Zihao Chen and Alex Sheldon

Daylight Harvesting Potential on the UC Davis Campus

I. Abstract

Daylight is abundant in buildings across the UC Davis campus. When implemented correctly, daylight harvesting can save a significant amount of energy by reducing the need for artificial lighting. This project seeks to determine the potential savings associated with daylight harvesting on the UC Davis campus. After measuring illuminance data in Meyer Hall, a model was created to estimate the savings from implementing a daylight harvesting system. The model showed that for large rooms, energy savings can be as much as $33/year while small room may only save $3/year as a results of daylight harvesting. In addition, a test run was completed with the existing daylighting system, which was found to not be functioning correctly. Some recommendations for the Energy Conservation Office (ECO) will be made in order to rectify the existing problems and start saving energy.

II. Introduction

UC Davis is a large campus and there is no doubt that it consumes a lot of energy. Currently, the campus spends about $25 million per year on energy purchasing (Slaughter, 2019). The UC System as a whole is trying to reach carbon neutrality by 2025, so it is crucial to significantly reduce energy consumption on campus. The Energy Conservation Office (ECO), which strives to implement cost-effective projects on campus to cut down on energy consumption, has identified daylight harvesting as a potential source of savings. This project, for which the ECO is the client, will serve as a baseline study for evaluating the potential for daylight harvesting on the UCD campus.

Daylight harvesting is an energy conservation technique that involves supplementing artificial lighting in buildings with sunlight. In order to make daylighting an effective practice, advanced controls are needed to monitor how much sunlight is entering a room and dim the artificial lights accordingly. The daylight harvesting control system carefully monitors the illuminance in a room. Illuminance is the amount of light hitting a surface and decreases proportionally to the distance from the light source. Thus, while there might be enough sunlight to light the parts of the room closest to the window, it is likely that some artificial light may still be needed in some areas of a room even on sunny days. The UC Davis campus employs WattStopper as a daylighting control system. In addition to controlling the daylighting system, WattStopper also monitors UC Davis's energy consumption which is helpful in validating energy conservation projects and providing insight into where energy can be saved. The daylighting system at UC Davis is not well understood, and thus necessitates research in order to verify its functionality and quantify the energy savings.

In a review of the literature on daylight harvesting, the energy saving potential of daylight harvesting systems was estimated to lie between 20-60% compared to no system. However, there are several challenges associated with implementing a daylight harvesting system, including technical robustness, architectural integration, and human acceptance (Gentile & Dubois, 2015).

In a real-life study conducted in Belgium in a school building, the total annual energy savings varied from 18% to 46% for a classroom with three banks of lights and a calibrated daylight control system (Delvaeye et al., 2016). It is possible that the usage of daylight harvesting systems is not widespread due to the difficulties in design, installation, calibration, commissioning, and uncertainty of the payback time. While daylight harvesting has a significant amount of energy saving potential, the path to achieve the estimated savings is difficult.

III. Methodology

In order to be able to understand the potential for daylight harvesting for an entire university campus in only one academic quarter, the scope of the project was narrowed accordingly. Meyer Hall, one of the many buildings on the UC Davis campus featuring offices, classrooms, and lab spaces, was selected to use in this study. This building was selected in part because it already has 87 daylight sensors installed in various locations throughout the building so the potential to test the currently installed system is available. This building also made a good proxy for the entire campus because it’s four outside walls were directly facing the four cardinal directions. Thus, Meyer Hall had the potential to provide a reasonable baseline estimate for daylighting potential that could be applied to other buildings on campus based on the directions that the windows were facing. In this study the influence of the wall to window ratio on the daylighting potential is not assessed.

To better understand the amount of daylight entering various rooms in Meyer Hall, daylight sensors that record illuminance were purchased. Illuminance is the measure of the intensity of a light source at a given point and has dimensions of luminance per area. These data-loggers were placed at the window in 8 locations on the fourth floor of Meyer Hall as shown in Figure 1.

Figure 1: Locations of daylight sensors in Meyer Hall that recorded daylight illuminance for approximately two weeks. All locations with a sensor are highlighted in the figure. Floor Plan Credit: (University of California Davis, 2016).

