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Balancing Daylight, LEDs, and Controls: The Future of Lighting for Designers

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Lighting design requires a balance between natural and electric sources to address the contemporary issues of sustainability and human well-being. The current generation of designers is being tasked with finding a balance between these light sources, while also addressing performance metrics, codes, and user satisfaction. Despite advances in technology, many practitioners still use previous work experience and rules of thumb to rely on lighting choices during the schematic design phase [3].

Current methods to evaluate daylight prior to the design phase are wide-ranging and not standardized nor regulated. Simulations offer an effective means to refine a daylighting concept later in the design process, but since many design teams still lack the know-how, time, or resources for such detailed design investigations, the daylighting analysis of many buildings begins and ends with the use of rules of thumb [3]. Rating systems and energy codes require a performance metric related to daylight in order to show compliance, but to date there is not a widely accepted metric to recognize well-daylit buildings [1]. LEED (Leadership in Energy and Environmental Design) requirements acknowledge the advantages in daylight, but there is still disconnect between theory and practice of planning for natural light. As a result, designers are resorting more to simulation as a means of demonstrating compliance with various rating systems [2]. Additionally, new technology in electric sources, like LEDs (light emitting diodes), require designers to understand the characteristics and energy savings potential and the trade-offs between natural and electric light.

Literature Review

Daylighting has always been an important issue in architecture and interior design, as it affects multiple areas throughout a built environment, including the functional arrangement of spaces, occupant comfort (both visual and thermal), structural elements and energy use [4]. In today's society, daylighting has been recognized as an important aspect of sustainable buildings, although it can be difficult to evaluate its quality and quantity [5]. Utilizing daylighting can offer many benefits, the main one being the ability to offset electric lighting and thereby reducing energy consumption. In turn, using daylighting can improve occupant satisfaction, as it increases productivity and health. Other benefits include ventilation abilities, emergency egress, and visual relief through the use of windows to connect occupants with nature.

Current daylighting design practices vary widely within the industry. While many design practitioners agree that daylighting is a regularly employed and established technique for sustainability, it can be difficult to quantify and implement because of its versatility and far-reaching implications [6]. A widely accepted system of metrics to evaluate good daylighting does not exist yet, although some rating systems in the design industry are attempting to associate various metrics with daylighting; such as the daylight factor distribution (LEED-NC); glazing factor distribution (LEED-NC); and the daylight saturation percentage (LEED for schools). Until a unified set of daylighting metrics is agreed upon, design professionals rely on the variety of tools available today that include design guides, simulation programs, and rules of thumb [6].

Before computer simulations were widely used, the practice of using physical scaled models had been incorporated to predict daylighting within an interior structure. This practice can still be used today, but in the article from the 1997 issue of Lighting Research and Technology, an article titled, "Simple scale models for daylighting design: Analysis of sources in error in illuminance prediction," discusses the use of small scale physical models to study lighting performance and the errors involved. The research review determined that the majority of lighting researchers assumed scale models to be accurate predictors of illuminance levels in real interiors, however, the article suggests that because the small scale tends to overestimate luminance levels, then the finished structure would also incorporate over lit spaces. The analysis showed that the causes of the errors in lighting performance were based on two cores factors: dimensional accuracy and correct simulation of photometric properties [7]. It should be noted that computer based models can suffer from the same errors when attempting to analyze daylighting performance in a simulated structure.

In 2006, Christoph Reinhart and Annegret Fitz conducted a survey on the current use of daylighting simulations in building design, where they found seventy-nine percent of survey participants used daylighting computer simulations [5]. The most common factors that were calculated during simulations were the daylight factor and interior illuminances, while the shading types and controls were the most common design areas that were influenced by a daylighting analysis. Lighting simulation software was the least frequently used software by architects and engineers within building simulation, as architects primarily used rendering tools for presentation purposes, while engineers focused on electric lighting software from manufacturers. In a total of one hundred and thirty-four participants in the survey, they reported using forty-two different daylight simulation programs [5], which illustrates how much of a range is available and used in daylighting simulation. The final responses from the survey suggested what could be done to enhance the use of daylighting in buildings. Respondents commented on the need for several things including: more intuitive and user-friendly design tools with clear examples and documentation for use; performance indices for good daylighting, with significance of the interactions between daylighting, electric lighting, control strategies and shading devices; general information on daylighting should be more available as to its correlation to other building design elements; daylighting standards should be a part of energy or building codes [5].

