Improving Daylighting in Existing Buildings: Characterizing the Effect of Anidolic Systems

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ABSTRACT

Because of the longevity of the built environment, it is important not only to study methods of daylighting in new buildings, but to consider daylighting in existing buildings as well. Technologies exist which could benefit these buildings, but predicting the impact of these technologies on a daylit space remains difficult, and the highly computational modeling process probably discourages many people from even considering such devices. The aim of this study, therefore, is to produce an intuitive set of guidelines and recommendations for the applicability of a certain daylighting technology to a given space. The device on which this study focuses is the zenithal anidolic collector, and data is gathered using the software RADIANCE. **Keywords:** Daylighting, Anidolic, RADIANCE, Daylight autonomy, Daylight Factor, Renovation

1. INTRODUCTION

Awareness of the benefits of good daylighting has risen in recent years, and the designs of many new buildings take daylighting into consideration. The problem is that the majority of our infrastructure is older than this trend and was not designed with daylighting as a top priority. For instance, a Department of Energy tabulation published in 1999 [8] showed that 85% of US commercial buildings were more than ten years old. A need exists, therefore, to find an efficient means of improving the daylighting of existing buildings.

Unfortunately, some of the most important elements in passive solar design – such as building orientation, room depth, and window head height – are difficult or impossible to alter in existing buildings. Where passive design is impossible, though, daylighting can be improved by semi-passive, light redirecting technologies like structured glazing, louvers, light shelves, etc. A survey of such technologies can be found in Littlefair's works [11, 13], and in the outcomes of the IEA Task 21 [10]. Also, the British Building Research Establishment (BRE) did a thorough 1-1 scale evaluation of four different types of redirecting devices, and this data set is valuable, not only for rigorous testing of the devices, but also for its potential as a validation data set for light rendering programs [1, 17]

In his write-up on this study, Aizlewood observed that "any system for light redirection must cause transmission losses," [1], which at first seems counter productive. The purpose of most redirecting systems, however, is to increase the *useful* daylight in a space, either by eliminating glare (and thus the need for blinds), or by evening out the daylight distribution (which makes the room seem brighter to our eyes), or both. As will be discussed below, anidolic daylighting systems have the distinctive capability of being one of the only redirecting systems to constantly and substantially increase the deeper daylighting levels in a side-lit room.

While some redirecting technologies have been around for a while, they are not yet mainstays of architectural practice – possibly from lack of public familiarity or knowledge. Directional transmission data can be found for some of these devices, thanks to goniophotometric measurements or computer modeling [3, 4, 9], and despite their limited use in practice, several case studies exist to demonstrate their effect on an architectural space. [1, 10, 12] Several recent studies have also been done, assessing the daylighting impact of complex fenestrations by means of computer simulation using programs like RADIANCE, ADELINE, and the recently created DAYSIM [18, 19], these programs themselves having been validated by comparative studies between real measurements and computer simulations of complex systems [15]. While these studies have made significant contributions to the problem of predicting illumination, they still generally focus on only one or two space configurations, as part of the validation process for their computational approach [14]. This paper takes a slightly different path.

For the acceptance of any new technology into the toolbox of current practice, general guidelines and recommendations are needed to help determine this device's applicability in any given situation. The ability to have a rough idea of the device's level of benefit – *before* any computer simulation has been done – could convince many project managers to keep it as an option.

The purpose of this study, therefore, is to document the expected daylighting improvement of a specific light-redirecting device – in this case, the zenithal anidolic collector – based on the physical characteristics of an existing room. The metric of daylighting used in this study is daylight factor, as calculated by the program RADIANCE. Daylight factor is influenced by neither the location of the building, nor the climate of its surroundings, because it is dependant upon architectural geometry only. By not taking weather and orientation into account, the daylight factor remains simple and broadly applicable to multiple locations and façade orientations. The emerging metric called "daylight autonomy" [18] (or similarly, "Annual Daylight Profiles" [16]) on the other hand, allow for local weather, façade orientation, and hours of operation, and measure lighting levels as much as every five minutes over a statistical year. They are more thorough and more accurate to real sky conditions, but are also more numerically cumbersome and location-inflexible. Because of this, the results of a daylight autonomy calculation will only be used to evaluate the results of this study.