At the end of 13 days of data logging, the sensors were collected. Data was removed from the loggers and stored for later analysis (see Appendix 2). Additionally, single light measurements were taken at 2-foot increments, moving away from the window, to understand how light dissipates in a given space. All measurements were taken at a vertical height of approximately 6 feet. This data is recorded as shown in Table 1.

Table 1: Light dissipation measurements used for creating a light dissipation model. All locations correspond to the fourth floor of Meyer Hall. The data for 4145 Hallway was not recorded because it was not an enclosed room.

Dist. From Window (ft)	0	2	4	6	8	10	12
4322 Walkway	167.73	111.30	67.80	46.30	31.4	23.90	18.9
West Stairway	1094.97	1244.00	1270.00	1248.00	1389.4	1575.00	N/A
4335	373.63	187.80	138.4	89.10	55.2	34.50	24.00
4328	200.97	129.50	65.70	33.90	22.2	15.20	12.00
4138	49.96	29.00	21.10	13.50	9.40	6.90	5.90
4145 Hallway	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4218	227.60	133.00	95.60	63.20	45.10	32.50	25.80
4247	196.57	104.50	68.40	46.50	30.70	20.90	15.80

The light dissipation data was used to make the Daylight Dissipation Model (DDM), which predicted illuminance as a function of distance from the window. The window in the room was assumed to be sufficiently large such that any point in the room with the same perpendicular distance from the window had the same illuminance. Vertical dissipation of light was assumed not to be significant and was thus neglected. The DDM was then used to create the Daylighting Savings Model (DSM) to quantify the potential savings from using daylighting controls. The DSM assumed the daylight sensors functioned optimally and that each bank of lights in a room could be dimmed independently. The efficiency of the lights was assumed to be captured by the efficacy. The values assumed for the DSM are shown in Table 2.

Table 2: Assumptions for parameters used in the DSM.

Parameter	**Value**	**Units**	**Rationale**
Required Illuminance	46.5	FC	Illuminance standard for educational spaces (DiLaura, Houser, Mistrick, & Steffy, 2011)
Cost of Electricity	0.1458	$ per kWh	Estimate from US Energy Information Agency for average price of electricity for California (U.S. Energy Information Administration, 2019)
Efficacy	130	Lumens/watt	Stated by client
Hours of operation (daily)	8AM-6 PM	hours	Reasonable hours a room could be occupied during normal working hours
Days per week of operation	5	days	Five working days in a week
Weeks per year of operation	50	weeks	50 working weeks in a year due to holidays
Cost of daylight sensor	85	$	This is an average price of a few daylighting control technologies on the market.

The DSM computes the wattage needed in order to ensure proper lighting in a given space using the equation Watts=Illuminance x (1/efficacy) x room size, where illuminance is in FC (Foot-candle), efficacy is in lumens per watt, and room size is measured in square feet. In computing the wattage needed per area, it becomes easy to apply the DSM to different room sizes. The model considers two rooms: a small room, of 129 sq. ft., which is likely a personal office, and a large room of 1000 sq. ft., which is likely a lab or large classroom. In the small room case, one bank of lights running parallel to the window is assumed. In the case of the large room, three banks of lights are considered, running parallel to the window. The number of individual lights in a room does not need to be explicitly considered because all lights were assumed to have the same efficacy. Thus, the total watts needed to light a given space can be shared among all fixtures because illuminance from difference sources adds together. The small room case estimates the needed watts to light the room based on the darkest place in the room, which is at the max depth of the room. On the other hand, the large room case estimates the needed wattage for each of the three banks of lights separately by assuming that each bank will illuminate one third of the room, as shown in Figure 2. Like the small room case, the wattage needed to light each third of the room is decided by the darkest point in the lighting zone.

