

**Improving the Daylighting Conditions of Existing Buildings:  
the benefits and limitations of integrating anidolic daylighting systems using the  
American classroom as a model**

by

Siân A. Kleindienst

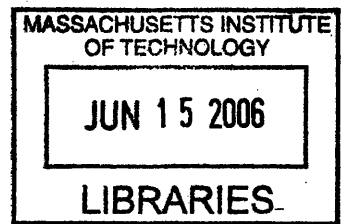
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**ABSTRACT**

Awareness of the benefits of good daylighting has risen in recent years, and the designs of many new buildings take daylighting into consideration. However, the majority of our built environment is older than this recent trend, and was not designed with daylighting as a top priority. A need exists, therefore, to find an efficient means of improving the daylighting of existing buildings. Furthermore, along with the development of such a daylighting technique, a set of guidelines should be developed to determine this technique's applicability to a given existing space, thus facilitating its acceptance into the toolbox of current building practice.

This paper focuses particularly on the integration and adaptation of anidolic daylighting systems into existing buildings. By using mostly RADIANCE simulations, this thesis seeks to discover a range of conditions for optimal integration of an anidolic daylighting system. These conditions are then simplified and displayed in the form of a set of recommendations and guidelines for the benefit of architectural practitioners.

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## TABLE OF CONTENTS

1	INTRODUCTION AND MOTIVATION.....	7
2	STATE OF THE ART	
	2.1 Daylighting Strategies and Systems.....	13
	2.2 Anidolic Systems.....	17
	2.3 Daylighting Analysis.....	21
3	DAYLIGHTING AND THE HISTORICAL AMERICAN CLASSROOM	
	3.1 The Century in Brief.....	27
	3.2 Recent Daylighting Case Studies.....	30
4	PROCEDURE	
	4.1 Project Goals.....	31
	4.2 Tools.....	31
	4.3 Variables.....	38
	4.4 Anidolic System Design.....	41
	4.5 RADIANCE simulations.....	44
	4.6 RADIANCE Simulation Error.....	47
	4.7 Data Analysis.....	49
5	RESULTS	
	5.1 Distribution Variables: detailed contour graphs.....	51
	5.2 Quantity Variables.....	55
	5.3 Recommendations.....	66
6	VALIDATION	
	6.1 Applying the tables	
	6.1.1 Boston Classroom Example.....	71
	6.1.2 Bronx Classroom Example.....	73
	6.1.3 MIT Classroom Example.....	74
	6.2 Daylight Autonomy with DAYSIM.....	76
7	DISCUSSION.....	79
8	CONCLUSION.....	83
9	APPENDIX A.....	85
10	APPENDIX B.....	117
11	APPENDIX C.....	127
12	BIBLIOGRAPHY.....	129

13 ACKNOWLEDGEMENTS.....139

## 1 INTRODUCTION AND MOTIVATION

For countless millennia, architectural forms have been beholden to the need to maximizing daylight, and many buildings have been built around the principals of exterior light interacting with interior space. This has inspired some architects, most notably those of sacred buildings, but it frustrated many others: in the *Architectural Record* in 1908, one author cries in exasperation at “the need for light, for more light, for all the light” [AR 1908]. Over two decades later, the *New York Times* ran an article excitedly describing the buildings of the future as entirely controlled, artificial environments: the headline ran “Now the Windowless Building With its Own Climate,” and the authors were convinced man could create a more pleasant, more healthful, less costly environment than that created by nature [TAL 1930]. More recent research has shown every one of these conjectures to be dubious, but unfortunately, this fantasy became a reality during the 1960’s thanks to the windowless schools of that era.

Fire-based artificial lights, such as candles and gas lamps, have been available for hundreds of years, of course, but their disadvantages (they are more dangerous and dirty) and lower illuminances made it such that they were not a real competitor for daylight. The invention and dissemination of “cleaner” electric lights, however, reversed the tables. In 1936, one author for the *Architectural Record* remarked that “science has advanced to the point where artificial lighting can be a competitor of daylight” [ROD 1936], and just over four years later, in the same magazine, the tune had changed such that “natural light [was] a competitor of artificial light, asked to show cause why it should not be replaced by its younger brother” [BLU 1940]. By the 1950’s and 60’s, daylighting had become a luxury. It enjoyed a slight revival during the energy crisis of the 70’s, but it wasn’t until more recent years that people began to recognize the great benefits of daylight and to think of it seriously again as a real and desirable source for light in a building.

One of the most obvious benefits of daylighting is the substantial decrease in the cost of electric lights and in the energy required to run them. This is appealing both from an energy-efficiency view and an economic view. Certainly this economic argument was the reason for the renewed consideration of daylighting during the several energy crises, and it always carries weight from an energy point of view. According to a Department of Energy (DOE) residential end-use survey from 2001, lighting is 8.8% of electricity use in US residential buildings (which are often substantially daylit) [DOE 2001]. In terms of energy, this amounts to about 940 kWh per household or about 90 billion kWh in total annually. Another way to put this is that residential lighting produces about 120 billion tons of CO<sub>2</sub> annually. This is assuming the DOE’s reported value of approximately 1.35 lbs of CO<sub>2</sub> per kWh generated [DOE 2000].

This may seem like a lot, but it pales in comparison to the commercial sector’s energy use for lighting. A DOE commercial end-use survey from 1999 shows lighting to be 23.1% of total electricity use, or 716 trillion Btu annually (approx. 210 billion kWh). In other words, the commercial sector produces nearly 280 billion tons of CO<sub>2</sub> per year from lighting energy use alone. (These numbers do not take into account the helpful or harmful heating loads from electric lights in such buildings.) Greater emissions in the

commercial sector, despite the greater number of residential buildings, are partially because they consume more energy than residential buildings, and partially because they rely more on electric lights than residential buildings. In any case, it remains true that if we could substantially reduce the energy used for lighting in this country, while still controlling solar gains, a great deal of energy could be saved each year. For example, the façade of the Solar Energy Laboratory (LESO) of the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland was renovated in 1998, and great thought was given to daylighting. Their average electricity savings have been calculated at 8 MJ/m<sup>2</sup> per year (2.22 kWh/m<sup>2</sup> per year) [ALT 2002], and it is rare for any electric lights to be on in that building during the day. The Belgians Bodart and De Herde claim in their article, *Global energy savings in offices buildings by the use of daylighting*, that 50 to 80% energy savings can be made in office buildings, just by adding photosensitive dimmers to the electric lights [BOD 2002]. In the United States, the LEED Platinum rated Genzyme Center of Cambridge, MA, was designed such that 75% of the workspaces do not require electric light under normal daytime conditions. A City of Cambridge report states that they use 45% less electricity for lighting than a similar sized “conventional” building [MUR 2004].

The economic argument, though pertinent in times of energy crisis, is less convincing when energy is cheap. However, it is always possible to save significant amounts of money with good daylighting practice. If the possible energy savings quoted above are not enough, R. P. Leslie of the Rensselaer Lighting Research Center points out that daylight availability corresponds well, not only to the operating hours of most commercial buildings but also to the peak demand hours in which electric companies charge higher rates [LES 2003]. He continues with the thought that the economic value of increased worker productivity and happiness, though much harder to quantify, probably outweighs even the economic benefits of daylighting.

Increased worker productivity is only one example of how daylight can theoretically benefit both physical and psychological health in human beings. Humans have evolved over millions of years to live in an environment lit by our sun. For instance, our eyes are highly specialized for the wavelengths and intensities of the solar and sky spectra. Research at the Rensselaer Lighting Research Center has also suggested that our biological clocks are regulated by light levels and wavelengths typical of daylight (through the suppression of melatonin), and that disruption of this cycle may push circadian rhythms out of sync with the diurnal cycle, causing fatigue and symptoms akin to jet-lag [REA 2002, LES 2003]. Recent research into the depression type known as Seasonal Affective Disorder (SAD), a seasonal depression attributed to the lack of winter daylight in northern climates, has revealed that not only does the disorder have a likely biological cause relating to the availability of daylight, but that it can be treated by daylight spectrum light therapy. SAD, like most forms of depression, is probably caused by low turnover of serotonin in the brain. (Most anti-depressants are Selective Serotonin Reuptake Inhibitors, SSRIs, meant to increase levels of serotonin.) Lambert *et al.* showed that not only was serotonin turnover lowest in winter, but that serotonin production was directly related to the duration of exposure to bright sunlight [LAM 2002]. Research also suggests that as little as 3 weeks of light therapy treatment is

enough to cause SAD patients to perform as well in psychological assessment scales as those without SAD [LEV 2002].

A similar crossroads between the psychological and biological effects of daylight was discovered in a study of Swedish elementary school students. Four classrooms with four different levels of daylighting were observed, and the students were monitored for behavior, health, and the stress hormone cortisol. The study suggested that lack of daylight interrupted hormone patterns, leading to less concentration and cooperation and affecting growth and absenteeism [KUL 1992]. Similarly, a much quoted study by the Heschong Mahone Group tracked the scores of 21,000 students on the Pacific coast and the daylight quantity and quality in their classrooms. After controlling for wealth, school district, and other influences, they found (to 99% statistical certainty) that students with the most quality daylighting progressed 20% faster in math and 26% faster in reading, and furthermore, that students in better daylit classrooms had 7 to 18% higher absolute standardized test scores [HES 1999]. Similarly, in the working world, R. P. Leslie suggests that good daylighting improves the mood and productivity of office workers, and that windows, especially those with a view, are associated with status, and make an employee feel valued [LES 2003].

Awareness of these and other benefits 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 DOE tabulation published in 1999 [DOE 1999a] showed that 85% of US commercial buildings were more than ten years old. Because of this longevity, a need exists to find an efficient means of improving the daylighting of existing buildings.

Fortunately, where need exists, there also exists opportunity. A great many large concrete buildings built in the 1950's, 60's, and 70's are due for façade renovation. If a way can be found to materially improve daylighting by changing the façade alone – not the room configuration, the building structure, or orientation – then it may be possible to improve a large portion of the existing infrastructure. Office buildings, school classrooms and laboratories, warehouses, hospitals, and libraries are all candidates for daylighting improvement thanks to their frequent dependence on multistory, deep, side-lit spaces.

For the purpose of this study, school classrooms were chosen as a model, partially because of the health and learning benefits listed above, and partially because of certain characteristics of school architecture. First, school buildings tend to be better characterized by chronology than location. Because of the importance universally attached to the education of children, most school buildings try to be up to date with the architectural and teaching philosophy of the times. Therefore, with a few notable exceptions, school buildings constructed in the same era tend to be very similar across the country, which is useful when one is trying to locate a building with particular characteristics. Secondly, there are definite periods of time in which school daylighting suffered. Furthermore, unlike some businesses, schools are often under strict budgets. If

a way can be found to increase daylighting while saving much of the existing building structure, daylighting renovation may become a realistic possibility for institutions constrained by money. A more complete history of daylighting in American schools is discussed in Section 3.1, but suffice it to say that school classrooms are ideal candidates for façade-based daylighting renovation.

Anidolic daylighting systems were selected as a promising façade-based daylight redirecting system for existing spaces. They are a configuration of parabolic mirrors whose design draws from the principals of non-imaging optics, and in fact, the name “anidolic” is an ancient Greek synonym for “non-imaging” [COM 1993a]. 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. There are several different types of anidolic devices (see Section 2.2), but all are comprised of the same two basic elements: the exterior collector and the interior distributor. The exterior collector, generally a parabolic mirror with a certain angular view, gathers all angles of light from that sky portion and focuses it through an opening in the plane of the façade. The interior mirrors redistribute that light towards the ceiling or back of the room. Section 4.4 explains how these mirrors are arranged in such a way 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 somewhat uncommon in the world of redirecting technologies. The performance of most redirecting devices depends upon the angle of the direct sunlight. In general, they are designed to deflect sunlight and bounce it off the ceiling for added daylighting. 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.

This affinity for diffuse light is valuable in the case of existing buildings, especially on façades that do not see a lot of direct sunlight and in overcast climates. While direct sunlight has an inalterable and uneven relationship with each façade, diffuse light (which is preferable for daylighting anyway) 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.

The daylighting benefits of anidolic devices have been studied at length (see Section 2.2), and it is clear that they provide a good potential solution for daylighting in deeper spaces. What is less obvious is which kinds of spaces can make the most of these benefits. Although buildings of the same type often have similarities, the reality is that each building provides a unique daylighting problem, and practitioners must choose from amongst a set of possible solutions. The question then becomes: how does one tell whether or not an anidolic system is an appropriate solution for a given space? This

thesis will attempt to answer that question by providing guidelines based on the physical characteristics of that space.