Advanced Lighting Simulation (ALS) is a way to create an accurate simulation of a design that appears mathematically and logically correct [8]. One of the simulation tools available for ALS is Radiance, a ray-tracing software program that enables accurate and physically valid lighting and daylighting design [8]. It was used to study the lighting design of an existing historical building in Singapore and evaluated in its terms of being able to construct a reasonably accurate simulated lighting environment of the Empress Place Building. Radiance software was developed by the Lawrence Berkeley Laboratory and was chosen for the study based on its suitability and validation in predicting accurate illuminance levels with a high range of sky conditions, and ability to handle complex geometry and complex lighting environments [8]. The simulated results from the daylight simulation were compared with actual measured results on site. Conclusions from the study indict that Radiance had the ability to produce a reasonably accurate simulated lighting environment under overcast skies in the tropics, primarily with no external or internal obstructions to complicate the data.

In 2006, computer simulations were used in a study of daylighting performance and energy use in heavily obstructed residential buildings in Hong Kong [4]. The study noted that the daylighting performance of a building is dependent on many factors, including a thorough understanding of the subtle interactions of design features. Utilizing a computer simulation can reduce the amount of calculations required to accurately assess daylighting performance. The authors reviewed the importance of using the Daylight Factor (DF) as the assessment criteria, which is the ratio of the internal illumination to the illumination simultaneously available on a horizontal plane from the whole of an unobstructed overcast sky, expressed as a percentage. The study additionally identifies the five key building parameters that affect the interior daylighting illuminance. These are building area and orientation, glass type, window areas, shading, and external obstruction. The study used the computer simulation tool EnergyPlus to model the daylighting performance of a high-rise in Hong Kong. The software was chosen based on its ability to handle interior inter-reflection calculation, reflection from neighboring buildings, and handling of complex fenestration systems. The results of the study found to accurately predict illuminance levels based on the given criteria, and produced results in terms of lighting levels in lux and time of day observations.

Another study on daylight simulation was conducted in 2006 and published in the AIML Journal that presented a time series prediction model for daylight interior illuminance obtained using Adaptive Neuro Fuzzy Inference Systems (ANFIS). The computer model also utilized Radiance software. The article notes that in order to accurately analyze visual and energy properties produced by daylight, an accurate prediction of daylight entering the building is needed. The Daylight Factor (DF) calculation approach has been employed for the past fifty years, but isn't flexible enough to predict dynamic variations due to sun position and sky condition changes [9]. The authors sought to use time varying illuminance predictions (similar to those used for meteorological data) to predict a more realistic account of daylighting conditions. Radiance software was used to collect one full year of data with various sky conditions, which uses simulated data rather than measured values throughout the year, based on "if-then" statements. The article concludes that using such a model provides the opportunity to predict daylighting conditions to apply to lighting control systems.

A more recent article by Aaron Seward in the Eco-Structure magazine for the American Institute of Architects discusses various lighting calculation tools for designers. Seward suggests that all lighting calculation tools use two metrics to quantify light: illuminance, the amount of luminous flux per unit area, measured in lux or footcandles; and luminance, the intensity of light reflected from a surface, measured in candelas [10]. Most projects that are determining lighting needs use illuminance as a measurement, as it provides the amount of light that reaches a horizontal work plane. Measuring the amount of light from an electric or artificial source can often be straightforward, as lighting calculation tools often quantify light at a specific given time. However, daylight provides many more challenges, as the quality and quantity of light can change based upon the time of day, season, location, and weather. Lighting calculation tools must be able to account for these variables in order to provide an effective lighting solution that can both reduce energy and ensure adequate light levels [10]. The various programs available can offer anything from quick and easy calculations to assess energy targets and wattage; moderate programs that can calculate the amount of daylight at given times and locations; higher-end packages that will determine how both daylight and artificial light can work together using photometric information from the manufacturer that will also produce high quality renderings. The higher end programs offer more flexibility, but also require more time to set up the computer models [10]. The next level of program, Daysim, attempts to analyze the amount of daylight available over a dynamic time range, not just a static period. All of the lighting calculation tools can offer needed information, but generally a mix of tools are used by designers and architects in order to get an accurate idea of the lighting and energy needs a project requires.