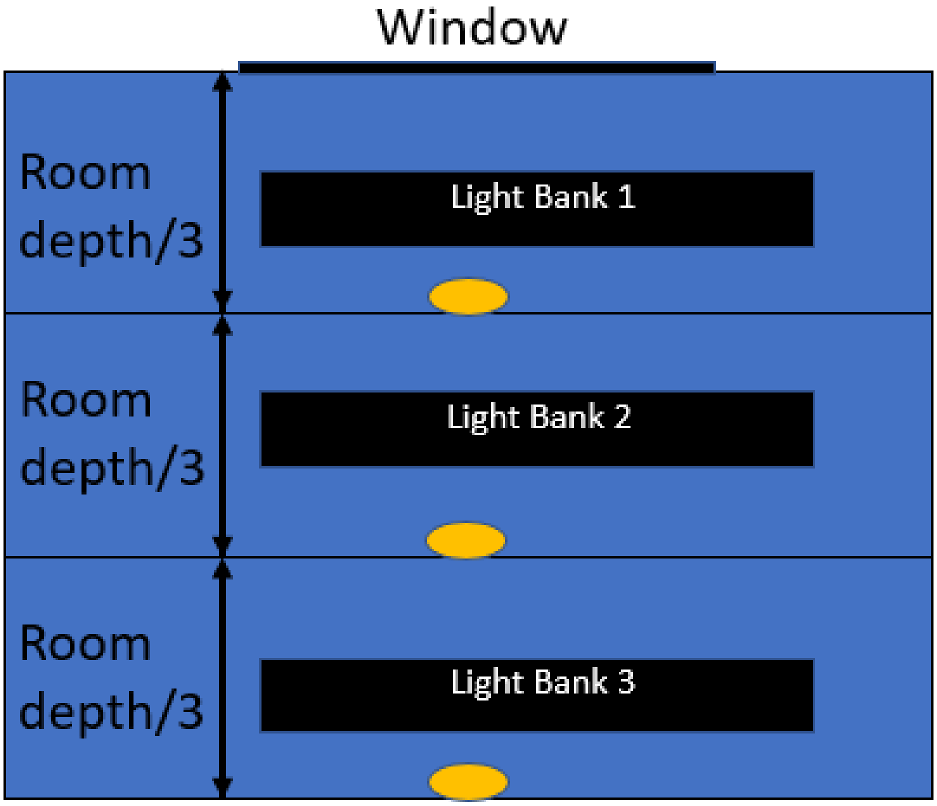

Figure 2: Diagram of the large room case of the DSM. The yellow ovals indicate the darkest point in the lighting zones of the room where the lighting need for the corresponding section of the room is estimated. Note: not to scale.

Using the DSM, estimates of yearly savings for rooms facing each of the cardinal directions were created. A sensitivity analysis was conducted to assess the effects of error in the data used as well as the effect of model assumptions on the DSM outputs. Weather sensitivity was evaluated by decreasing the initial illuminance by 50% and increasing it by 20%. The illuminance value was decreased more than increased because the input data was collected under sunny weather conditions in May. Usage patterns were varied by assuming that the lights were never turned off and then assuming that the lights were only used during the illuminance peak for each direction as shown in Figure 4. Electricity cost and the illuminance standard were simply varied by 25% increase and decrease.

Lastly, as mentioned there are daylight sensors and dimming technology presently installed in Meyer Hall but that are not in use. As part of this study, the parameters for operating the daylighting system were optimized and a test run was completed. The daylight loggers were put in place to ensure that the system was working correctly. While the sensors ultimately did not perform as expected, important qualitative conclusions were learned from this experiment.

IV. Results and Discussion

To better understand how sunlight entering a window disperses into a room, the DDM was built to better understand this phenomenon. Table 1 shows the recorded illuminance data and it is apparent that in most cases there is a sharp decrease of illuminance with increasing distance. In classical physics, the intensity, and the illuminance, of a light source decreases proportional to the inverse of the square of the distance from the source. This is known as the inverse square law (SoftSchools.com, n.d.). Ideally, this relation would have been suitable to illustrate how light dissipated in a room. As shown in Figure 3, this was not the case. This was likely because the sun was not shining directly into the window and thus did not act like a point source of light.