Finally, it must be stated that, as this is ongoing research, the data analysis and validation portions of this study are not quite complete. This paper will therefore focus on the method and procedure used to gather the data and will give preliminary conclusions and validations.

2. ANIDOLIC DAYLIGHTING SYSTEMS

Anidolic daylighting systems are a configuration of parabolic mirrors whose design draws from the principals of non-imaging optics. [21, 22] In fact, the name "anidolic" is an ancient Greek synonym for "non-imaging". [5] This new approach in daylighting was developed at the Solar Energy and Building Physics Laboratory (LESO-PB) of the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. [6, 7] The original anidolic device, the zenithal anidolic collector, is comprised of one external parabolic mirror, which gathers light from the sky's zenith, and two internal parabolic mirrors, which redistribute the collected light. The curves of these internal mirrors are designed and positioned according to the "edge-ray principal" of non-imaging optics, which stipulates that the extreme rays entering a system should be also be the extreme rays exiting the system [22]. This means that every ray of light which enters the system makes it all the way through with a minimum number of bounces, ensuring that reflection losses are reduced and that no ray is trapped and wasted. Such highly efficient geometry helps the anidolic systems to outperform similar redirecting devices, because it makes them ideal for redirecting diffuse sky light rather than direct sun light.

The ability to collect and redistribute diffuse light is one of the biggest advantages of the anidolic system, and it is

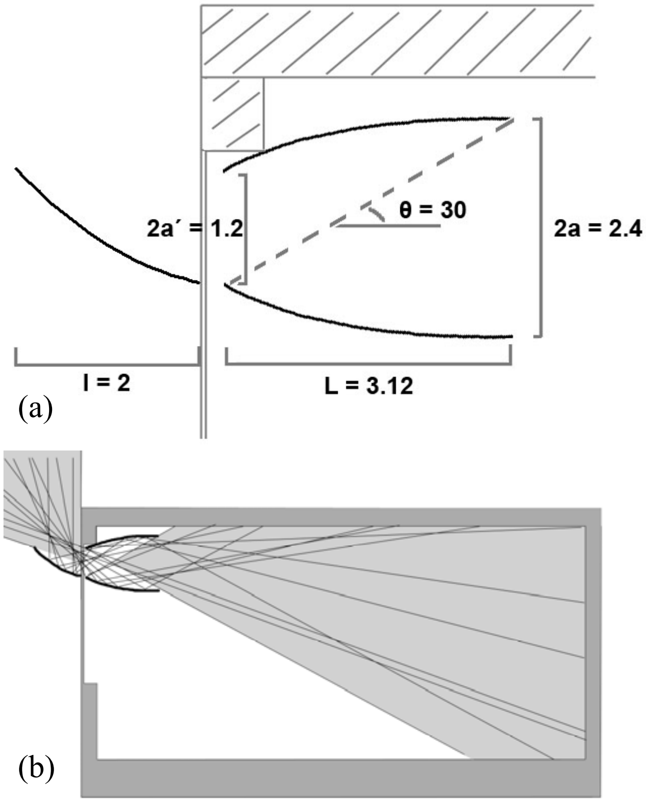

Fig. 1: (a) Diagram of the zenithal anidolic collector modeled in this paper (dimensions given in feet). (b) The ray-trace diagram (inspired by [20]), illustrates the anidolic system gathering light from every angle in its range (shown in light grey).

somewhat uncommon in the world of redirecting technologies. The performance of most redirecting technologies depends upon the angle of the direct sunlight. In general, they are designed to deflect sunlight and bounce it off the ceiling for added daylight. In these cases, diffuse daylight is not intense enough at any one incident angle to have a great effect. Anidolic systems, on the other hand, have the ability to accept softer light from a wide range of incident angles at once, to focus this light, and to redistribute it deep within the room. In fact, the exterior collector provides the anidolic system with such a large angular view of the sky that , despite reflection losses, the anidolic system manages to do what most redirecting systems cannot: provide a net daylight *increase* in the deeper parts of the room. Figure 2 shows a daylight factor comparison between a sample room before (dark) and after (white) the addition of an anidolic system. It is important to note, in this case, that the anidolic system was placed in façade without changing the size or shape of the original window. The aperture of the anidolic system is thus installed in the top foot or so of the window and blocks part of it, yet still manages to increase the deep light levels.