## 2 STATE OF THE ART

### 2.1 Daylighting Strategies and Systems

Because mankind existed for so many years without electric lighting, the principals of building design which are conducive to good daylighting are well known and time tested. Most experts would agree that a higher window head height will give better daylight penetration, that the walls and ceiling should have a high reflectance value, and that shallow rooms are easier to daylight than deep rooms. The effects of clerestory windows, skylights, sawtooth roofs, and other building shapes have been well documented. These experts would also agree that building orientation is important – that it is easier to control solar gains and glare on the south façade than on the east or west façades – and that a house in the desert environment of Phoenix would want to avoid or heavily shade windows on the south façade while a house in the cold climate of St. Paul might want south-facing windows for solar gains in the winter. Several authorities have published guides espousing these and other commonly accepted principals: the Illuminating Engineering Society of North America (IESNA) Handbook always has a chapter on daylighting [IES 2000, 1993, '84, '81, '72, '66, '59, '52, '47], the International Energy Agency (IEA) put out a book called *Daylight in Buildings* [IEA 2000], and the New Buildings Institute, Inc, published the *Advanced Lighting Guidelines* in 2003 which includes several sections on daylighting [ALG 2003], so it seems superfluous to rehash all of these ideas here.

The basic principals of daylighting may be as old as the hills, but there are many far newer technologies that have grown out of its more recent revivals. Many of these newer technologies could easily be termed “light redirecting devices.” As opposed to daylighting strategies involving the building shape, orientation, or material properties, this category would include any device using reflectors, prisms, or other means to change the direction of some or all incident light. They are usually installed in or near building apertures, and generally require some modification of building fenestration.

A very important observation about redirecting technologies was made by M. E. Aizlewood of the British Building Research Establishment (BRE). After compiling 1-1 scale data on several systems, he concluded, “Any system for light redirection must cause transmission losses,” [AIZ 1993]. Indeed, treated or shaped glass always has lower transmission than clear glass, mirrors are rarely more than 90% reflective, and there is usually some sort of shading component associated with the physical structure of the system. Why, then, if the aim is to increase useful daylight, would anyone use a redirecting system? The answer is in the word “useful.” Redirecting daylighting systems aim to do at least one of two things: first, they seek to block or bend direct light, which can cause glare and solar gains, while allowing as much diffuse light as possible. In this way, redirecting devices seek to make it unnecessary to pull the blinds and turn on the lights. Secondly, redirecting devices seek to even out the light levels in a space. Any unilaterally daylit space will have a large amount of natural light next to the window, but the levels will drop off exponentially as one moves further into the space. A redirecting device attempts to throw some of the light that would have ended up near the window

towards the back of the room. Though it may seem counter-intuitive, an evenly lit space often seems brighter to our eyes than an uneven one, even if the absolute light levels are lower in the first case [AIZ 1993].

There are many different types of light redirecting devices, some old ideas, and some which are relatively newer. They can generally be divided into two categories: mirrored systems which reflect light, or glazing systems which bend it. One of the oldest glazing systems is glass block, which was meant to both bend and diffuse direct light by the refractive index and sheer thickness of the glass itself. It was used extensively in American schools during the middle of the century [LIT 1990]. Furthering this idea, prismatic panels are sawtoothed sheets of acrylic which act as many little prisms. They can be used to bend both daylight and sunlight, or to exclude sunlight and allow daylight. They are meant largely to guard against the glare of direct light, and as such, work best under direct sun conditions. The effect of the prismatic panel on diffuse light is slightly to even out the daylight levels in a room, but mostly its effect is a blanket reduction of diffuse transmission [LIT 1990]. Under direct sun conditions, however, they even out light levels (despite an overall reduction in transmission) in summer, they significantly boost deep lighting levels in spring and fall, and they boost near-window light levels while reducing deep room levels in winter [AIZ 1993]. Prismatic film panels, which are a similar idea, except that the prismatic elements are in the form of a thin film coating a sheet of glass (and are thus much smaller in dimension), behave in the same fashion, except that they cause less reduction of diffuse light and are able to raise light levels in summer as well [AIZ 1993].

Laser cut panels are acrylic sheets with very thin horizontal cuts. Technically, these cut surfaces act as tiny mirrors and reflect, rather than bend, light. They neither cause much reduction nor have much redistribution ability under overcast skies, and under direct sun, they are most effective at increasing deep sun levels if optimized for time of day and year. They have pretty specific blocked and transmitted incident light angles. For example, for a 0.7 depth to width ratio, a vertical panel will generally block most light above  $45^\circ$  and transmit most below  $20^\circ$  [IEA 2000]. Sun-directing glass, which is generally a double-glazed window enclosing stacked acrylic elements that have a jelly-bean shaped profile, is a similar idea except that the tiny “mirrored” surfaces are curved and much closer together. Not meant to maintain any sort of view, the panel redirects all incident light, especially in the  $15^\circ$  to  $65^\circ$  angular range. Again, they produce a net transmission loss under diffuse skies, and are really only useful under direct sunlight [IEA 2000]. Holographic glass, which Littlefair listed in his 1990 survey as a new, barely researched idea (and which *Daylight in Buildings* describes as “hardly tested” a decade later) [LIT 1990, IEA 2000], is a “polymeric film with holographic diffraction gratings,” [IEA 2000]. In other words, three-dimensional laser-light patterns are inscribed in a thick photographic emulsion using volume holography, and the result is a panel which deflects all light within a certain range to the same exit angle (all exit angles for previously mentioned systems depend upon the angle of incident light to some degree) [LIT 1990]. As stated above, they have been little tested, and sometimes there can be problems with color separation, but there are now examples of their use in contemporary projects [IEA 2000].

Using mirrors to reflect light to where it is needed is a very old idea – at least as old as the ancient Egyptians who, it is theorized, used systems of mirrors to light the interior of the pyramids during construction and decoration [PET 1985]. Similarly, narrow shafts can also be used in modern buildings to provide daylight to lower-level, underground, or deeply internal spaces, and in modern times, they are known as light pipes or light ducts. Most are silvered on the interior or contain fiber optics (though the latter is expensive), but because they are narrow, all require some sort of light collection and focus mechanism – often heliostat mirrors (see below) and/or lenses [LIT 1990]. Some recent work has been done quantifying the light distribution functions and possible applications for certain light pipes [ROS 2005], and computer simulations of a new proposed horizontal light pipe show the possibility for significant deep lighting improvements and a very even daylight quantity profile (although data was only given for two days of the year) [CAN 2004].

Perhaps the most ubiquitous reflecting system, however, is the light shelf. An old idea, it is based on the thought that sunlight could be reflected off the top of a horizontal solar shading projection. Light shelves can be internal, external, or both, and have been extensively used and tested – in particular by Aizlewood of the BRE [AIZ 1993]. It has been found that they provide good shading near the front of the room, but the amount and depth of light level improvement depends very strongly on incident sun angle (the shallower the sun angle, the deeper the effect), and that even these boosts rarely return the back of the room to pre-light shelf levels [AIZ 1993]. As in all previously mentioned cases, light shelves work best, both as shades and daylight boosters, under direct sunlight, and have no effect under diffuse light, other than to reduce general transmission.

Reflective louvers are functionally somewhere between light shelves and reflective blinds. In general, they are shallow, repeated light shelves, spaced vertically, although some louvers can tend in the direction of screens or meshes. They are based on the idea that for low latitudes, a light shelf would have to have a very long projection to cover the optimal window area. Louvers often block more view, however, and do not even work as well as light shelves in increasing deep daylighting [LIT 1990, AIZ 1993]. Reflecting Venetian blinds, on the other hand, are primarily meant for solar shading, but are silvered to glean any possible daylighting benefit. Unlike most louver systems, they are adjustable and can be set to optimal reflection angles.

One twist on some of these systems is that they have been made into “smart” technologies. “Smart” systems are dynamic in the sense that they adapt themselves to the conditions of the moment (through motion or change in material property), and they often use electricity to do so. For example, heliostat mirrors track the sun throughout the day and reflect direct light into light pipes, louvers, or atrium areas [LIT 1990], and on the vertical façade, self adjusting, reflective Venetian blinds rotate to the optimum angle or close to block glaring light [IEA 2000]. (This self adjustment principal also applies to rotating louvers, adjustable angularly selective panels, and Variable Area Light Redirecting Assemblies, or VALRA [IEA 2000].) On the interior, photosensor circuits can be wired to allow electric lighting to dim, and different zones can be set up on different dimming circuits, to allow the deep part of the room to dim less than the zone

near the window, for instance. Several types of “smart” glazing have also been developed which go from transparent to translucent with the application of heat (thermochromic), light (photochromic), or electricity (electrochromic). These glazings are useful if you want to block solar transmission with excessive heat (solar gains during the summer), excessive light (glare issues), or at the touch of a light switch. The Genzyme Center building, previously mentioned, incorporates heliostat mirrors (redirecting sunlight into their louvered atrium), self-adjusting blinds, and photosensor dimmers, and these features helped it to win a LEED Platinum rating [MUR 2004]. The LESO building also uses photosensor dimmers which are wired separately for different zones in each room [ALT 2002].

One major advantage of automatic reflectors is that they always provide the greatest possible benefit, even considering the variable nature of daylight and sunlight. The great advantage of automatic blinds and lights is that they override certain user habits which are detrimental to daylighting. Several studies have found that people tend to close blinds and switch on lights the moment daylight becomes too bright or too dim, but because of inertia, group social dynamics, or some other reason, they will not often adjust them again in favor of using natural light [REA 1984, BOY 1980]. In discussing his observational study of blinds position in a Canadian office building, Rea noted that “occupants apparently made little or no attempt to change the blinds throughout the day, even on the east and west faces where penetrating solar radiation would change dramatically on clear days,” [REA 1984]. Similarly, Boyce noted in his study on light switching habits, that most switching (either on or off) was due to the initiative of a few individuals, but that others might have felt stymied by social constraints [BOY 1980]. Behavioral patterns on MIT campus support both of these conclusions. For instance, the MIT building 26 has long east and west façades. About 50% of the large windows on these façades have the blinds pulled nearly all the way down, and it is very unusual for them to be pulled back up again – and of course, with the blinds pulled all the way down, the electric lights must be switched on all the time. (This observation was made by Edward Rice, a student at MIT, in the course of his thesis work.) The other 50% of the windows belong to people who are more active in adjusting their blinds. Automatic blinds and dimmable lights make adjustments such that the daylight may be used to the fullest extent without the occupant having to think about changing the environment themselves.

Although this correction of passive user habits is certainly an advantage to daylighting and ultimate energy use, user acceptance of such devices can be low if users feel they do not have ultimate control over their environment. There are also maintenance issues to consider, for with the greater complexity of moving parts comes the greater likelihood of malfunction. A tour of the Genzyme Center in 2004, which included an interview with building maintenance staff, led the author to believe that both the automatic blinds and heliostat mirrors were difficult to keep in working order.

## 2.2 Anidolic Systems

Anidolic Daylighting Systems of all forms are based upon the idea of several of the reflecting systems mentioned above. The zenithal anidolic collector is similar to the idea of a light shelf, the anidolic ceiling to a horizontal light pipe, the anidolic zenithal opening to a directional skylight or vertical light pipe, and the anidolic solar blinds are like mesh or grid louvers [SCA 2002, COU 1996]. The very important improvement that is made by the anidolic system is one of geometry: anidolic systems use the concepts of non-imaging optics to create a reflective shape so efficient that it is effective in redirection of *diffuse* rather than direct light. With the added concepts of half anidolic systems, truncated systems, or any configuration of custom-designed systems for integration into a particular façade, the specific possibilities for anidolic shapes are vast. This thesis, however, focuses on the original anidolic system design, the zenithal anidolic collector, for the reason that the author deemed this design the most practical for integration into existing structures.

The zenithal anidolic collector combines the ideas of the traditional light shelf and the concepts of non-imaging optics, and the result is a directional, highly effective light shelf for redirecting diffuse light. As discussed, a traditional light shelf is often more of a shading device than a redirecting device. Because the reflective surface is flat, the angle of incident light plays a large role in how deeply it penetrates the room. For instance, light rays from the sky's zenith (steep incident angle) would hit the ceiling close to the window, whereas light rays from nearer the horizon (shallow incident angle) would bounce further into the room. Unfortunately for this scheme, the brighter light from the zenith is thus less useful than the dimmer, and sometimes masked, horizon light. Furthermore, since a traditional light shelf has no focusing mechanism, diffuse light is too weak to make a significant contribution to the natural light levels in a space. Only sunlight, despite its constantly changing incident angle, is intense enough to make a difference.

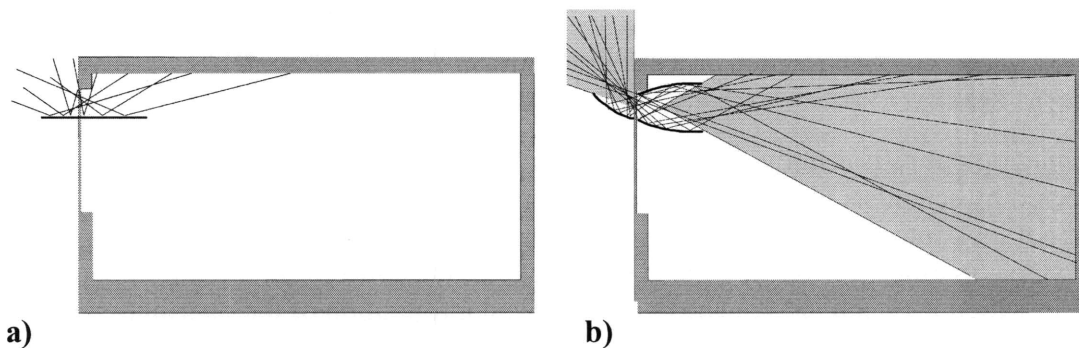


FIGURE 2.1: a) The behavior of a flat light-shelf at various incident ray angles. b) The behavior of an anidolic zenithal collector at a wide range of incident ray angles.