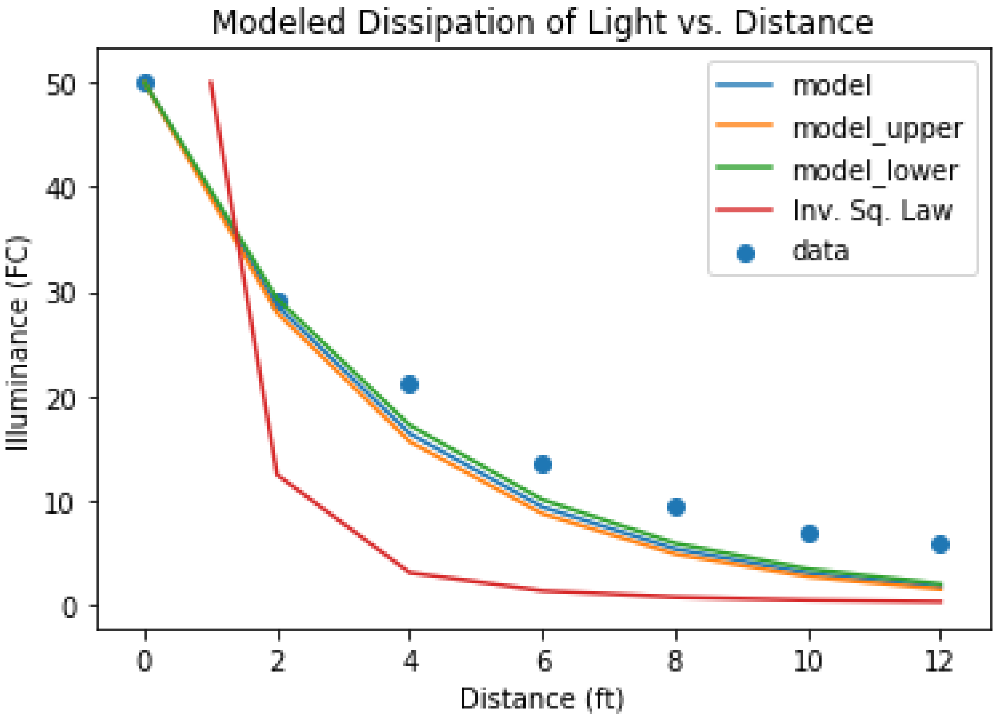

Figure 3: Plot showing the DDM prediction with the uncertainty of the decay constant compared to the actual data points. The prediction made by using the inverse square law is also shown.

However, a simple exponential decay was found to describe the dissipation of light with respect to distance with reasonable accuracy. The results of the DDM are shown in Figure 3. Five of the six light dissipation data sets (see Table 1) were used to make the model and the last was plotted against the model prediction as a test. Data recorded in the West Stairway was not used in the analysis because it has many clear outliers. When taking these illuminance measurements, there was direct sunlight into the West Stairway which likely caused the odd values to be recorded. The general decay used to model the dissipation of light is given by $I=Ne^{(-bd)}+k$ where I is illuminance at a point d, N is the illuminance entering the room at the window, b is the decay constant, d is the distance in feet from the window, and k is a constant. It was determined that background interference in the data-taking process was not significant as including a constant (k) did not increase the accuracy of the predictions and was thus neglected. The decay constant, b, was found to be 0.28 +/- 0.01 with units of 1/feet. As shown in Figure 3, the uncertainty in the decay constant does not affect the model predictions significantly. The uncertainty in the distances from the window where illuminance measurements were taken was neglected as it was difficult to quantify.

Illuminance from daylight was measured at the same locations shown in Table 1 for 13 days in order to be able to quantify the daylighting potential of Meyer Hall. An average day was created from this data (see Appendix 2) and Figure 4 shows the approximate amount of daylight entering Meyer Hall for all cardinal directions throughout an average day. It is interesting to note that the North side of the building gets more sunlight than the South side of the building, the opposite of what would be expected in the northern hemisphere. While this anomaly was investigated, no finite cause could be established and was assumed to be somehow related to the architecture of the building. With the average day data and the DDM, the DSM was built considering the parameters shown in Table 2. The overall findings from the DSM are organized in Table 3.