The review of literature on the subject of daylighting simulation shows a variety of techniques and software are employed to prepare and plan during the design phase of a structure. Since daylight is highly variable with many factors to consider, there is not one universal method to calculating quality or quantity. Although many designers strive to capture natural light properties, the tools available for daylight analysis generally have a high learning curve, require excessive computation or data, and are time intensive.

Problem Statement

The goal of this project was to address how undergraduate design students could study daylight in order to use it as an effective lighting solution. The digital analysis of exterior façade systems, fenestration design, interior space, and building orientation helped provide a complete picture of both successful and unsuccessful daylighting solutions and controls. Analyses were completed through visual studies and software analysis.

There were three main objectives for the students in this study. The first objective was to analyze an existing structure as to its daylighting potential, in relation to site location, building orientation, climate, and solar geometry. The second objective was to determine how much interior daylight penetration occurred within the structure as measured in footcandles and the daylight factor metric. The third objective was to determine if the existing daylight would be viable as a light source, or if electrical supplementation was needed and how much.

Current methods to evaluate daylight prior to the design phase of a building project are wide-ranging and not standardized nor regulated. To be effective in preparing to design and plan for daylight in their future careers, students must understand how to use current technology and computer simulation models to account for this balance between natural and electric light sources.

Methodology

Calculation tools and simulations were used to provide a lighting solution that could reduce energy and ensure adequate light levels for a given interior space. Students used different software tools to establish design criteria for natural light, and then analyzed the data to incorporate electric light in supplemental spaces. Appropriate lighting and shading controls were discussed and a lighting control plan was developed to account for switching between the use of daylight and electric light.

Simulation accuracy required correct dimensions and architectural detail placement, while daylighting viability required closed geometric forms, surface orientation (surface normals that define the front and back of a face), and model resolution. Students first had to create a three dimensional model from a two dimensional floor plan and elevations, with exact dimensions.

Software selection was determined by computing requirement availability, cost, and user-friendly interfaces. The primary rendering engine required for daylighting computation is Desktop Radiance, which was developed out of the University of California – Berkeley in the late 1980s. The rendering engine is utilized within a variety of existing programs, and is often built into many software rendering applications now. DAYSIM, which was developed to use the Radiance programming algorithms, was the first software evaluated for use in this project by the faculty. DAYSIM is defined as a daylighting analysis software that can calculate the annual daylight availability in buildings, using climate-based daylighting metrics. Additionally, the software can mimic occupant use of personal controls (light switches, blinds, dimming), annual glare analysis, and is capable of generating occupancy schedules, electric lighting loads, and shading device status.

While DAYSIM is very worthwhile for computing daylighting levels in addition to artificial light levels, it was deemed unusable at the start of this project due to problems with model translation. The computer models generated by the students proved to be overly complex for the DAYSIM software simulation. A less complex model was tested for use, but the results that DAYSIM provided were not sufficient for complex daylighting analysis. DAYSIM offered a detailed analysis of what lighting levels would be available during typical work days based on occupancy for a future commercial building. While valuable information could be extracted from the software, the learning curve and complexity of the software was deemed unacceptable for the lighting analysis by undergraduate students.

Relux is a software that was evaluated as a free light simulation tool that focuses primarily on the artificial lighting aspect. The company receives a large amount of current product data from luminaire, lamp and sensor manufacturers for accurate analysis and planning. Because of the lack of daylighting analysis within program, it was deemed unsuitable for this study.

AGI32 was a software evaluated that is described as a comprehensive point-by-point program with photometrically correct color rendering tool, and is widely used by the lighting design industry. Although it offered daylight calculations, the primary focus was on artificial luminaires and rendering visualizations. Additionally, the software's price point was out of scope for the student projects at $895 and was determined to be inaccessible for this study. Later developments did prove that educational use versions could be accessed for free, which have the potential to be used in future projects.