An anidolic light shelf, on the other hand, uses parabolic geometry to collect and concentrate diffuse light. The exterior portion of an anidolic system, that which directly

sees the sky, is nothing more than a parabolic mirror whose focal point is no higher than the opening in the façade. In fact, this exterior collector by itself, termed a “light scoop” by Littlefair, is the only previous light redirecting device which has any effect on diffuse light [LIT 1990]. Each collector has an angular “view” of the sky (shown in grey below), which is restricted only by the building façade and the lip of the collector. If the parabolic axis (line  $AB$  below) is aligned with the more vertical edge of the “view” angle, all light striking the collector and falling between the extremes of this view range should cross the plane of the façade between the focal point (point  $A$ ) and the vertex (point  $B$ ) of the exterior collector (curve  $1$ ). This light, and some which bypasses the exterior collector, enters a space between two parabolic mirrors (curves  $2$  and  $3$ ). These two mirrors, which are arranged according to the principals of non-imaging optics, distribute this light towards the top and back of the room in question. The parabolic axis of curve  $2$  in the schematic below passes through point  $B$  (which is also the focal point of curve  $2$ ) and is parallel to line segment  $AD$ . Curve  $3$  is a mirror image of curve  $2$ .

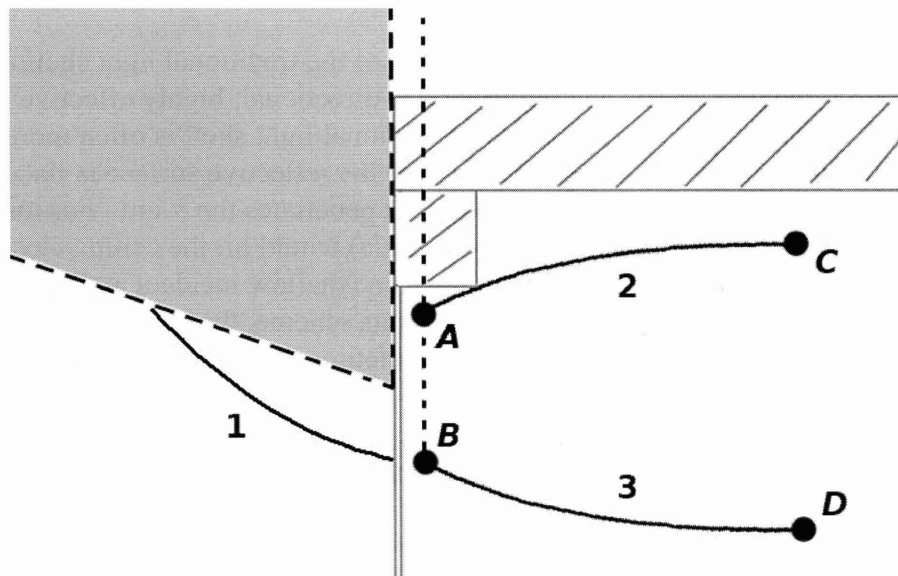


FIGURE 2.2: Schematic of zenithal anidolic collector.

Nonimaging optics is a study and a strategy for high collection concentrators, which was pioneered by scientists like Welford and Winston. “Nonimaging” merely means that one could not look into the mirror element and see an accurate picture of what was on the other side – in other words, the light rays do not exit the collector in the same spatial order in which they entered it. The two-parabola configuration of the distribution portion of the zenithal anidolic collector is a compound parabolic concentrator (CPC), a geometry that was originally developed for concentrating light onto a solar cell, or other such application. Used in the other direction, it redistributes the concentrated light from the collector with the minimum number of bounces possible. This capacity is a product of the Edge-Ray Principal of nonimaging optics, which states that the most extreme ray entering the distributor should be the most extreme ray exiting the distributor. In this way, no ray is lost, and the transmission is geometrically efficient. [WEL 1989]

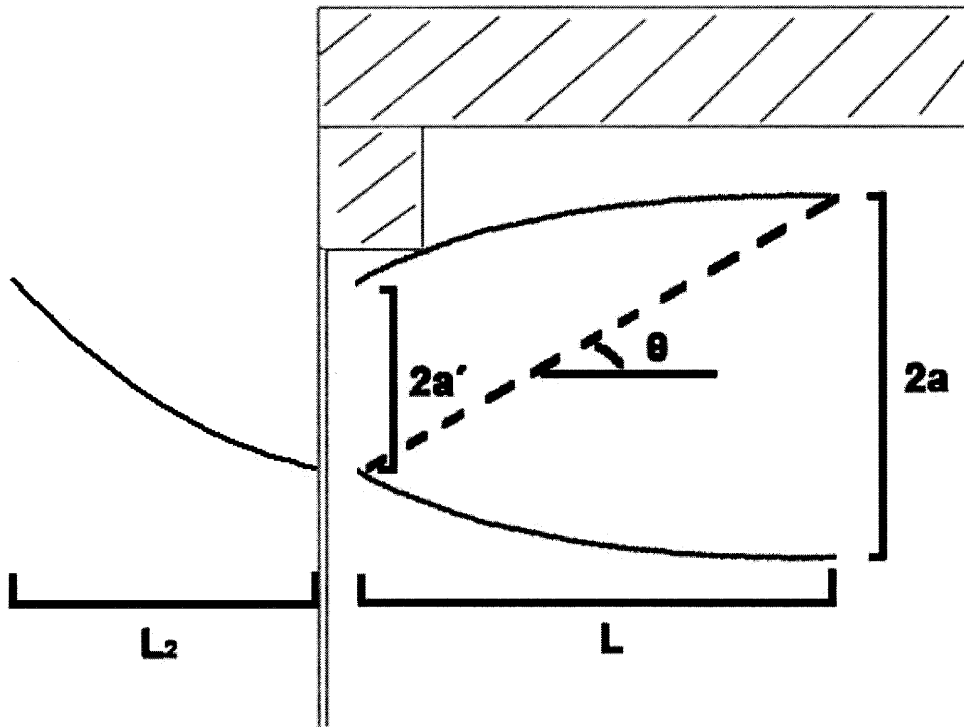


FIGURE 2.3: Schematic of a zenithal anidolic collector with labeled dimensions.

Since the interior distribution parabolas 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 [WEL 89]:

$$f = a' \times (1 + \sin\theta) \quad (2.1)$$

$$a = a' / \sin\theta \quad (2.2)$$

$$L = (a' + a) \cot\theta \quad (2.3)$$

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  $\theta$  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,  $\theta$ , has an effect on the distribution of light (see Section 4.4). The absolute equation of the CPC is also given in Welford and Winston:

$$0 = (z \cos\theta + y \sin\theta)^2 + 2a'(1 + \sin\theta)^2 z - 2a' \cos\theta (2 + \sin\theta)y - a'^2(1 + \sin\theta)(3 + \sin\theta) \quad (2.4)$$

where  $a'$  and  $\theta$  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 [WEL 1989].

Early testing on the zenithal anidolic collector was done with the modeling software ADELINÉ [COM 1993]. Later, a scale model of a slightly different design was tested under the diffuse sky scanning simulator at EPFL, and a 1-1 scale prototype was made and installed in a test office on the university campus [SCA 1996]. The scale model and prototype rooms were each approximately 3 m tall (9.8 ft), 6 – 7 m deep (19.7 – 23 ft). The prototype anidolic device has a system height of 74 cm ( $2a$ ), an interior length of 88 cm ( $L$ ), an exterior collector length of 108 cm ( $L_2$ ), and a characteristic angle of  $33^\circ$  ( $\theta$ ). The exterior collector has an axial tilt of  $10^\circ$  from the vertical, and the scale model has an anidolic system of similar dimensions. In both cases, the light levels in the room were raised from less than 1 or 1.5% daylight factor to over 3% daylight factor, even as deep as 4 or 5 meters into the room (13.2-16.4 ft). This is a significant improvement, 2% daylight factor being the minimum standard for daylighting in the United States.

A few years later, another 1-1 scale prototype zenithal anidolic collector was designed, built, and tested at EPFL, but this prototype was meant as an experiment in building integration. Within severe spatial restrictions, especially as concerns the exterior portion of the collector, a modified “integrated” anidolic design was conceived. [SCA 2000] This design, a tilted, flattened, and somewhat truncated version of the original anidolic design, was integrated into a “typical office” test room, next to a similar room with no system. Test results for this system were positive, although the peak benefit of the system was between 2 and 3 m (6.6 – 9.8 ft) from the window, as opposed to 4 to 5 m (13.1 – 16.4 ft) depth of peak benefit seen in the original design. In the “integrated system” case, there was still improvement more than 4 m from the window, but it was not dramatic improvement.

As mentioned in Section 1, the headquarters of the Laboratoire d'Énergie Solaire et de Physique du Bâtiment (LESO-PB) at EPFL had its south façade renovated in 1998, and LESO took that opportunity to go beyond single prototypes and to install a full façade of anidolic systems. Since the south-facing offices were only 4 m (13.1 ft) deep, many of them only had half anidolic systems or light scoops installed. Several offices, however, had anidolic systems that were more complete (see Figure 2.4) [ALT 2002]. The view windows are slightly recessed, and the whole casement is finished in wood. Exterior diffusing blinds run on separate electronic controls for each view window and each anidolic system, providing shading for those times when direct sun penetrates the system or the window, and the slanted glass cover for the anidolic system is largely protected from the rain by the window sill above it.

Even the half anidolic systems make a noticeable difference in the office's daylighting. They provide shading near the window and heighten the illuminance in the rear of the room, producing a more homogeneous overall lighting level [ALT 2002]. The author spent a couple months during the summer of 2005 working in one of these offices and found it a very pleasant environment. Rarely did anyone in those offices use electric light during the day.

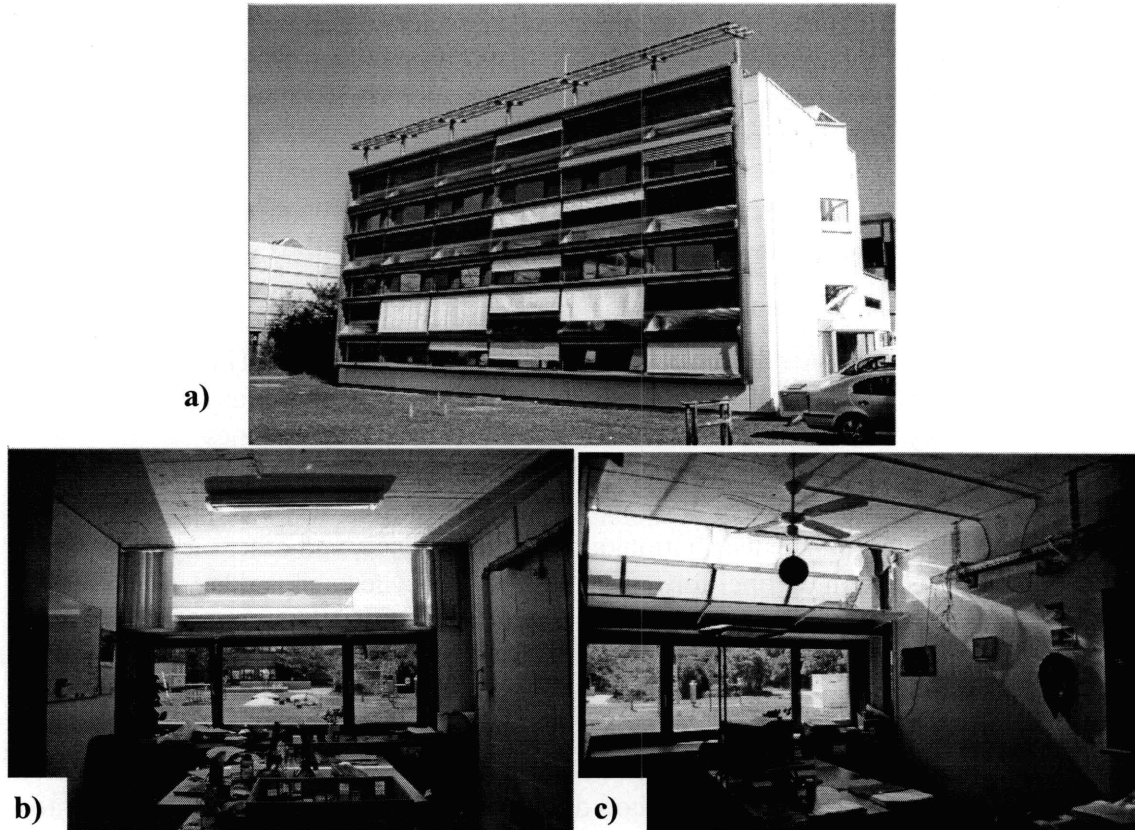


FIGURE 2.4: (a) The south façade of the LESO-PB building with some blinds deployed. (b) An anidolic system consisting only of the exterior collector. (c) An anidolic system consisting of an extended exterior collector and top interior distributor. Both (b) and (c) are underexposed because of the bright direct sunlight striking the anidolic system. Normally under these conditions, blinds would be drawn across the anidolic aperture. (Photographs by the author.)