This affinity for diffuse light is valuable in the case of existing buildings, especially on facades that do not see a lot of direct sunlight and in overcast climates that also do not get a lot of sun. While direct sunlight has an inalterable and uneven relationship with each façade, diffuse light is available on any façade and in any type of weather. In fact, Anidolic systems are at their peak performance under bright, cloudy skies, because it is then that the most diffuse light is available. In a situation where direct sunlight is penetrating the system, however, there is a potential for glare. As such, any anidolic system that might see direct sun should also have a shading system.

The one difficulty an anidolic system may have with existing buildings is that of integration. A new building or a complete façade renovation offers the opportunity to integrate the mirror systems into the design of the building skin, but an existing building offers a limited space in which to put the system. The anidolic designs used in this study were created with that limited space in mind, and are thus not entirely optimized from the performance standpoint. Interesting solutions, though, especially for the exterior collector, are possible even in very limited space, as shown by an experiment done at EPFL with installation a system the constrained space of a preexisting office layout [7, 21]. However, issues of façade integration, other than the restrictions of available space, are beyond the scope of this paper.

Despite possible problems with integration, anidolic daylighting systems have great potential for enhancing daylighting in existing buildings, and should thus be considered as an option. The question then becomes: how does one tell whether or not an anidolic system is an appropriate solution for an existing space?

3. PROCEDURE

The amount and behavior of daylight in a space depends upon many physical variables. Quantity variables, such as the transmission value of the glass, affect the amount of light that enters the space. Distribution variables, such as the size and shape of the room, determine the spatial dissemination of that light over the work plane. Using the program RADIANCE, a simple room was created in which these variables could be easily adjusted. If enough of these variable combinations are simulated and analyzed, patterns should emerge which indicate the effect of combinations of these variables on the performance of an anidolic system. The purpose of these simulations, therefore, is to find these patterns, and to use them to create a set of guidelines and recommendations as per whether an anidolic system is an appropriate solution for an existing space.

3.1 Method

Preliminary simulations suggested that four variables had a significant influence on light distribution in a space: window head height, total window width (as a percentage of wall width), wall and ceiling reflectance, and room depth. For the first three of these variables, five possible values were chosen. Three simulations, calculating the daylight factor profile of the given space, were made for every possible combination (125 combinations of 3 variables with 5 values each) of these three distribution variables: one control simulation with no anidolic system, one with an anidolic system with a 50° angular spread, and one with a 60° anidolic system. This process was repeated for each of three room depths.

The number of simulations done may seem unnecessarily large at first, but the shear number of data points aids in the search for patterns by giving a more complete picture from which to work. (Initial simulation sets used only two or three possible values per variable, and the data set produced was inadequate to the task at hand.) At the same time, studying the effects of any more variables would make the number of simulations required unmanageable. There are still several variables with a significant influence on the daylight factor profile of a given space, but fortunately, many of these affect the amount of light admitted to the space more than they do its distribution. It should be possible, therefore, to generalize the effect of these quantity variables as a certain percentage of daylight factor lost or gained from the original curve. The variables chosen to be studied in this manner are glass transmittance, window frame area, window area, and urban masking.

3.2 Variable Values and Ranges

Each distribution and quantity variable considered is shown in Table 1 below, along with its range of values. The value ranges were determined by common sense and by a historical analysis of the American classroom. (Although this study has applicability to any existing space, it should be mentioned that classroom space was the assumed model, when one was required.)

TABLE 1: DISTRIBUTION AND QUANTITY VARIABLE VALUES

Distribution Variable	**Range of Values**
Window Head Height	{7, 8, 9, 10, 11}ft [2.1-3.4m]
Width of all Windows *(% of wall width)*	{60, 67, 75, 84, 100} %
Wall/Ceiling Reflectance	{30, 42, 55, 69, 83} %
Room Depth	{20, 30, 40}ft [6.1-12.2m]
Quantity Variable	**Range of Values**
Glass Transmittance	{no glass, 90, 73} %
Window Frame Area	{0, 19, 35, 50, 63} %
Window Area	various areas
Urban Masking *(° altitude from horizon)*	{0, 15, 30, 45, 60, 75} °

Certain things were assumed constant: the ceiling is 1 ft (0.3 m) higher than the window head height, the width of the room is 30 ft (9.1 m), the floor reflectance does not make a great contribution (5%), the window area is 126 ft^2 (11.7 m^2), and the wall thickness is 0.5 ft (0.15 m).