Autodesk Ecotect was the next software chosen for evaluation, which proved to be the final selection for this project, and it was packaged as part of the Autodesk software suit already existing in university computer labs. Ecotect is billed as a sustainable design analysis software that offers a variety of simulation and building functionalities. Features include the ability to analyze buildings in whole-building energy analysis, thermal performance, water usage and cost evaluation, solar radiation, daylighting, shadows and reflections.

Ecotect was able to import the student computer models with some modification, and also was able to produce detailed daylighting analysis and visual displays for comparison and study as illustrated in Figure 1, 2, and 3.

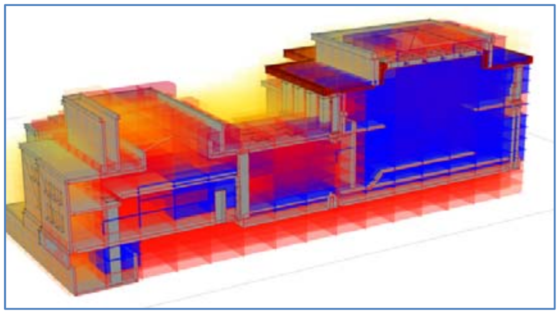

Figure 1: Sample Volumetric Daylight Levels

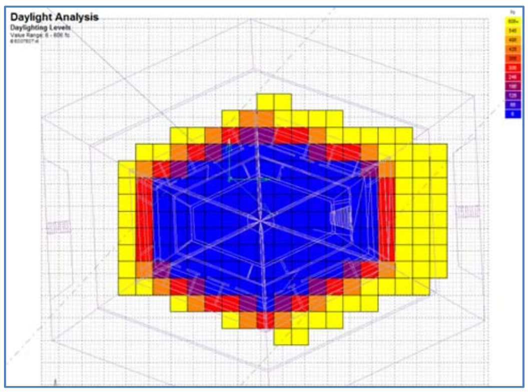

Figure 2: Sample Two-Dimesional Slice of Daylight Levels

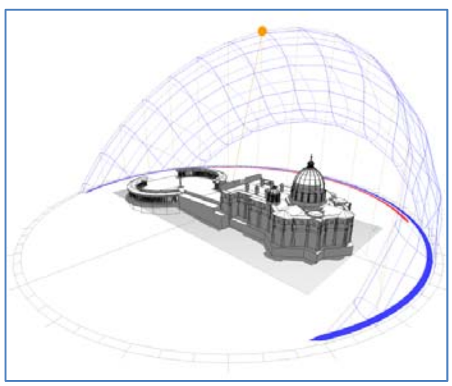

Figure 3: Sample Sun Path Diagram

As daylight is highly variable and can depend on many factors, students first had to comprehend the various units of measurement involved with natural and electric light. These included solar radiation, illuminance and luminance, and the daylight factor.

Solar radiation is the measure of solar energy from the sun, which includes both the total spectrum of electromagnetic radiation including visible, ultra-violet, and infrared wavelengths.

Solar radiation is measured in watts per square meter (w/m2). The World Meterological Organization uses the threshold of 1,020 w/m2 to define direct sunlight, and sunlight is measured at about 100,000 lux or 1,000 footcandles. However, the amount of solar radiation reaching the Earth’s surface is dependent upon the atmosphere, time of year, and geographical position. Simple illustrations were used to relay this information to design students, without excessive scientific backgrounds, as shown in Figure 4 and 5.