Outside of EPFL, there have been a couple building façade designs which use anidolic systems. The proposed “Gesellschaft für Innovation und Transfer” (GIT, Partnership for Innovation and Technology Transfer) building at the University of Siegen, Germany, has anidolic ceilings designed into several of its north-facing rooms. Simulations show that the light ducts, if installed, would give three extra meters depth of 50-60% daylight autonomy [HEI 2000]. Anidolic systems, in this case the zenithal anidolic collector, were also designed into the façade renovation of the Caisse-Conge building in Brussels, Belgium. Philippe Samyn and Partners fashioned the exterior collectors as an architectural expression and their design came in second in the project contest. Technical analysis of the design was done by the Belgium Building Research institute [LESO web, CAR 1996]

### 2.3 Daylighting Analysis

In this field, the measurement, prediction, and simulation of daylight require just as much creativity and technical skill as the design of the systems themselves. Although readily

measurable in real life, natural light is subtle and constantly changing, which makes providing a temporally unspecific daylighting analysis of any space challenging. It is important, therefore, to discuss the way in which we quantify daylighting levels and decide what “good” daylighting is.

Daylight factor (DF) is the metric which dominated the industry during most of the 20<sup>th</sup> century, although it did go through quite an evolution. J. B. Collins wrote a wonderful history of the development of DF (though only from the point of view of British research), which consists of a sum of three components: the direct component, the external reflected component, and the internal reflected component. The direct component, originally the only component considered, started purely as a measure of the fraction of the sky vault visible from the window. It was also sometimes called “sky factor,” and that term is still used today when describing this sky vault view angle [WU 2003]. This direct component went through several iterations of correction factors for CIE overcast sky luminance distribution, glass transmittance, and other elements [COL 1984], until it was put in its final form in 1968 by J. A. Lynes, who added weighting corrections based on the measurement position in the room [LYN 1968]. The external reflected component, like the direct component, was calculated by angular view, and then divided by 5, under the assumption that the ground and all building materials have an average reflectance factor of 20% [COL 1984]. For the internal reflection component, there was no good calculation until Hopkinson, et al., published what they called the “split-flux method” in 1954. This method divides the light flux entering the room into two parts: one seen by the upper part of the room and affected by the average reflectance factors from the higher spaces, and one seen by the lower part of the room and affected by the reflectance factors of the floor and lower walls [HOP 1966]. All together, these three components add to produce the total daylight factor, which is defined, for any point in a space, as the fraction of the luminance that one would receive on a horizontal plane with an unobstructed view of the CIE overcast sky.

Daylight factor has been the dominant method of analyzing daylight for the better part of a century. It analyzes the geometry of a building without reference to location, orientation, or weather, but this is often seen as more of a weakness than a strength. In his 1968 book *Principals of Natural Lighting*, alongside detailed calculations, Lynes notes that DF only stays constant “when the *pattern* of sky luminance is static... The use of daylight factors is therefore restricted in practice to solidly overcast weather,” [LYN 1968]. Then in 1980, Tregenza’s study of the internal illuminances of several models found DF to be unreliable under real skies. This was mainly because the CIE sky distribution is idealized and uncommon [TRE 1980]. More recently, Christoph Reinhart did a study in which several daylight analysis methods were compared, and his data shows DF often vastly underestimated the illuminance values in comparison with other analysis tools [REI 2000]. Most recently Mardaljevic published a paper which compared standard daylight factors to those measured in life. He found that the standard DF tended to underestimate the real DF by at least 20% (and in many cases as much as 40-77%) [MAR 2004]. One of the primary reasons given for this discrepancy was again the difference between the CIE overcast sky and real skies.

It is because of the general dissatisfaction with the accuracy of DF that Mardaljevic, Reinhart, and other experts are now advocating the adoption of a metric which takes into account weather, statistical realistic skies, location, and building occupancy over the period of a full year. Mardaljevic calls the resultant illuminance predictions “Annual Daylight Profiles” (ADP) [MAR 2000, 2001]. Reinhart et al. are developing and pushing another version of this concept in North America, called “Daylight Autonomy” (DA) [WAL 2002, REI 2002, 2004]. Daylight Autonomy compares the many time-stepped illuminances to a minimum reference value, and the result is displayed as a percent of occupancy time for which each measurement point can be “autonomous” from, or not dependant upon, electric lighting.

ADP or DA can be calculated by brute force repetition of illuminance calculations, however the sheer number of iterations needed for an accurate calculation makes this method prohibitively time-intensive – although if less accuracy is required, one could pick a few representative skies and sun positions as representative of the whole year. This was the approach used by Wittkopf et al. in their comparative study of anidolic ceilings in Sheffield and Singapore [WIT IP], however it vastly reduces the statistical base for the average prediction. A more calculation efficient method of finding ADP or DA is that of daylight coefficients (DC). Introduced by Tregenza in 1983, this method assigns to each “sensor” location a coefficient dependent upon room geometry, reflectivity, sky visibility, etc, similar to the concept of daylight factor. Unlike DF, however, these coefficients take minute changes in each angular segment of the sky into account. They allow the input of intricate, realistic skies and thus solve the greatest weakness of daylight factor.

The obvious advantage of DA and ADP are their potentials for calculating long term, realistic daylighting averages, and though many are still unfamiliar with these types of calculations, they are gaining support in the lighting community. Daylight autonomy has even been adopted by the Collaborative for High Performance Schools (CHPS) program, in lieu of daylight factor, as a measure of daylighting standards [CHPS 2006]. There is one major roadblock for the adoption of these metrics, however, and that is the intensity of calculation they both require. As mentioned, it would be impractical to find these numbers without a computer, and even when the daylight coefficient method is employed, the computation time needed for DA or ADP is several orders of magnitude greater than that of DF. Despite this, the concepts driving DA and ADP are valuable and are headed in the right direction for accurate daylighting analysis. Several programs have been created to calculate these yearlong statistical daylighting levels: the Dynamic Lighting System program was created at De Montfort University – by Paul Cropper, as part of his doctoral thesis – to calculate ADPs (amongst other things) [CRO 2001]. Christoph Reinhart and others at the Canadian National Research Council have released a program called DAYSIM which calculates Daylight autonomy [WAL 2002], and the CHPS program in California recommends a program called SPOT (Sensor Placement and Optimization Tool) [CHPS 2006]. Both Dynamic Lighting System and DAYSIM use the program RADIANCE as their calculation base, although DAYSIM alters one of the RADIANCE functions to do so.

RADIANCE, created at Berkeley by Greg Ward, is a backwards ray-tracing program and is recognized as one of the only physically accurate daylighting software available today. The RADIANCE program itself runs in a UNIX/LINUX environment, but it is also the calculation base of many other lighting programs, including DLS and DAYSIM mentioned above, and also ADELIN and ALware, amongst others [RAD web]. Validations of the RADIANCE software have been made against the BRE's International Daylight Measurement Programme (BRE-IDMP) dataset, which is an extensive and thorough set of 1-1 scale illuminance data made on some test rooms with several different complex fenestration systems in comparison with an identical reference room, and is generally thought to be the most detailed reference data set in existence [AIZ 1993, MAR 2001]. The most important aspect of this dataset is the detailed sky illuminance data which was gathered at the same moment of every set of internal illuminances. Under these accurately modeled skies, Mardaljevic's RADIANCE predictions for the BRE-IDMP rooms had a mean difference from actual measurements of 5.6% with a standard deviation of 3.4% [MAR 1995], although where a CIE sky is used to provide daylight factors, RADIANCE has been found inaccurate by about 50% [NG 2001]. The latter study, however, is more a comment on the inaccuracy of the daylight factor method than on the accuracy of the RADIANCE program. In cases where a backwards ray-tracer is not an appropriate tool, there exist programs like TracePro, which is a forward ray-tracer, albeit less sophisticated than RADIANCE. Other available daylighting software includes the part radiosity, part forward ray-tracer program Genelux [MIT 1997] and the radiosity-based DELight, which is based on the calculation algorithms for the earlier program SUPERLITE [HIT 2003].

RADIANCE, TracePro, and others can be used to model complex fenestration technologies as well as architectural spaces. Several recent studies have been done comparing the computed Bidirectional Transmission (Reflection) Distribution Data, or BT(R)DF, of several different devices to the BT(R)DF measured by goniophotometer, and the two methods seem to deviate by about 10-20% [AND 2003, MAA IP]. A goniophotometer is an instrument for measuring the light scattering distribution of a material sample. Peter Apian-Bennwitz, whose goniophotometer design consisted of a columnar light source, a rotating sample holder and a moveable detector, did a lot of work on both the goniophotometers themselves and the calculation of BT(R)DF's by integrating spheres [API 1994, API 1998]. More recent work on the subject includes that of Marilyn Andersen, whose video-goniophotometer drastically cut measurement time by using digital imaging to evaluate the resulting light scattering on a rotating diffusing screen [AND 2004, AND IP]. BT(R)DF data, whether measured by computer or goniophotometer, is important to our further understanding of complex fenestration technologies. Such information can then be integrated back into computer programs to help simulate the effect these technologies have on modeled architectural spaces [REI IP, HIT 2003].

Although the complexity of several of these window systems and the computationally intense calculation associated with DA and ADP seem to be moving us solely in the direction of computer simulation, scale models also deserve consideration as a daylighting tool. For centuries, scale models have been used by architects for qualitative

daylight assessment, and with the introduction of daylighting as a quantifiable science, they have also been used to predict daylight factors and illuminance levels under both real and artificial skies [COL 1984]. Real skies are more accurate for daylight measurement, but not controllable, so artificial skies are sometimes preferred. Generally, an artificial sky consists of a large room with a hemispherical array of lights that can be set independently to different illuminance levels. A more recent artificial sky is the scanning sky simulator at EPFL, which simulates one sixth of the sky at a time, and then adds the contributions of each slice to produce a total illuminance [MIC 1995, 2002].

There have been several recent studies done on the accuracy of scale models, and the results indicate high levels of error and a tendency to overestimate illuminance [CAN 1997, MAR 2002, THA 2005]. A notable study by Cannon-Brookes used simultaneous measurements in an empty building and a model of that building to compare predicted to actual daylighting levels. After correction for inaccurate modeling of the fenestration and the floor specularity, Cannon-Brookes reported a model divergence of +10% to +25%, and compared these results with those of similar studies (which ranged from 10% to 55%) [CAN 1997]. Michel et al. reported similar results from EPFL's scanning sky simulator [MIC 1995, 2002], and Thanachareonkit et al. reported divergences of +30% to +35% in another set of simultaneous model and 1-1 scale tests under real skies [THA 2005]. Furthermore, Mardaljevic did a computer simulation study on artificial skies, and found that parallax error alone was in the range reported above for model error under real skies. He concluded that reducing the parallax error to 10% was nearly impossible, and that an error of 25% would still impose strict size limits on the model [MAR 2002]. It should also be noted that the reported divergences of Cannon-Brookes and Thanachareonkit were second passes, after initial corrections had been made to the model geometry or materials – the first results of Cannon-Brookes were +60% and those of Thanachareonkit were initially +60% to +105%. Both of these studies also tried to pinpoint the reasons for the scale model overestimation, and both agreed that dimensional accuracy, photometric properties of materials, and glazing transmittance had a great effect on the accuracy of the measurements, but Thanachareonkit added that the cosine responses of the photometric sensors also had a large impact.

As D. L. Loe commented, in his discussion of Cannon-Brookes' article, "This leaves the questions of whether architectural models have a value in daylighting design," [CAN 1997]. Loe answered his own question in the affirmative, if for no other reason than their qualitative assessment value. This is a valid point, as not all lighting simulation software has RADIANCE's realistic looks, but there are further arguments to be made. Most scale-model measurements are quicker than computer calculations of any accuracy, and the accuracy of any computer model depends upon the accuracy of the input information – as is apparent in the comparison between Mardaljevic's validation of the program RADIANCE using the BRE-IDMP data, which found less than 10% error [MAR 1995, MAR 2004], and Ng's simulation of a building in Hong Kong under CIE overcast skies, resulting in 50% error [NG 2001]. In other words, the accuracy of any measurement depends upon the accuracy of the model, and although computer models may have more potential for accuracy, a computed measurement is not necessarily more accurate than a scale model measurement just because it was done by computer. As with any new

measurement technique, the addition of computer simulation – just as with the addition of daylight autonomy or annual daylight profiles – should add depth and diversity to the daylighting toolbox, rather than wholly replacing those tools, such as scale models or daylight factor calculations, which were already in use.