3.3 RADIANCE Simulation

For each variable combination, a representative room is created using the RADIANCE software, and daylight factor profiles are calculated. Figure 2 shows the daylight factor curves for a specific room with and without an anidolic system. One way to quantify the value of the anidolic system is to determine how much the "good daylighting" in the space has increased. Unfortunately, one then needs to quantify "good daylighting" – which is easier said than done. This study has adopted 2% daylight factor as the minimum benchmark for "good daylighting", because it the number used by both the Green Building Council's LEED Rating System [24]. For each variable combination, then, the expected improvement caused by the addition of an anidolic system is the ratio:

$$\frac{\text{room depth above 2\% daylight factor \textit{with} anidolic system}}{\text{room depth above 2\% daylight factor \textit{without} anidolic syst.}}$$

The expected improvement of the particular room represented by Figure 2 is the ratio of the white shaded area to the dark shaded area. The peak in the white daylight factor curve (around 15 to 18 feet, or 4.6 to 5.5 m, from the window) is characteristic of an anidolic system, and the peak's location in the room depends upon both the angular spread of the anidolic system and its height above the floor. This peak is the area of greatest benefit, but even the furthest portion of this room should maintain a level of improvement – including the portions of the room that do not quite make it to 2%. The particular room configuration of figure 2 has a depth of 30 ft (9.1 m), a window head height of 10 ft (3 m), a wall and ceiling reflectance of 69%, and a window width of 100%. The anidolic system used has a 60° angular spread. Similar simulations and comparisons were done for every other combination of distribution variables and for a 50° anidolic system.

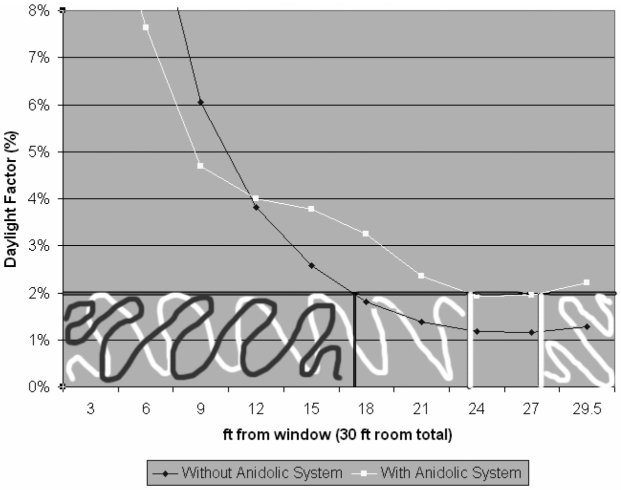

Fig. 2: Comparison of the daylight factor curve, as a function of distance from the window without an anidolic system (dark) and with an anidolic system (white).

3.3 Data Presentation

The expected improvement results are displayed on contour graphs, where each point represents one specific combination of distribution variables. "Room depth" and one other variable are held constant for each graph, while the contour shows how the expected improvement changes over the range of the other two variables. The other piece of information on each contour graph is the absolute percentage of the room over 2% daylight factor. The overlaid dotted lines represent room configurations with no anidolic system, and the overlaid solid lines represent the same rooms with an anidolic system.

At the moment, the only quantity variable integrated into these contour graphs is glass transmittance. Figure 3, for example, assumes a window with 90% transmittance, similar to single pane glass. Sets of graphs have also been done for 73% transmittance, which is approximately that of double pane, low-e glass.

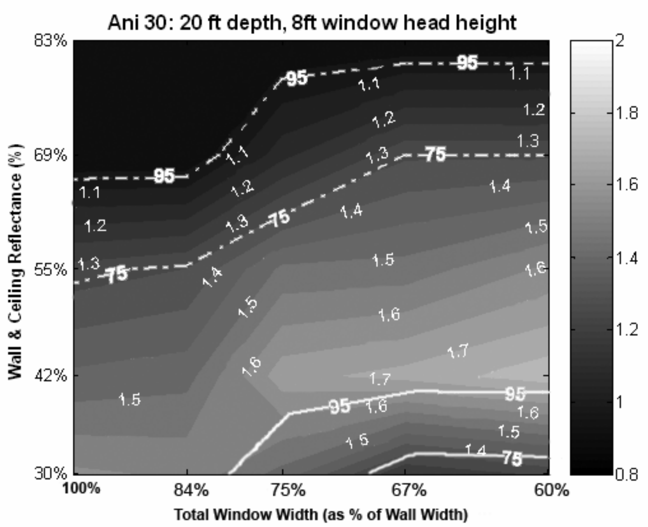

Fig. 3: This contour graph shows how the expected improvement (after the addition of an anidolic system) changes with window width and wall reflectance.