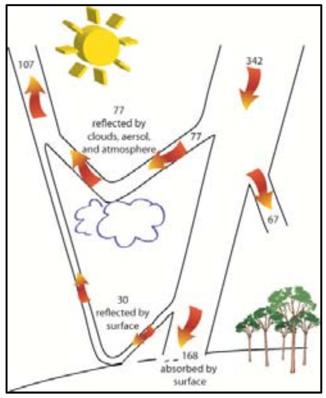

Figure 4: Distribution of solar radiation

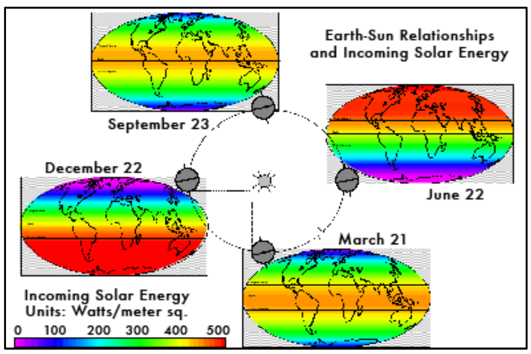

Figure 5: Intensity of solar radiation based on geography and season

Students were to understand that solar radiation reaches a unit of space near the Earth’s orbit at a rate of 1,366 W/m² (watt per square meter). This number is the "solar constant". Of this energy, about 19% is absorbed by the atmosphere, and clouds reflect a further 35% of the total solar energy. Therefore solar energy received at sea level is much less. As stated, its peak power is generally accepted to be 1,020 W/m². The actual solar radiation is based upon geographic location. Students used the software to generate a graph that would show the average solar radiation for a given location during calendar months and time of day. Figure 6 shows the graph for Nice, France. By viewing the differences in solar radiation for different locations, the students began to understand how daylight in different parts of the world could begin to be quantified based on a unit that would begin to describe light and energy.

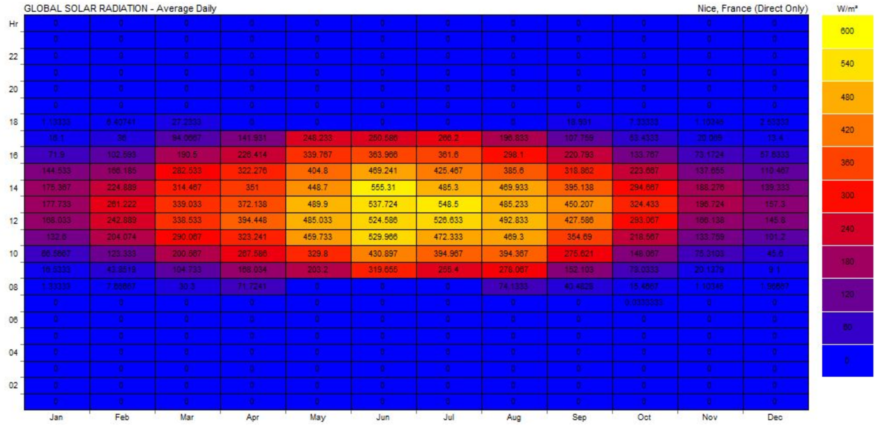

Figure 6: Global Solar Radiation for Nice, France

The next term introduced to the students was “illuminance” and “luminance”. Illuminance refers to the actual amount of lighting striking a surface, which is therefore greatly affected by the amount of light from the sky. The term “luminance” refers to the amount of light reflected off of a surface, which means the sky’s luminance is affected by the position of the sun, the location of the clouds, and the opacity of the clouds in the sky, as shown in Figure 7. All of these factors can change within a matter of minutes, which causes difficulty in trying to perform computer simulated analyses of daylight. The concept was emphasized to students in order to understand that one still image render was not an accurate representation of natural light within an interior space.

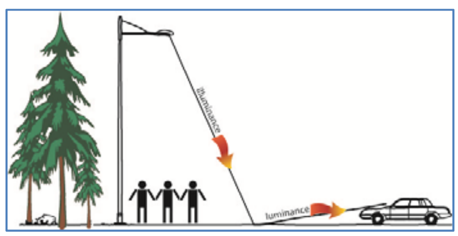

Figure 7: Illuminance vs. luminance

In order to account for variables in daylighting, much of the literature regarding daylighting refers to the “daylight factor” as the design criteria in spaces as opposed to the actual illuminance. Daylight coming through a window is either reflected off the window material, transmitted through the window, or absorbed by the surrounding surfaces, as illustrated in Figure 8.

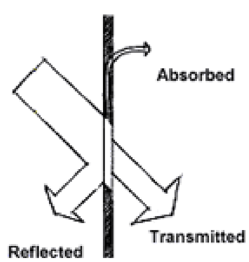

Figure 8: Daylight pathways

The daylight factor is expressed as the percentage of natural light falling on a work plane compared to the amount of light that would fall on a work place with an unobstructed horizontal surface under the same sky conditions. Therefore, the daylight factor is expressed as a ratio or percentage such as 20%, which means that the surface is only receiving 1/20th of the maximum available natural light, as illustrated in Figure 9. The higher the DF, the more natural light is available in the room. Typically ranges are usually 0 - 100%, but for interior spaces the range is usually 1-10%. Illuminance factors are measured in lux (metric) or footcandles (US standard) and are generally more important to designers when determining adequate light levels within a space.