### 3 DAYLIGHTING AND THE HISTORICAL AMERICAN CLASSROOM

#### 3.1 The Century in Brief

In order to better understand existing classrooms spaces, a historical study was done on daylighting in American schools in the 20<sup>th</sup> century. This study took the form of a literature review of a century's worth of articles – dealing with schools, lighting, or daylight – published in the *Architectural Record*. The *Architectural Record* was chosen because it is a respected journal which has been in print for more than one hundred years, and because it covers architecture in general and does not focus on lighting or daylighting. In this way, it is more likely to provide a sketch of the general contemporary attitude towards lighting and is not overly biased towards technological prototypes or special cases of lighting design. What follows is a brief sketch of how American classrooms and their lighting strategies changed in response to architectural and educational theories, economic developments, and technological advances. It also serves as a description of what kinds of spaces exist in the current building stock.

The new century started in the middle of a movement to improve the quality of life in school buildings. Older schools in New York and other cities, which had been criticized for darkness, bad ventilation, and an unhealthy atmosphere in general, were being replaced with buildings literally plastered with windows for better penetration of light and air [ROB 1898]. These new buildings often had 14 ft ceilings, classrooms that were wider than they were deep, and large, tall windows on every available face. Although the incandescent light had been invented several decades before, and was continually being improved, it was still a luxury that most schools could not afford – daylight was the expected method of lighting.

Somewhere in the late teens or early 1920's, these monumental schools buildings became very standardized as the accepted philosophy for education architecture introduced some very specific rules for how classrooms should be configured. The dimensions were standardized (30 ft wide by 22 ft deep by 12 ft high), and all daylighting became unilateral. This means that no matter how many exterior walls a classroom had, it could only have windows on one of them. Three reasons given for this arrangement were to avoid confusing cross-shadows, to avoid glare in the teacher's field of view, and to provide for more than four classrooms per story [CAS 1932]. It was even recommended that the windows should be to the left of the students as they faced the chalkboard, so that right-handed students would not get shadows on their paper caused by their hand and the pencil. By the 1930's, although school construction was down due to the Great Depression, most new schools conformed to these widely accepted regulations with one addition: the notion that artificial light must always be used to supplement daylight [LOG 1931].

California was a notable exception in that many schools in that state did not conform to these standards of educational architecture. As early as the 1920's the *Architectural Record* was running articles on Spanish-influenced California schools with one-story bilateral daylighting and classrooms which opened directly to shaded porticoes and the

playground [HEN 1927]. By the end of World War II, these “California Schools” had spread to other parts of the country, and in the post-war economic boom, daylighting enjoyed a brief and enthusiastic focus from the educational architecture community. Bilateral and trilateral daylighting strategies, louvered skylights and monitors, clerestories, and other daylight-conductive building shapes were amongst the strategies explored in this brief renaissance of daylighting.

With the turn of the century, however, came the first of the baby-boomers. School districts across the country were suddenly flooded with kindergarteners and nowhere to put them, so new schools were constructed by the thousands. People still liked the larger, less constrained floor plan and teaching style of the new California Schools, but shaping roofs and providing daylight for such deep spaces was expensive and more difficult in climates that were not as sunny as the southwest [AR 1950, 1951]. The recent introduction of fluorescent lamps as a cheaper source of light made artificial light the more appealing option to many people. Finally, the introduction of new Audio/Visual teaching techniques made it necessary to easily control exterior light. Classrooms in the 1950’s, therefore, had varying depths, which could be as much as 40 ft, and ceilings were not often taller than 10 ft, on account of construction costs. Although most every classroom still had windows, the rooms were designed to be operated purely on artificial light.

The popularization of air conditioning in the late 1950’s took this classroom design and compacted it to produce designs with as little exterior wall as possible. Suddenly, there were interior classrooms without the possibility of side or “view” windows, although to begin with, many of these rooms were lit by skylights. This new compact plan gave architects the ability to arrange classrooms in clusters or other configurations, and dividing walls sometimes were little more than partitions. The teaching philosophy of the time was also evolving along with this new open floor plan, and in the 1960’s the traditional classroom was all but abolished in many parts of the country. Many schools had moveable classroom walls, or none at all, ceilings were often 8 ft in height, A/V teaching was popular, “open plan team teaching” was the hot educational theory, and the new buzzwords were “flexibility” and “adaptability”. Most importantly, however, a great many of these school buildings had only tiny “vision strips” or no windows whatsoever. These windowless schools were justified by the ability to have total control over the interior environment, the lack of “exterior distraction,” the greater freedom of floor plan, and the reduced cost of construction [AR 1964].

In the early 1970’s, an energy crisis hit the nation, and people began to be more concerned about environment, but especially about operating efficiency. Daylighting was still seen as a liability, however, because of glare control factors and thermal solar gains. Not until 1980 did people begin talking about the benefits of daylight again, and even then, it did not catch on like it did in the late 1940’s.

During the 1980’s, open plan team teaching was abandoned in favor of more traditional divided classrooms, which, to this day, are often 800-900 ft<sup>2</sup> or 1200 ft<sup>2</sup>. Box-like, flat roofed massing also began to be replaced by more complex forms, although budget



FIGURE 3.1: The central building of Chaparral High School (Scottsdale, Arizona), built in 1975. Every building on campus is either windowless or nearly so. (Photograph by Evan Korzon)

remained a serious consideration, and architects seemed more willing to consider regional architecture types for school construction. There was also a drive to make schools into social centers for the wider community [AR 1988].

By the late 1990's, several different educational architecture philosophies had developed around the re-division of classrooms and the idea of schools as community. Some used a capitalism or market-type model, some saw the school as a small town, centered around some common "town squares," and some saw information-technology as the guiding light, thinking that classrooms should be a subsidiary computer to a centralized core facility [AR 1997]. This just suffices to point out that unlike the highly standardized nature of school architecture in previous decades, school buildings from the 1980's to the present day are a diverse set of architectural infrastructure, and it is the specific aims of the project which inform the size and shape of the building and the nature of its daylighting. There are, however, certain things that remain common to many classrooms. For example, 30 ft also remains a common width for school classrooms, and 30 ft, or even as much as 40 ft, remains a common depth. The size and shape of windows, as well as the height and shape of the ceiling, on the other hand, is more variable.

### 3.2 Recent Daylighting Case Studies

One thing that did emerge from the 1990's was a new enthusiasm in some quarters for daylighting design. Not only did this enthusiasm lead to the much-quoted Heschong Mahone Group report *Daylighting in Schools* (see Section 1), but it produced some interesting case studies for daylight in the classroom. The Durant Road Middle School in Raleigh, North Carolina, was designed by architects from Innovative Design and top-lights most of its classrooms by means of diffusing roof monitors. It was completed in 1995, and the daylighting and other passive strategies saved a combined total of over \$77,000 in the first year of operation [INN 2004]. It also maintains a 98% attendance rate, which the principal attributed to the high level of daylighting [PLY 2000].

Innovative Design has designed several other schools upon the same principals, including Smith Middle School in Chapel Hill, North Carolina, Roy Lee Walker Elementary School in McKinney, Texas, and East Clayton Elementary School in Clayton, North Carolina. A study done at several of these schools, including the latter, concluded that students in daylit schools were outperforming those in non-daylit schools by 14% [INN 2004].

In a similar way, wide skylights with interior, adjustable louvers were incorporated into a 1-1 scale classroom prototype built in Mt. Angel, Oregon. The University of Oregon, SOLARC Architecture and Engineering, and BOORA Architects teamed up to produce this model classroom that should never require artificial lighting during the day [BB 2005]. On a different note, the architecture firm Jersey Devil designed Montessori Island School, in Tavernier, Florida, to be passively cooled and naturally lit through side windows and a central monitored space [AR 1997].

The trend in new classroom daylighting strategies seems to be toward large skylights and monitors, however the vast majority of our school infrastructure was not designed in this way, and tends to have unilateral side-lighting from windows of various shapes and sizes. Before the 1980's, the era in which a school was designed was a fairly good indicator of classroom characteristics with a couple notable exceptions – Southern California and other parts of the southwest cultivated an early interest in daylighting and were influenced by Spanish styles of architecture in those times, and parts of the northeast, most notably Boston, are very traditional in architectural style. For instance, the model Boston classroom introduced in Section 4.2 was built in the late 1960's when much of the country was producing windowless schools, but it is configured far more like a standard classroom from the 1920's and 30's. In most cases, however, school design was influenced by contemporary teaching philosophies, economics, and oftentimes a desire for control over the interior environment.

## 4 PROCEDURE

### 4.1 Project Goals

Although it would be wonderful if every new building had the maximum benefit of daylight from multiple sides, clerestories, and skylights, the reality of architecture is that it usually deals in spatial and budgetary restrictions. Because of this, unilateral sidelighting is likely to remain the most common form of daylighting, with all the uneven illuminance, glare potential, and lack of deep light penetration which that implies. As discussed in Section 2.1, many redirecting technologies can improve the first two of these problems. Anidolic systems are one of the only technologies that have great potential for improving deep daylighting levels. However, though some redirecting technologies have been around for a while, even they are not yet mainstays of architectural practice – possibly from lack of public familiarity or knowledge – and the relatively new anidolic systems have had little to no practical application outside of the university in which they were developed.

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. Directional transmission data can be found for some redirecting devices, thanks to goniophotometric measurements or computer modeling [AND IP, API 1994, GRE 2000], and despite their limited use in practice, several case studies exist to demonstrate their effect on an architectural space. [AIZ 1993, IEA 2000, LIT 1995] Several recent studies have also been done, assessing the daylighting impact of complex fenestrations by means of computer simulation. 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 [MAA IP]. This thesis takes a slightly different path.

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 goal of this thesis 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. To accomplish this, many configurations of a box-like room with adjustable parameters were simulated both with and without a zenithal anidolic collector. The resulting daylighting improvement was analyzed as a function of the corresponding room configurations.

### 4.2 Tools

Before proceeding with the experiment, certain choices had to be made concerning the practicality and appropriateness of different simulation and analytical tools. The first of two major choices was whether to use a physical model or computer model. Because access was granted to the EPFL scanning sky simulator in the summer of 2005, the author was able to do a comparative test before making that choice.

This comparison was made using a model of an anonymous classroom from the greater Boston area. Due to limited access and equipment, the direct data from this classroom was limited to geometric measurements, a few pictures, and several workplane illuminance readings, which were compared to an outdoor horizontal illuminance to get rough daylight factors. The day on which these measurements were taken was pretty evenly overcast, but bright, and there was at least a five to ten minute lag between the indoor illuminance tests and the outdoor measurements. Because of this, the geometric data taken was considered more valuable than the illuminance data (as model specs for a realistic classroom), however the latter was considered accurate enough for a ballpark comparison between computer simulations and physical models (see Appendix C for model specifications).

The physical model was made at EPFL with the help of Pierre Loesch and the architectural model department. It is 1:15 scale, the interior reflectances were approximated using colored paper, and the only furniture replicated was that which might directly block light from the windows. The rough, spaghetti-like acoustic ceiling was approximated using a white bath towel. The computer model was made using the LINUX-based software RADIANCE which, as discussed in Section 2.3, can be a very accurate daylight simulation program (depending, of course, on the accuracy of the input). In the case of the RADIANCE model, furniture was included. In both cases, the original position of the shades was noted and simulated (as they were fixed with knots in the classroom and had been in place during measurement). The illuminance data in all cases was taken in front of the only completely unshaded windows. The resulting daylight factor curve is shown in figure 4.3.

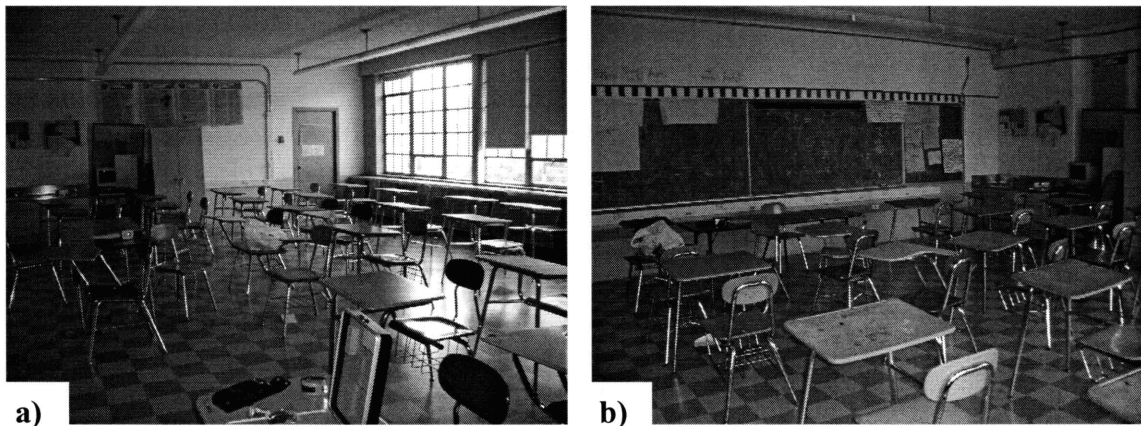


FIGURE 4.1: Two photographs of a sample classroom in greater Boston (taken by author).