4. GENERAL RESULTS

4.1 Discussion of Room Depth

Several patterns have emerged from a preliminary analysis of the results (further analyses will be conducted to refine these conclusions). The room depth of 40 ft (12.2 m) was slightly too deep for these particular anidolic systems to handle the entire floor space; a 50% expected improvement was about the highest achieved, but there was a fairly even gain of 25-40% daylit area over most variable combinations, which is still a significant increase.

The 30 and 20 ft (9.1 and 6.1m) deep spaces were able to get improvements of 75-90% under the right circumstances, and 50-65% gains were not uncommon. Coupled with this, however, was an increased incidence of expected improvement of "1" (i.e. no improvement).

An anidolic system nearly always improves the daylight factor curve for a room, but there are two reasons why this improvement would not show up on the contour graphs. The first is that these graphs are a measure of "daylit" floor area, and it's possible that the original daylight factor curve was so bad that even the "improved" daylight factor curve could not make the 2% benchmark. The second reason is caused by what can be called "the point of diminishing returns." Applicable to the shallower spaces, this implies the original space is already so well daylit that any improvement would be small by default. This phenomenon becomes very noticeable when the space without anidolics is already over 75% daylit, and the upper part of the contour graph in Figure 3 is a good illustration. It is important to note that the anidolic system *is* improving the space in these situations, but the original space had already met our qualifications for "good" daylight factor. An anidolic system might raise all daylight factors above 5%, which could be seen as a more desirable result, but would still be "no improvement" on this contour graph.

4.2 Other Distribution Variables

Besides room depth, the most influential physical variable in a room without anidolics seems to be window head height, followed by wall and ceiling reflectance, followed by total window width. When an anidolic system is added, however, the influences of reflectance and window width become greater in relative terms. This is probably because much of the light exiting the anidolic system bounces off the ceiling or walls before reaching the work plane, and because the width of the window dictates the maximum width of the anidolic system.

The variable values that give the best improvement are similar to what would be expected of good daylighting design, with a few exceptions. In accordance with good daylighting design, higher wall reflectance and greater window width produce better results. The only exception in these cases is when the room has hit the "point of diminishing returns" – in that case, anidolics may be of more use in a room that was less well lit. On the other hand, window head height involves a bit of a tradeoff. While the peak benefit from an anidolic system is greater with *lower* window head height, it is also closer to the window. With a higher window head height, one sacrifices some daylight quantity for the ability to throw daylight deep into the room.

4.3 Quantity Variable Integration

The effects of quantity variables are difficult to integrate into the contour graphs in a straightforward way. Quantity variables have a significant impact in realistic models: for instance, most windows have some frame area, and most local environments mask a bit of the sky. These variables, however, could have either an adverse effect on the expected improvement, or a helpful effect, depending upon the situation. For instance, urban masking on the horizon is more selectively harmful to the daylight factor in the back of the room. However the back of the room is exactly what the anidolic system seeks to improve, so if the anidolics can reach the 2% benchmark, the improvement might be better than expected. On the other hand, lower glass transmittance or higher frame area could reduce the daylight factor curves enough such that they do *not* reach the 2% benchmark, thus diminishing the expected improvement. The data integration issue currently being faced is that of reconciling relative percent improvements with an absolute daylight factor benchmark. For example, glass transmittance and window frame area decrease the daylighting levels by an approximately uniform percentage in situations both with and without an anidolic system. However, if the daylight factor "hump" of a room with an anidolic system dips below this absolute 2% benchmark, it would have a disproportionately detrimental effect on the room's improvement levels, as they are currently being defined.

5. VALIDATION

The ultimate goal of this project is to apply some recommendations to realistic situations. Since these recommendations are to be determined by the data in the aforementioned contour graphs, it should be possible to match the simulated improvements in a more realistic model to those predicted by the graphs. Figure 4 is a RADIANCE rendering of a classroom in the Boston area. It is 35 ft (10.7m) wide, 24 ft (7.3m) deep, has 10.5 ft (3.2m) ceilings, and the windows, which take up about 85-90% of the façade wall, are single-pane glazed and face approximately north. The mean wall reflectance, taking into account the blackboards, etc, is about 60% (83% is white paint).

