 shows AGI32 rendering images under CIE clear sky condition. As shown in the images, it is easy to see the direct sunlight hitting the floor near the window wall. The blue color of the sky represents the clear sky condition. In case #3, the floor area lit by direct sunlight shows a shadow pattern caused by the exterior overhang. In case #4, it is possible to see the reflected light on the ceiling by interior part of the overhang.

3. Results

To better understand the results, the lighting levels are shown in Excel graphs.

3.1 Case #1

Under the overcast sky, changing building orientations does not affect indoor illuminance levels in all three software programs. Changing time settings under overcast sky condition causes slightly different results in both Ecotect and 3ds Max but the difference is too small to be considered as an important design variable. However, AGI32 shows a maximum 170fc higher light levels at 12:00PM than at 9:00AM or 3:00PM as shown in figure 6. This result shows that overcast sky in AGI32 changes by different times of a day.

The other two software programs show very similar patterns for the front half of the space, which is different from the results from AGI32. However, 3ds Max shows 0fc at the light meters starting from the center of the space to the deepest area. This unrealistic result needs further investigation. At 1ft from the window wall, AGI32 shows 418fc, Ecotect shows 272fc, and 3ds Max shows 236fc. This discrepancy happens in all four test cases. This means that if AGI32 is used for daylighting analysis, it would be easier to get higher predicted light levels than from the other software programs.

As shown in figure 7, there is huge discrepancy between clear and overcast skies near the window wall. This happens especially when the window wall faces the sun. Under clear sky, the results from 3ds Max and AGI32 are not the same. AGI32 show over 5,000fc near the glass wall but 3ds Max shows a maximum value of 944fc with east orientation at 9:00AM. Again, it can be easier to achieve higher predicted lighting levels from AGI32 than 3ds Max. A further study, beyond the scope of this project, would be to compare these lighting levels with physical models. One example of this type of validation has been done comparing 3ds Max Design with Daysim 3.0 and real indoor illuminance measurements [8].
3.2 Case #2

Indoor illuminance levels are almost similar to case #1 in Ecotect and 3ds Max (see figure 7 and 9). However, AGI32 shows lower illuminance levels than case #1. Before performing case #2, it was assumed that light levels will be increased due to the exterior ground reflecting daylight into the indoor space but the results were totally opposite. By adding exterior ground surfaces, the light levels were decreased up to 10fc maximum. An additional test is required to find out why this happens.

The exterior ground surface also affects indoor light levels in Ecotect but the difference between case #1 and case #2 is less than 1fc per light meter. In 3ds Max, indoor illuminance levels are identical in case #1 and case #2 thus it is assumed that there is no effect from exterior ground in front of window wall.
Under clear sky, AGI shows 7,389fc with a south orientation at 12:00PM. This is the highest value in this study as shown in figure 10.

![Figure 10. South Orientation at 12:00 PM and Enlarged Image](image)

### 3.3 Case #3

Again, overcast sky provides much lower indoor light levels than clear sky. In AGI32, the maximum light level is up to 5,000fc right inside the window wall. Due to the exterior overhang, there is a huge drop between 5ft to 7 ft from the window wall in both AGI32 and 3ds Max. By looking at figure 11, it is possible to see the extreme contrast between the daylight areas and the shadows inside the space. In AGI32, this drop is up to 4,200fc. The enlarged image in figure 11 shows that 3ds Max has a maximum value of 797fc at 1ft from the window and that the light level drop is up to 500fc. However, both programs show the light level drop at the same location. It is possible to assume that the sun angles in both programs are identical, but direct illuminance from the sun might be different.

![Figure 11. East Orientation at 9:00 AM and Enlarged Image](image)

As shown in figure 12, when the window wall is not facing the sun, the results are not very different under clear and overcast skies. In AGI32, clear sky shows almost similar pattern to overcast sky. 3ds Max shows the lowest light levels among the results under both clear and overcast skies.
3.4 Case #4

The results are not very different from case #3. Due to the location of the overhang, the light level drop happens at different locations between 5ft and 9ft from the window. AGI32 and 3ds Max show light levels drops at different locations.

Under clear sky, AGI32 still shows much higher light levels than 3ds Max.

With the west orientation, a smooth decrease of light levels are shown through the entire space. However, there are still discrepancy between the programs and sky conditions. Again, 3ds Max shows the lowest results with both clear and overcast skies.
4. Conclusions

After performing calculations, it was found that, as expected, clear sky provides much higher indoor light levels than overcast sky. The light level difference between overcast and clear skies was significant near the glass wall and should be considered in daylighting calculations.

However, certain anomalies were uncovered including lighting levels that don’t match between software programs under the same conditions. This study shows that using different daylighting simulation software programs gives different simulation results. It is interesting to see that AGI32 calculates the highest results and 3ds Max the lowest light levels in all test cases. It is clear that designers should not rely on one specific software program for their analysis. Instead of calculating actual light levels, daylight factor, the ratio between indoor and outdoor illuminance values, could be a better method and should be considered for daylighting designs. However, this does not mean that CIE overcast should be always used for daylighting analysis. For sunny climate areas, it is proper to use clear sky condition since the simulation results between clear and overcast skies are totally different as shown in this paper. By using clear sky conditions for sunny climate areas, designing more efficient daylighting strategies can be achieved since building geometry, orientation, and time should be considered in analysis. It is generally considered that the overcast sky provides the worst daylight condition; selection of more nuanced sky models will provide better designers better predictive simulations [9].

During this study, the author contacted software technicians to ask for clarification about unclear calculation results from these software programs. Here is a summary of some of the more critical points. In daylighting simulations, horizontal illuminance of the sky and direct normal illuminance of the sun are critical since these values totally affect the calculation results. By increasing or decreasing these values, it is possible to get higher or lower calculation results. Ecotect, which provides only CIE overcast sky, has a very useful tool to show what horizontal illuminance value of the sky should be used for a given project location based on different latitudes. 3ds Max also gives quick assumptions of these two values based on different project locations, but these values cannot be fully trusted. In 3ds Max, users can easily modify these values thus there is a possibility to get wrong results by applying wrong values. In AGI32, this information cannot be even checked by software users. Without getting these values, it is difficult to understand why AGI32 gives much higher calculation results than other two software programs in this study.

Further study is required to find out how to get correct horizontal/direct normal illuminance levels for a specific site location. Providing this information would be valuable for designers and consultants to get more reliable simulation results from different software program. The assumptions in daylighting simulations should be also open to users as much as possible.

Although the overall results of the study were not completely unexpected, the results do emphasize the importance of knowing the difference between daylight factor and daylight availability, the choice of an appropriate sky condition, and that even well tested software have unexplainable glitches occasionally. With more reliance on daylight harvesting as one method for achieving better energy efficient buildings, understanding the assumptions of software programs will become more important.
References