The difference between the RADIANCE simulations and the Boston classroom measurements ranged from +14.4% to +63.1%, which is a believable number given the admitted inaccuracy of the situation. The RADIANCE simulations were done under CIE overcast sky with a horizontal illuminance of 20,000 lux (which was the exterior illuminance value recorded), and so the best literature comparison for this data is Ng's

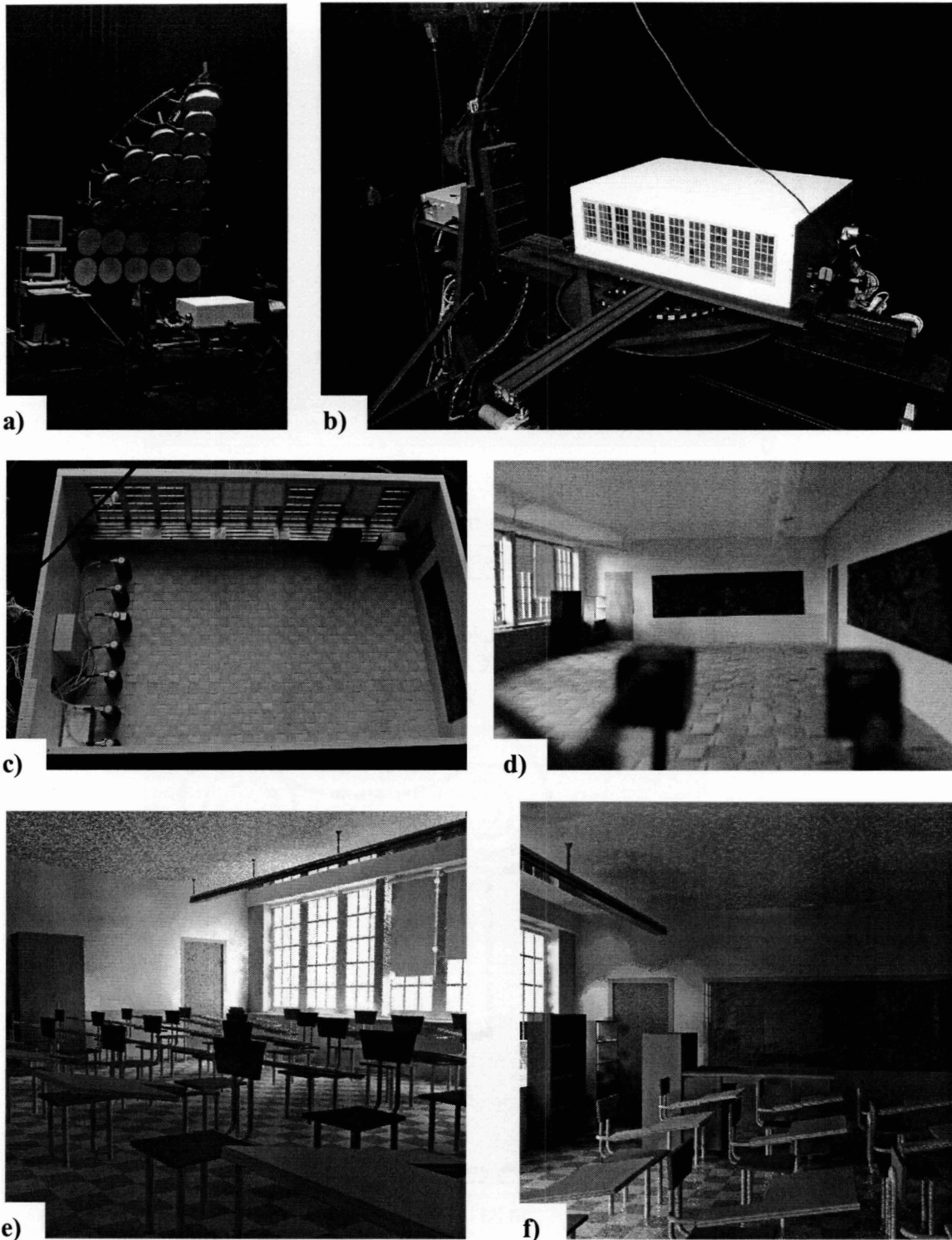


FIGURE 4.2: (a) The scanning sky simulator at EPFL. (b) The exterior of the 1:15 scale model of the Boston classroom. (c) A top view of the Boston classroom scale model with shades deployed. (d) An interior view of the Boston classroom scale model. All photographs were taken by the author. (e, f) Two interior renderings of the RADIANCE model of the Boston classroom. Furniture is simulated and shades are deployed.

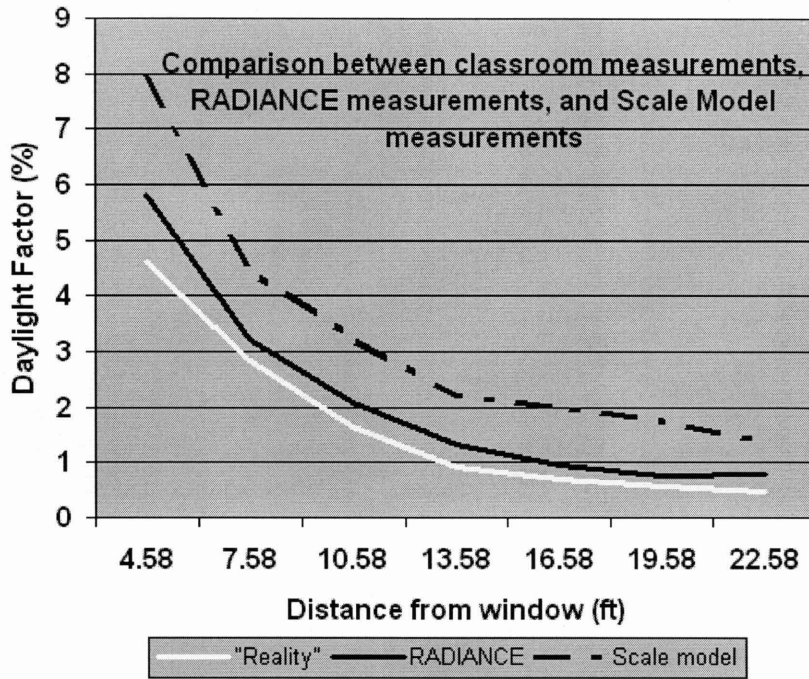


FIGURE 4.3: Daylight factor measurements taken inside the Boston classroom in comparison with the RADIANCE model and the SCALE model (window shades included).

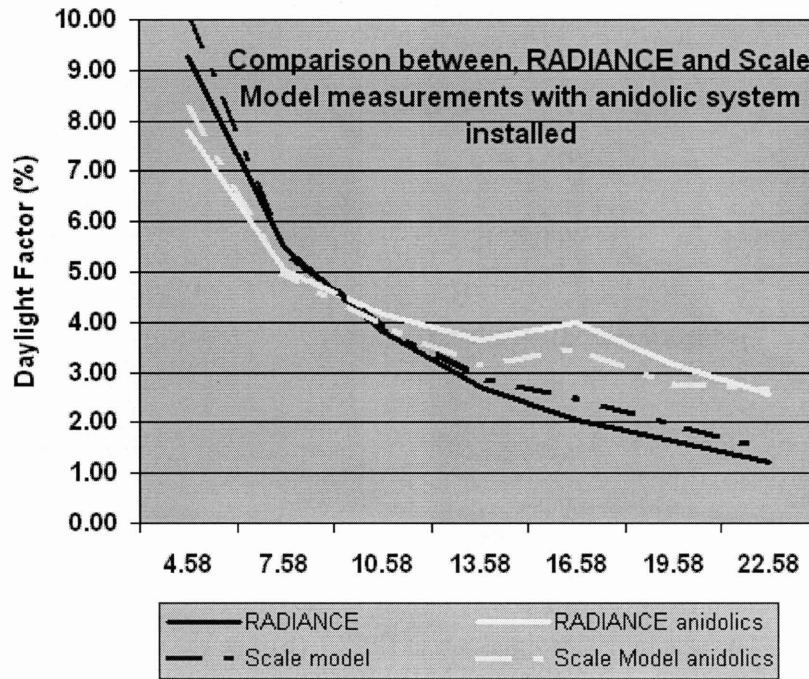


FIGURE 4.4: Daylight factor measurements before and after the installation of an anidolic system in both the scale model and the RADIANCE model. In this case, all daylight factor calculations are made in the center of the room with no shades deployed.

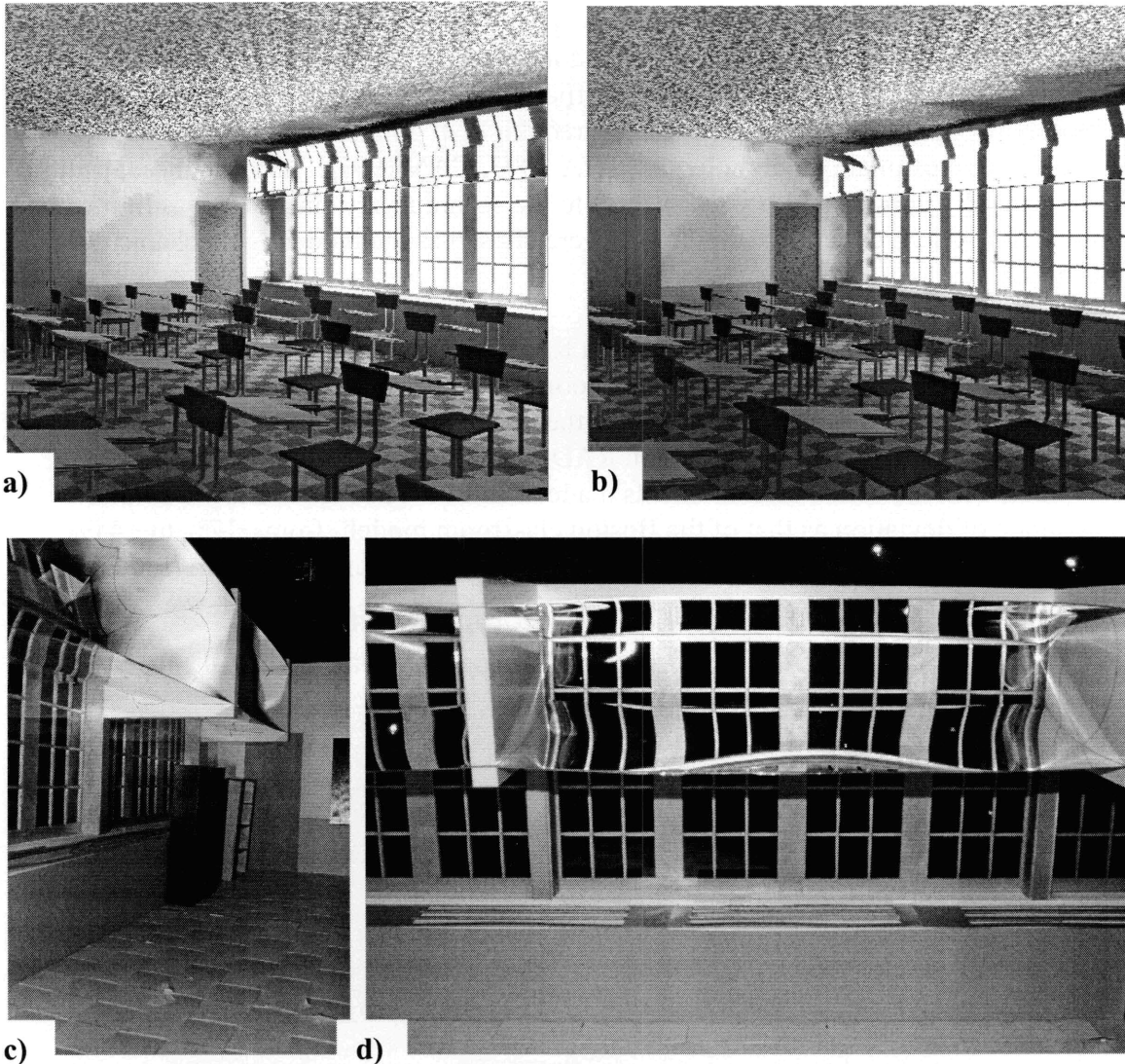


FIGURE 4.5: (a, b) RADIANCE renderings of the Boston classroom with a 30 degree anidolic device installed, first without removing some window frame, then with removing some window frame. (c, d) Two photographs of the scale model with 25 degree anidolic system (photographs taken by author).

simulation study of office buildings in Singapore (see Section 2.3) [NG 2001]. That study, in which the RADIANCE simulations were also calculated under CIE overcast sky, found that RADIANCE overestimated daylight factors by up to +50%, which is in the same realm as the difference range given above.