Fig. 4: RADIANCE rendering of a Boston classroom.

Since the depth of the room is significantly greater than 20 feet, it is safer to work with the 30 ft graph. In that way, at least, the graph will not show a false point of diminishing returns caused by the reference room being too short. Figure 5 shows the contour graph applicable to this situation: 30 ft room depth and 9 ft window head height are held constant, and there is a mark on the graph in the area of interest. According to the graph, the original room should be a bit more than 50% x 30 ft (a bit more than 15 ft) above the 2% benchmark, with an expected improvement of just under 1.4 after the addition of an anidolic system. These results will be affected somewhat by the presence of the window frame.

As Figure 5 shows, the original classroom had a daylight factor curve which stayed above 2% until about 17 ft (5.2m) from the window. The addition of a 60° anidolic system extended the daylit depth to 22.6 ft (6.9m), giving an improvement ratio of 1.33. If we perform the daylight factor calculation again after removing all the window frame area that was obstructing the anidolic system, the whole room is pushed over the 2% benchmark, for an improvement of 1.41. These are relatively close to the improvement numbers predicted by the contour graph.

The next step is to perform similar analyses on other sample rooms with different expected improvements, and to perform a comparative daylight autonomy calculation on this and other sample rooms. Daylight autonomy takes weather, façade orientation, and hours of operation into account by calculating the daylight levels in small time steps over the whole year. The results given are the percentage of time that a certain point in the room will be above a preset minimum illuminance. In other words, it is a measure of

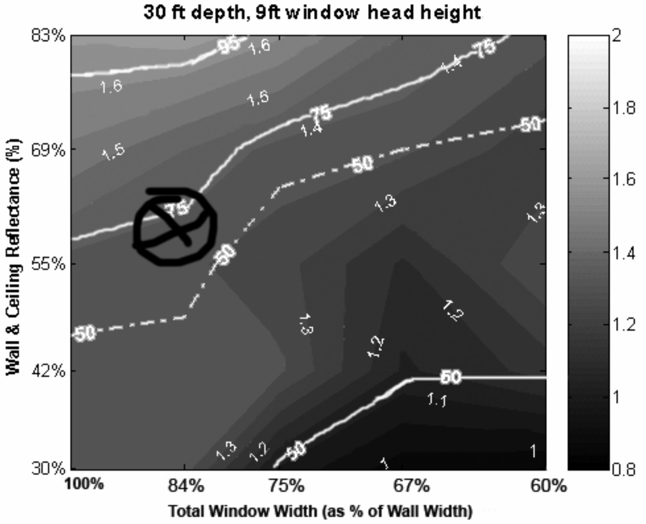

Fig. 5: The contour graph applicable to the sample classroom (above). The area of interest has been marked

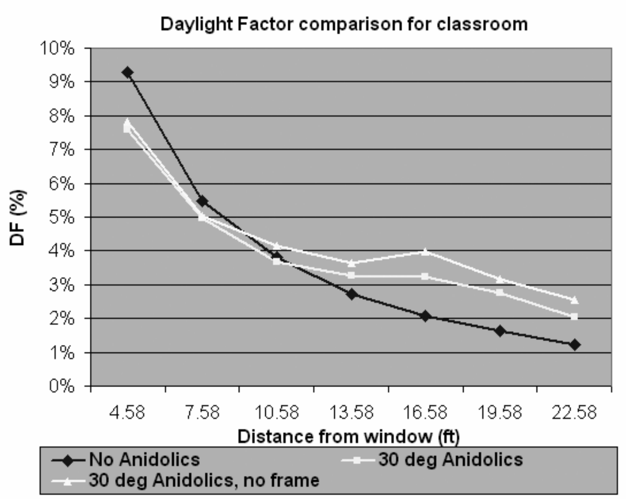

Fig. 6: The resulting daylight factor curves, before and after the addition of an anidolic system.

how much of the time each point in the room will not be dependent upon electric light. Hopefully, a daylight autonomy analysis will show similar levels of improvement to the above daylight factor analysis, so that some correlation between the two can be drawn.