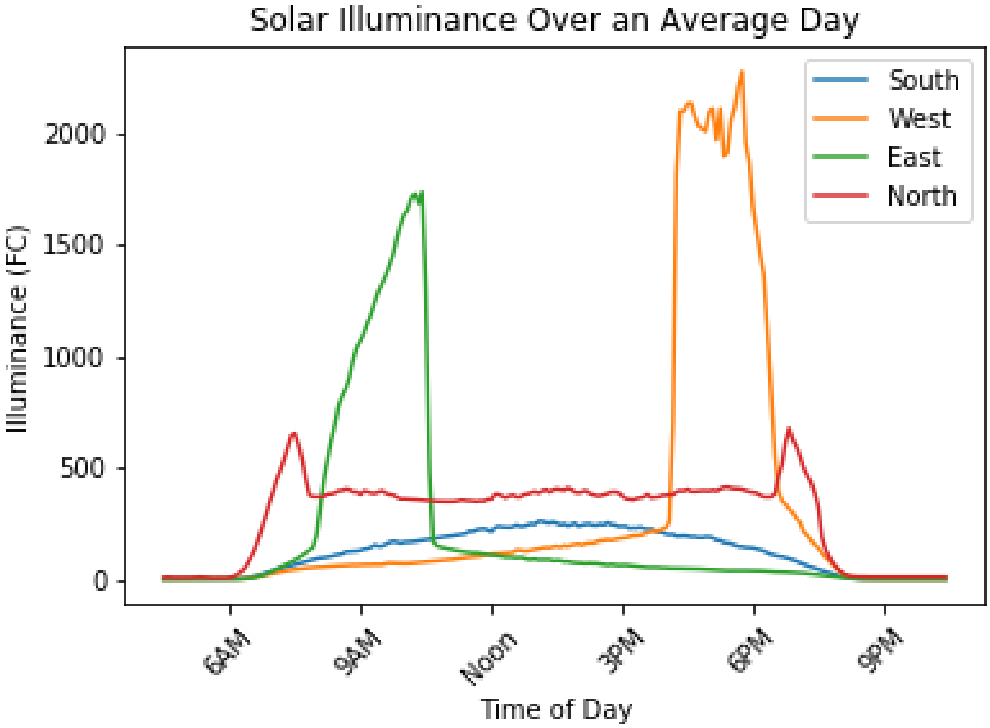

Figure 4: Illuminance of sunlight entering Meyer Hall from all four cardinal directions.

Table 3: Summary of main findings from the DSM. The size of the small room was assumed to be 129 sq. ft. while the size of the large room was 1000 sq. ft.

Finding	**Small Room**	**Large Room**
Cost without daylighting ($/year)	17	130
Average cost savings with daylighting ($/year)	1-3	19-40
Average cost savings (%)	6-18	14-31
Approximate payback time (years)	28-85	2-4

A large determining factor in the projected yearly savings proved to be the direction the room was facing. Another determining factor of the savings was the size of the room. Intuitively, these results seem to be what would be expected. As shown in Figure 4, not all directions receive the same amount of solar illuminance throughout the day. Additionally, it follows that more electricity would be used in lighting a large room because it likely has more lights and space to light. It is important to note that the payback time for installing daylighting controls in a large room is reasonable at 2-4 years, whereas the payback for the small room will likely never be reached. The payback time only considers the approximate cost of buying the technology and does not consider the time and costs associated with installation and maintenance. Still, if only the large rooms in a building were outfitted for daylight harvesting, it could quickly start saving UC Davis a significant amount of money. Another option would be to install a daylight sensor in only one office and use that to control neighboring offices which face the same direction. This would increase the benefits of using daylight harvesting in a small room while minimizing the payback time.

To understand how the assumed model parameters and input data may have affected the DMS outputs, a sensitivity analysis was conducted for the small and large room cases. The results of these analyses are shown in Tables 4 and 5, respectively.

Table 4: Sensitivity analysis of DSM predicted savings for a small room with changes from the base price for each direction reported as a percentage.