The difference between the scale model and reality ranged from +58.7% to +213.4%, which is a much higher deviation, although it also makes intuitive sense. This range is at least of the same order of magnitude as Thanachareonkit's first model before geometric and photometric corrections were made (see Section 2.3) [THA 2005]. Further simulations in both RADIANCE and scale models, in which the shades were taken out and an anidolic system was installed, showed the scale model to be more similar to (but

still greater than) the RADIANCE model with no anidolic system(see Figure 4.3). The anidolic system in the scale model predicted less daylighting improvement, probably because the physical anidolic model had difficulty holding its parabolic shape. The research of Cannon-Brookes and Thanachareonkit *et al* points to the tendency of scale models to overestimate daylight levels [THA 2005, CAN 1997]. Because these results were generally upheld, and because access to the scanning sky simulator was limited by time, RADIANCE computer simulations were chosen as the modeling mechanism for this thesis.

One other comparison was made between a RADIANCE model and a 1-1 scale room. There are a couple anidolic prototype test rooms at EPFL, and measured daylight factors were published along with a description of these rooms [SCA 1996]. Daylight factor measurements were calculated based on RADIANCE models of these rooms and compared with the actual measurements made at EPFL. The results show a similar magnitude of deviation as that of the Boston classroom model: from +17% to +44% without an anidolic system and from -9% to +47% with an anidolic system (see Figures

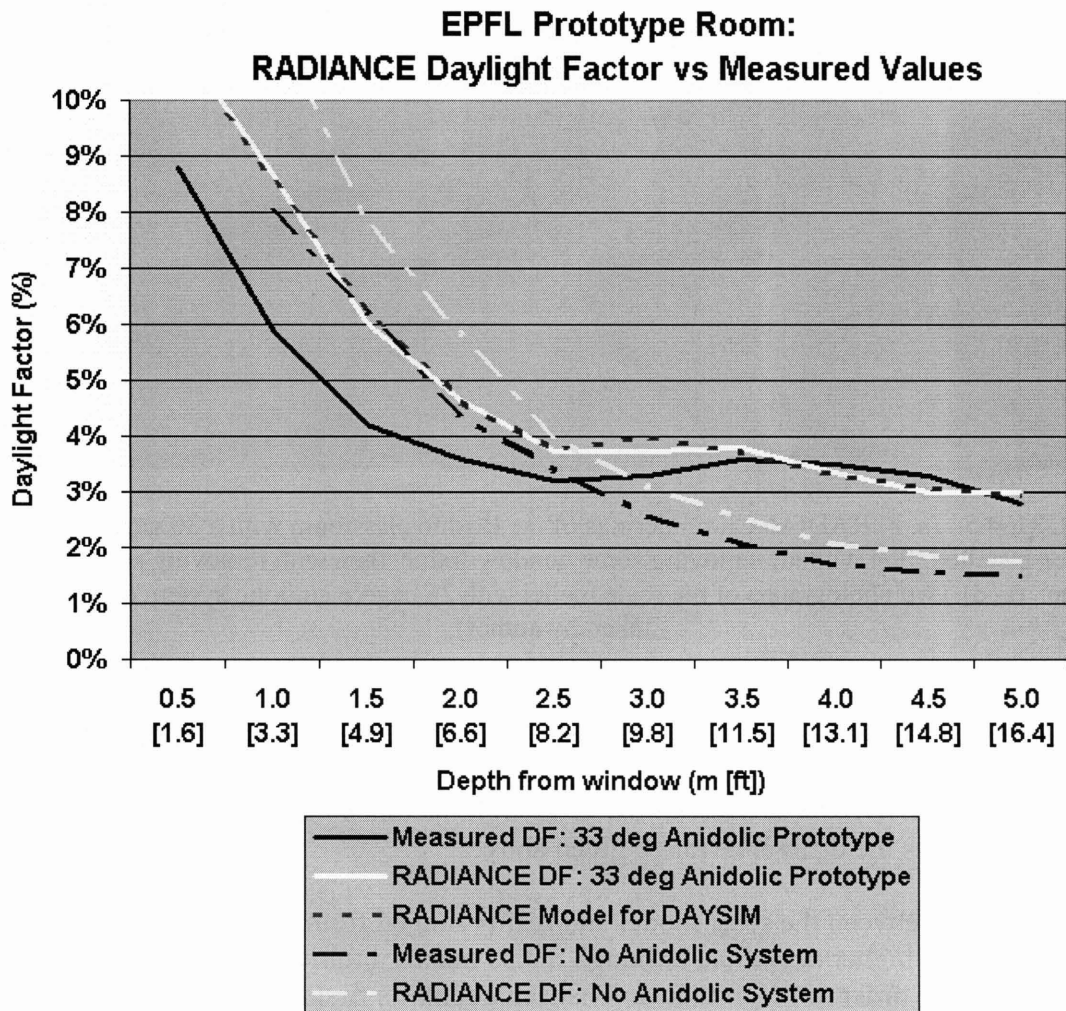
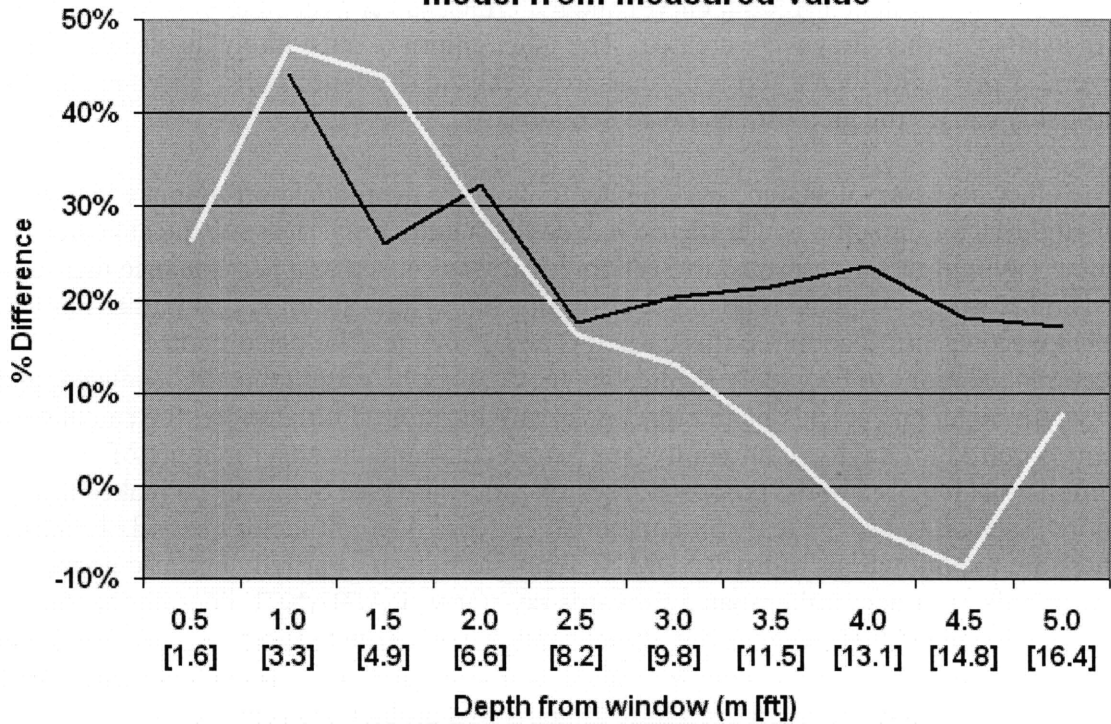


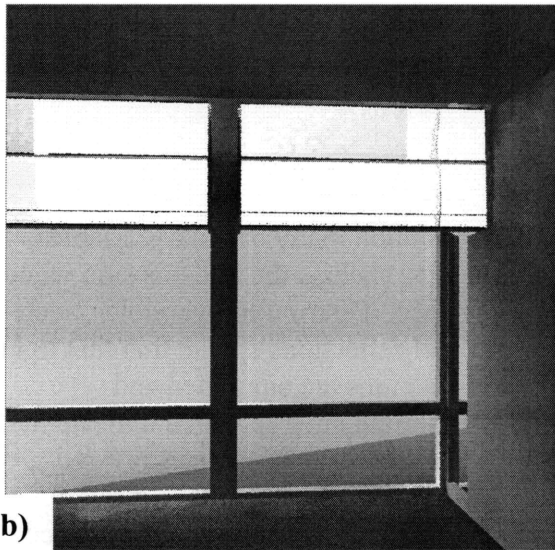
FIGURE 4.6: Daylight factor curves for the EPFL anidolic prototype 1-1 scale room. Measured values and RADIANCE calculations are shown.

**EPFL Prototype Room: % Deviation of RADIANCE model from measured value**

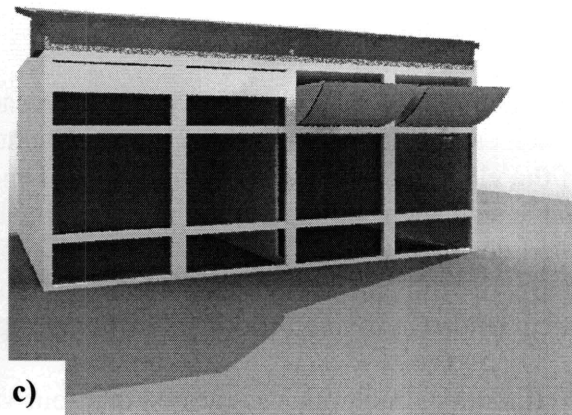


a)

— No Anidolic System    — 33 deg Anidolic Prototype



b)



c)

FIGURE 4.7: a) Percent deviation of RADIANCE model daylight factor curves from measured value in the EPFL anidolic prototype 1-1 scale room. Average absolute percent deviation for no anidolic system is 24.5%, and for 33 degree anidolic prototype is 20.2%. b) Interior view of the test room with the anidolic prototype. c) Exterior view of the anidolic test room and another test room.

4.6 and 4.7. The deviations of both models can be attributed partially to inaccurate modeling of geometry (especially of anidolic system, which must be modeled as segments, rather than a smooth curve) and materials, as very accurate information was not available when they were created. The other culprit is most likely the use of a CIE overcast sky rather than a series of measured, realistic sky luminances, and it is this that probably causes the greatest error (see Section 2.3).

The other necessary decision was whether to measure the model performance in terms of daylight factor, or some newer metric like daylight autonomy. Despite the concerns about daylight factor described in Section 2.3, it was chosen as a performance metric for several reasons. Although one of the criticisms of daylight factor is that it does not take local weather into account, in this case, it is an advantage. For performance recommendations to be widely applicable, they cannot be geographically localized, and daylight factor can at least be interpreted for any location. Furthermore, the calculation time required for daylight autonomy (see Section 2.3) and the sheer number of simulations required in the proposed research procedure (see Section 4.3) makes it far more practical to use the less computationally intense daylight factor method. Finally, there are the limitations of the RADIANCE program itself. Partially because it is a backwards ray-tracer rather than a forwards ray-tracer, RADIANCE does not handle intense, localized light sources (i.e. direct sunlight) on curved reflectors well [RAD web]. Raphaël Compagnon, in the course of his doctoral research, confirmed that using direct light on RADIANCE modeled anidolic systems was problematic but found that the program could handle anidolic systems under diffuse skies adequately if the curve of the system had enough resolution [COM 1993]. Since daylight factor is measured only under CIE diffuse skies and daylight autonomy requires a range of sky conditions, this makes one more argument in favor of daylight factor in this particular case. Instead, daylight autonomy will be used in a few cases as a comparison to the daylight factor results.

### 4.3 Variables

The amount and behavior of daylight in a space depends upon many physical variables, which can be divided into two groups. 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 how internal reflections spread that light over the work plane. If enough of these variable combinations are simulated and analyzed with and without an anidolic system, patterns should emerge which indicate the effect of this system on rooms of different types.

Preliminary simulations suggested that four variables had the most significant influence on light distribution in a space: window head height, total window width (as a percentage of wall width), wall/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  $\theta = 25^\circ$ , and

one with  $\theta = 30^\circ$ . This process was repeated for each of three room depths for a total of 1125 simulations. The actual values for each variable are given in Table 4.1.