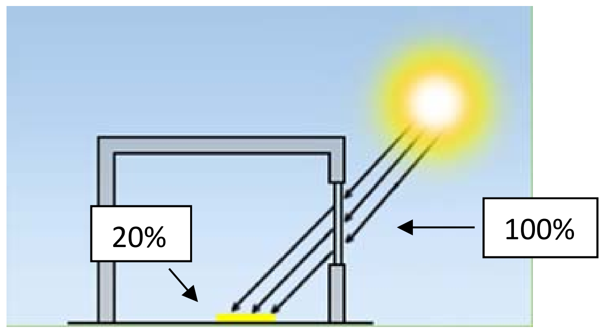

Figure 9: Daylight Factor

Autodesk Ecotect is capable of returning a variety of data after performing calculations on digital models. To keep the students interested and not overwhelmed with the amount of data, the focus was kept to geographic climate data of a site, daylight illuminance in footcandles, and the daylight factor.

The graph shown in Figure 10 displays the Monthly Diurnal (daily) Averages during the year. It also shows the changes in temperature, humidity, direct and diffuse solar radiation. This graph shows the standard comfort level (thermal neutrality) to determine how temperate the climate is for the average person. The Daily Conditions graph shows the average conditions for one of the hottest days of the year (summer solstice). Students were to output this data from their selected site locations for their buildings.

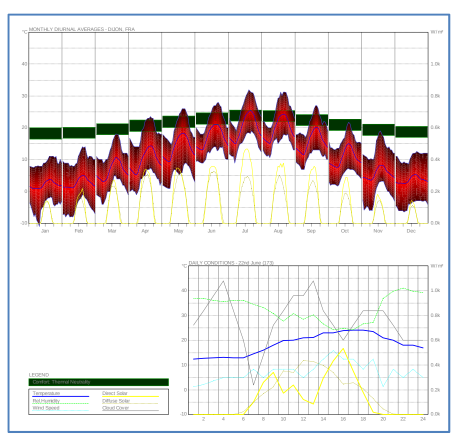

Figure 10: Monthly Diurnal Averages and Daily Conditions Graph

The software also was able to show the sun path diagram that represents the annual changes in the path of the sun through the sky, seen in Figure 11. This diagram provides a unique summary of solar position that a designer can refer to when considering shading requirements and design options. This also helped to illustrate to students that daylight is not a static light source.

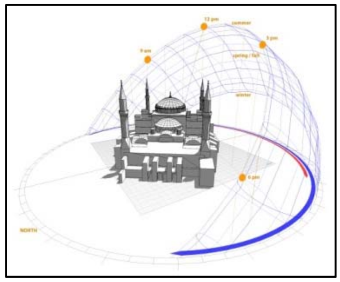

Figure 11: Solar Geometry or Sun Path Diagram

Student Process and Limitations

After the discussion on daylight terminology and exercises on software capabilities with existing buildings, the students then inputted their own structures into the software from provided floor plan. The evaluation of the student projects was a two-part process involving self-evaluation in addition to instructor evaluation.

However, there were some major limitations for this project, in terms of software computation and model complexity. The necessary time for computation on the analyses was more than originally planned for, and limited the amount of analyses that could be performed. A typical rendering on the available university computer hardware and software took approximately five days, and could not be viewed until completed. Therefore, any adjustments or errors required an additional five days of rendering time for corrections. In order to compute the daylight analysis over the entire building as volumetric data (beyond just a two-dimension slice through the structure at a specified height), approximately two days of computation time was needed. Again, any errors or adjustments would have to be recalculated for additional computation time.

Additional lack of information regarding software support was also a limitation, as the instructor had limited experience with the analysis software, which provided difficult when attempting to troubleshoot errors that students encountered. Therefore, there was extra time spent learning the software and utilizing limited resources available.

The results of the student structures were analyzed individually, and then compared to each other for analysis. Results were taken from several factors, including model structure, still visual renderings, animated visual renderings, and computed Autodesk Ecotect data. Not all of the results for each student were the same, due to previously mentioned limitations. Majority of the results extracted were similar, but not all of the students had animated data or interior footcandle diagrams for their particular designs.