6. CONCLUSION

One purpose of this study was to determine the expected daylighting improvement to a specific existing space after the addition of a zenithal anidolic collector, and the purpose of the ongoing work is to find a way to display this information intuitively. To accomplish the former, the physical variables with the greatest influence on daylighting were listed and divided into two groups. Daylight factor profiles were calculated for every possible combination of variables pertaining to the spatial distribution of light, first without, then with an anidolic system. As in the LEED's ratings, 2% daylight factor was chosen as a minimum benchmark for "daylit" space. The "expected improvement" value for each pair of daylight factor profiles represents the increase in daylit floor area after the addition of an anidolic system. These expected improvement values, which ranged from no improvement to 80-90% improvement, were then displayed as contour graphs, variable over the ranges of two distribution variables at a time, and the preliminary analysis found that in most, but not all, cases, good daylighting practice indicated good anidolic improvement. The exceptions were window head height and shallow rooms that were already "too good." The quantitative variables were analyzed separately, and the authors are still seeking an intuitive way to integrate them into the other results. In the end, these contour graphs should inform a simple set of recommended room configurations for which an anidolic system is ideally suited.

Finally, the RADIANCE model of a real classroom was put to the test. According to the contour graphs, the improvement after adding a 60° anidolic system should be nearly 40%. RADIANCE simulations with an anidolic system installed in two different ways gave improvements of 33% and 41%. In the near future, the authors would like to add more test cases and some daylight autonomy calculations to this preliminary validation.

7. APPENDIX A: ANIDOLIC EQUATIONS

Since the interior set of parabolic mirrors are usually limited by spatial concerns, it is important to note that their dimensions are intimately connected through three formulas, originally given by Welford and Winston [22]:

$$f = a' \times (1 + \sin\theta)$$

$$a = a' / \sin\theta$$

$$L = (a' + a) \cot\theta$$

where 2a is the width of the exit aperture, 2a′ is the width of the entrance aperture, f is the focal length of each parabola, L is the horizontal length of the two parabola configuration, and θ is the angle formed by the horizontal and the line connecting one entry edge with the opposite exit edge. The length and widths of the system obviously have an impact on aesthetic and spatial concerns, but the angular spread, θ, has an effect on the distribution of light. The absolute equation of the CPC is also given in Welford and Winston:

$$\begin{aligned} 0 = (z\cos\theta + y\sin\theta)^2 &+ 2a'(1+\sin\theta)^2 z \\ &- 2a'\cos\theta\,(2+\sin\theta)y \\ &- a'^2(1+\sin\theta)(3+\sin\theta) \end{aligned}$$

where a′ and θ are the same definition as above, y is the horizontal axis of the system profile, and z is the vertical axis of the system profile [22].

For the anidolic system used in the examples in this paper, f = 0.9 ft (0.27m), a = 1.2 ft (0.37m), a′ = 0.6 (0.18m), L = 3.12 ft (0.95m), and θ = 30° (see figure 1). The exterior collector had a vertical parabolic axis, a focal length of 1ft (0.30m), a vertex located in the horizontal plane of the lower edge of the entrance aperture and in the vertical plain of the interior wall, and an external horizontal projection of 2 ft (0.61m), leaving a gap of 0.25 ft (0.08m) between the end of the interior parabolic mirrors and the edge of the exterior collector.

8. APPENDIX B: RADIANCE PARAMETERS

The parameters which informed the rtrace RADIANCE calculation are as follows:

-ab	10	
-aa	0.1	
-as	64	
-ar	128	(scene size: 67.5)
-ad	1024	

Compared with the maximum values of these parameters which the author's computer could handle, there was less than 5% average deviation with no anidolic system and about 10% average deviation with an anidolic system. All scene materials were approximated as lambertian surfaces, except for the glass (which was defined using different transmittances of the "glass" material type in RADIANCE and made from an array of 1 ft^2, or $0.09m^2$, panes) and the mirror material (which was approximated using the "mirror" material type in RADIANCE with 90% reflectance and 100% specularity). The anidolic system was modeled as an approximate curve, made of 50 flat segments for each mirror. The error associated with this curve approximation is included in the 10% given above for the anidolic system (as compared to the performance of a curve with 1000 segments). The window used was merely a rectangular hole in a 0.5 ft (0.15m) thick wall with no frame, and so there is no complex detailing associated with it.

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