Direction	Base Savings ($/year)	Weather Sensitivity (%) (-0.50/+0.20)	Usage Sensitivity (%) (24 hrs/Peak)	Electricity Cost Sensitivity (%) (-.25/+0.25)	Illuminance Sensitivity (%) (-0.25/+0.25)
North	3	-50/+20	-33/+27	-25/+25	-0/+0
South	1	-50/+20	-20/+220	-25/+25	-0/+0
East	3	-50/+20	-53/+310	-25/+25	-0/+0
West	3	-50/+20	-30/+463	-25/+25	-12/+0

Table 5: Sensitivity analysis of DSM predicted savings for a large room with changes from the base price for each direction reported as a percentage.

Direction	Base Savings ($/year)	Weather Sensitivity (%) (-0.50/+0.20)	Usage Sensitivity (%) (24 hrs/Peak)	Electricity Cost Sensitivity (%) (-.25/+0.25)	Illuminance Sensitivity (%) (-0.25/+0.25)
North	40	-50/+20	-43/+4	-25/+25	-0/+14
South	21	-50/+20	-95/+25	-25/+25	-0/+0
East	19	-31/+9	-54/+243	-25/+25	13/+14
West	21	-22/+12	-45/+243	-25/+25	10/+10

From Tables 4 and 5 it is apparent that the usage pattern of a room has the most significant impact on the projected savings. Second to usage is weather. These two findings are logical because the amount of savings that would be expected correspond directly to the amount of illuminance coming into a room and the amount of time the lights need to be turned on. Electricity costs did cause uniform change to the results as would be expected. Lastly, the illuminance standard appeared mostly uniform in its impact of the projected savings. It is interesting to note that in general, the results shown in Tables 4 and 5 for the North and South directions seem to follow the same trend and the East and West directions follow another. This is likely since the North and South profiles shown in Figure 4 are steady whereas the profiles for East and West are characterized by one major peak. The major takeaway from the findings of the DSM is that location and usage of the room are key for maximizing savings.

Finally, the parameters for the current daylighting control system were examined, optimized, and tested. When the results of the experiment were reviewed, it was found that the daylighting controls did not work properly despite the revised input parameters. This indicates that there could be an error in the installation and configuration of the sensors that is preventing them from functioning correctly. It also became apparent that the installed controls may not be capable of using a perfect dimming configuration but rather may be better used by dimming the lights to preset levels given various thresholds of ambient illuminance.

V. Conclusions

Daylight harvesting is a valuable tool that the UC Davis campus has already put in place but is not fully utilizing. This study explored the potential of daylight harvesting on the UC Davis campus by using Meyer Hall as a case study. A model was built to help understand the potential for savings, considering historic weather conditions and other relevant parameters such as rooms size, illuminance standards, cost of electricity, and usage patterns. The projected savings varies from 14% to 31% in a large room and 6% to 18% in a small room. The projected savings are in line with the results found in a literature review (See Section II).

In completing a test run of the daylighting system in Meyer Hall, it was found that the daylighting system was not working as expected and artificial lighting was not being reduced. The first recommendation for ECO is to recalibrate the existing daylight sensors in Meyer Hall to ensure proper functionality. Based upon a review of the installation guide for the installed daylighting technology, careful calibration is critical for ensuring optimal performance. The calibration process is simple and will take approximately 5 minutes per sensor to complete. If this does not correct the behavior of the sensors, then the Dimming Mode should no longer be used. This leaves the Tri-Level Mode as the optimal choice. Use of this mode will necessitate further work to calibrate lighting thresholds but is less prone to complications than the Dimming Mode (WattStopper, n.d.). Furthermore, because of the savings estimates found in this study, it can be safely concluded that it is only worth the time and financial investment to implement daylight harvesting in large rooms with windows. Still, there is savings to be attained from those sensors already installed in small rooms and efforts should be made to commission these properly. With recalibration and proper mode selection, if needed, it is expected that the ECO will be able to start saving on electricity costs in the very near future.

VI. References

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VII. Appendices

Appendix 1: Daylighting Savings Model (Python Code)
See attached file: Appendix 1.py

Appendix 2: Measured Illuminance Data
See attached file: Appendix 2.xlsx