Sample Exercise Results

As mentioned, students first extracted data from existing buildings as an exercise. Shown below are the results from the Unity Temple in Oak Park, IL. The diagram in Figure 12 represents the amount of illuminance measured in footcandles. The summer solstice and winter solstice are both shown, and provide the actual measurements dispersed over the floor plan in order to see the daylight variation in two varying times of the year. Figure 13 shows the sun path diagram for the Unity Temple.

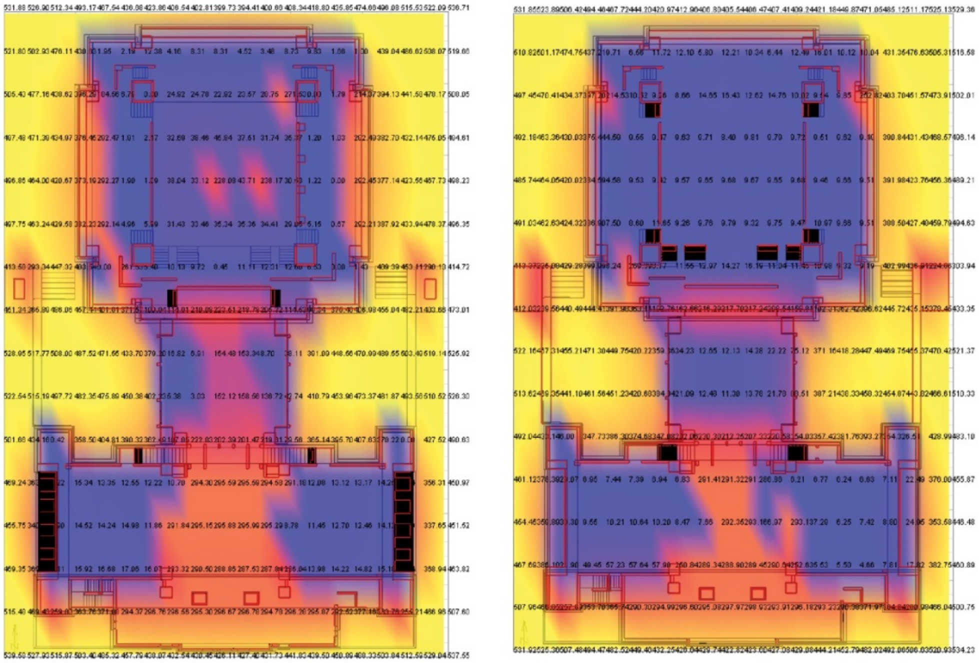

Figure 12: Unity Temple Summer and Winter Solstice (Illumination shown in Footcandles)

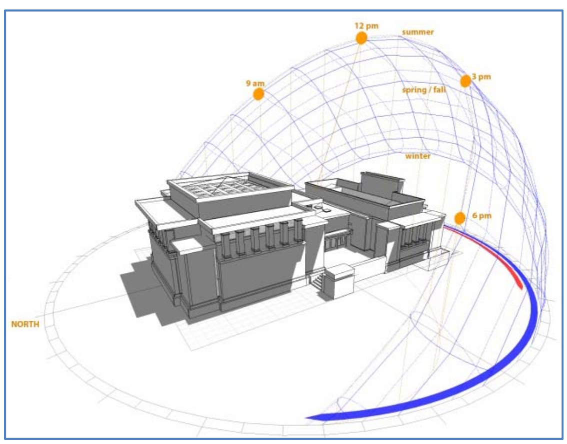

Figure 13: Unity Temple Sun Path Diagram

The next step was to use an existing floor plan and have each student design window openings and interior layout. The diagram in Figure 14 represents the amount of illuminance measured in footcandles for one student solution. The summer solstice and winter solstice are both shown and provide the actual measurements dispersed over the floor plan. Comparing the data reveals that the winter sun at noon provides an average illuminance level that is lower than the illuminance level from the summer sun. The summer sun also penetrates farther into the spaces, showing areas particularly from the clerestory windows designed by the student that receive more daylight.

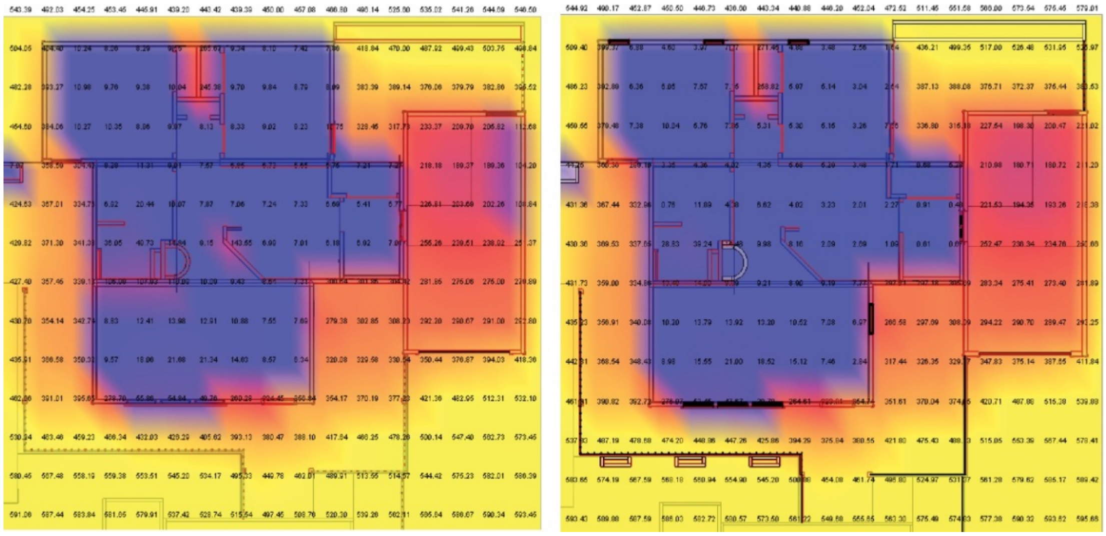

Figure 14: Student Floor Plan for Summer and Winter Solstice

Students then used the IES recommended footcandle levels to identify areas within the space that were not adequately supplied with natural light. This process was repeated for three times of the year at four different hours of the day. Due to the extensive time involved with the first parts of the exercise, this part of the project was limited to discussion and draft layouts of supplemental electric lighting. Discussion over daylight sensors and time of day changes in lighting took place over multiple course sessions. A draft layout of LED light sources accompanied each student solution, where footcandle level and watts per square foot were calculated.

Summary and Future Recommendations

The interior spaces studied reveal that natural light is integral to the success of the design and acts as a major unifying element within a space. Students discovered that aesthetically their designs were better with daylight, and the variation in light due to climate, time of year, and weather conditions impacted the interior spaces dramatically. Natural daylight within the buildings provides adequate illumination levels for tasks, and during the absence of natural light, the LED light sources supplemented the spaces with minimal energy requirements. Students understood that technology to predict the quality and quantity of light should be part of the design process from the beginning, and that a rendered still image did not adequately describe a space as it could not show the variations of lighting over time. From the perspective of design impact, energy savings, environmental benefit and occupant comfort, designers must plan for lighting (natural and electric) in the beginning of the design process.

Daylight, however, is highly variable and can depend on many factors, which can make quantifying any type of metric difficult for daylighting studies. Students began to understand that there are various units of measurement when dealing with lighting that pertains to different factors. The data examined for this exercise only provides a fraction of the information available related to daylighting analysis. Other examples of daylighting factors that were not computed include window glazing variables, surface reflectance of materials, glare, window controls, variable sky conditions and weather patterns.

The other major consideration when doing digital daylight studies is computation power of the hardware and software available. Various computer programs exist to aid in daylight analysis, but they require accurate building models, material representation, and weather data. The more accurate and complex the data available, the more computation power required to calculate the variables and produce an effective daylight analysis. The learning curve of the software can also add to frustration with technology when dealing with undergraduate design students.

Future student projects in this design program will strive to implement daylight analysis at the beginning of the project within the conceptual design phase. This should allow students to have a better understanding of natural light and how to maximize its potential while also allowing for an optimal balance with electric lighting, sensors, and control systems.

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