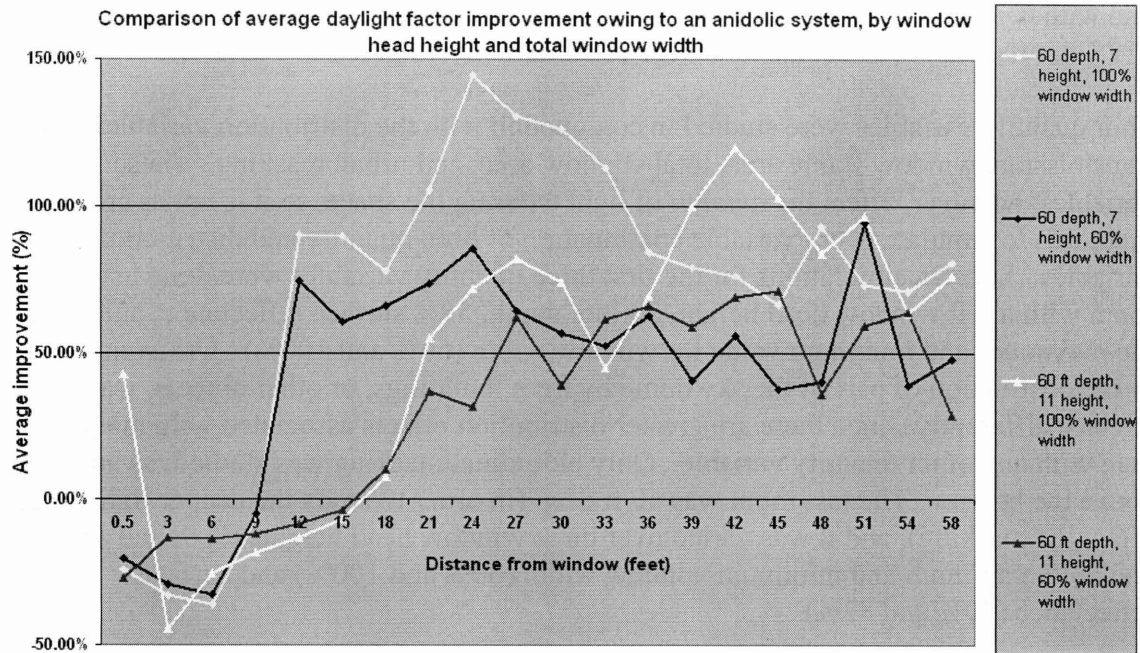
Four quantity variables were studied in conjunction with the distribution variables: glass transmission, window frame area, total window area, and urban masking. These variables, however, affect the *amount* of light entering the space, so it is not as critical (or practical) to simulate every variable combination of both quantity and distribution variables. Instead, simulations for the first three quantity variables were done using a room with a 9 ft window head height, 30 foot depth, 55% surface reflectance, and both the maximum and minimum value for window width (60% and 100%). Urban masking, or the obstruction of part of the sky dome by trees, buildings, or other objects, was treated slightly differently, since there are greater distribution effects associated with masking than with any other quantity variable. Only altitudinal masking was studied, as an angle above the horizon. The test room was 40 ft deep (in order to study the deeper light level effects of masking), and it was varied over three window head heights (7, 9, and 11 ft), and both maximum and minimum window width (60% and 100%) and surface reflectance (30% and 83%).

TABLE 4.1: Type and Range of Both Distribution and Quantity Variables

Distribution Variable	Range of Values
Window Head Height	{7, 8, 9, 10, 11}ft [2.1-3.4m]
Width of all Windows ( <i>% of wall width</i> )	{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	{90 (sgl pane), 73 (dbl pane, low-e)} %
Window Frame Area	{0, 19, 35, 50, 63} %
Window Area	{43 to 148} % of original area
Urban Masking ( <i>° altitude from horizon</i> )	{0, 15, 30, 45, 60, 75} °

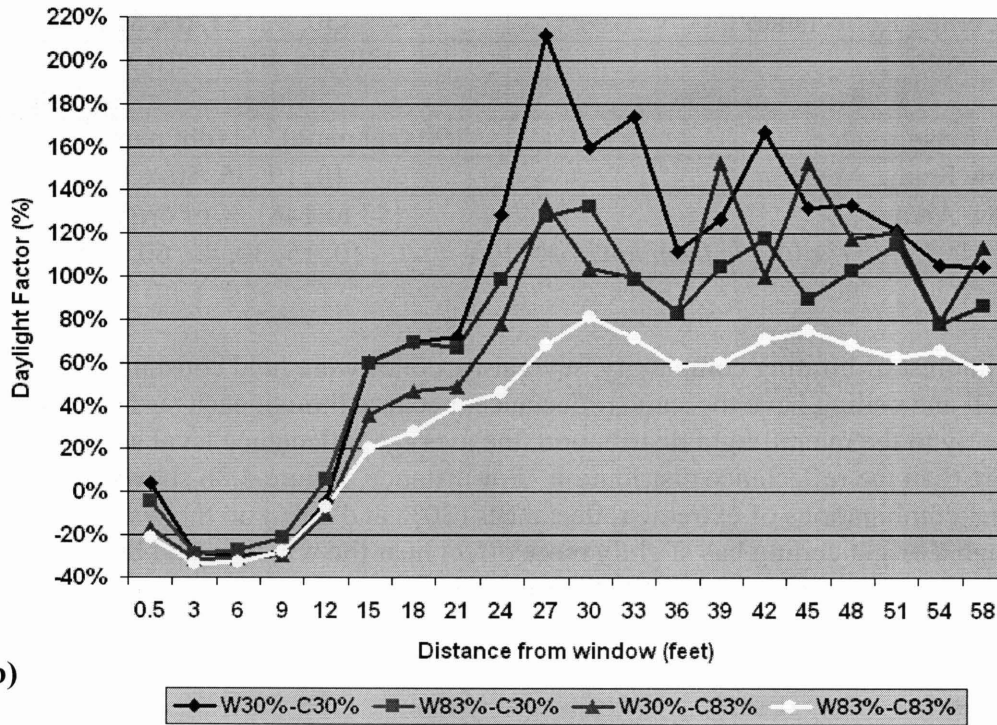
In the interest of limiting complexity, several variables were held constant. It is assumed that wall and ceiling have the same reflectance, because though each surface contributes differently to the overall light distribution, the average reflectance level seems to matter far more than the reflectance distribution. For instance, Figure 4.8b shows the average of different combinations of extreme reflectances (30% and 83%) on the walls and ceiling. Although a bright ceiling has slightly more effect near the window, and bright walls have slightly more effect near the back of the room, the lines representing a mix of dark and light reflectances are more similar to each other than to those rooms which are all 30% or all 83%.

Furthermore, the reflectance of the floor is a very conservative 5% because most floor materials have low reflectance, and because furniture often blocks much of the floor area. Beyond reflectance, other constants were given values that, from the historical research done, would seem to be reasonable in a classroom model. The width of the room is held



a)

Average improvement in Daylight Factor after addition of 25 degree anidolic system, as a function of Wall (W) and Ceiling (C) reflectance: 60 ft depth, all other variable combinations averaged



b)

FIGURE 4.8: (a) Average percent improvement of daylight factor, as a function of window head height and window width. (b) Average percent improvement of daylight factor as a function of wall and ceiling reflectances.

constant at 30 ft, there is 1 foot between the window head height and the ceiling height, the wall thickness is half a foot, and the window area is 126 ft<sup>2</sup>. This last constant was chosen because it was the maximum possible window area which would fit within the geometric bounds described by the changeable distribution variables, and it corresponds to 60% of the wall area for the shortest ceiling height and 35% of the wall area for the greatest ceiling height.

#### 4.4 Anidolic System Design

The specific performance of an anidolic system depends upon its geometry. The amount of light gathered from the sky's zenith depends upon the size and angular range of the exterior collector, and the pattern of its distribution inside the room depends upon the size, height, and angular spread of the interior parabolic pair. In the interests of practical and aesthetic design, however, certain spatial restrictions must also be placed upon the system, and these restrictions will affect the performance. For any architectural situation, a box may be drawn in section indicating the maximum space that is available for the anidolic system, which can then be designed to fit inside that space. Anidolic designs can

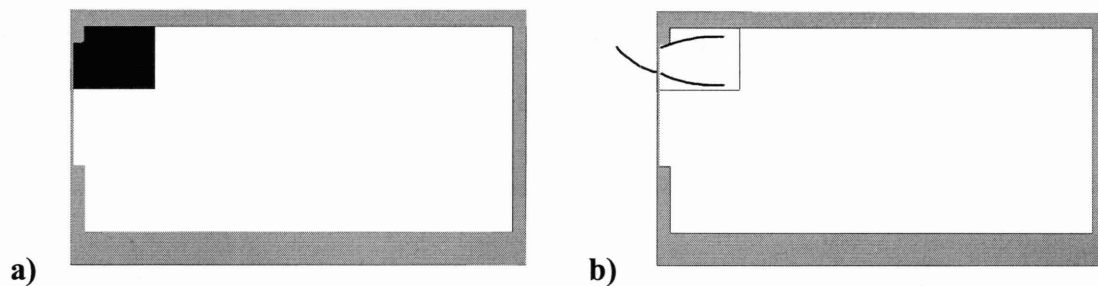


FIGURE 4.9: (a) One example of possible interior space allotted for a standard zenithal anidolic collector and (b) an anidolic system design which fits within that space.

thus vary a great deal [COU 1994]. The “integrated” anidolic prototype (see Section 2.2), designed at EPFL to be retrofitted onto an office façade, severely restricted the available space, especially the projection of the exterior collector (which was only 30 cm in depth). The result was a highly modified and somewhat flattened anidolic curve which, although it did improve the office lighting performance, did not produce a typical anidolic light distribution [SCA 2002].

In the case of the “adjustable classroom” used in this project, the challenge was to design one or two anidolic systems which would be generally applicable to many slightly different room configurations. A two foot façade projection was considered reasonable for the exterior collector (the greater the projection, the greater the daylighting benefit, but much more than two feet might seem excessive). For the interior parabolic mirrors, the height of the system should be three feet or less to make the space underneath it somewhat usable. This is tantamount to having a soffit near the window which is three feet shorter than the ceiling itself, so if the room is 10 ft in height, the space underneath

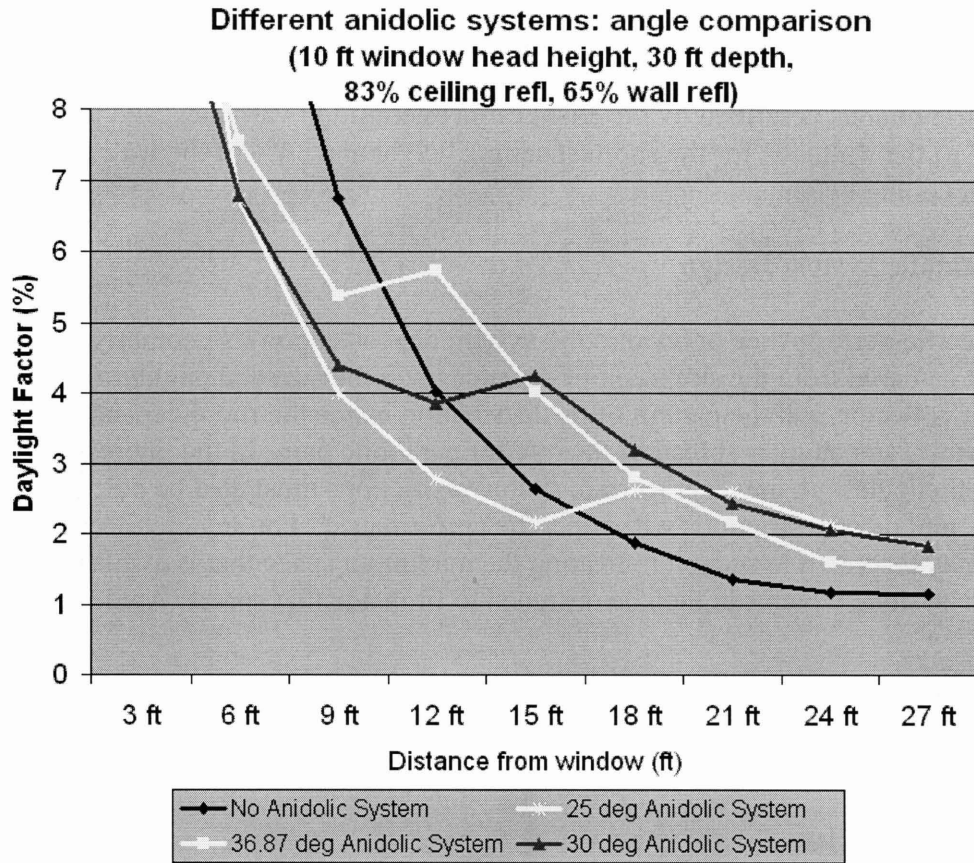


FIGURE 4.10: An illustration of the effects of anidolic system characteristic angle on the daylight factor profile.

the anidolic system is 7 ft and does not alter the usable floor area of the room. Below 10 ft in height, however, the few feet next to the window becomes less accessible to adults, although it is still perfectly usable for heaters, bookshelves, or any other space which extends the window ledge. The length of the spatial “box” is, in this case, a 4 ft interior projection, however, this was later thought to be too long, and the second system designed was limited to a less than 3 ft projection.

The daylight factor curve of an anidolic system has a peak value which, when combined with the daylight factor from the view window, looks like a normal side-lit daylight factor profile with a bump in it. Once the exterior collector has been sized, the distance of this “peak benefit” from the window façade and its magnitude are determined largely by two factors: the characteristic angle of the anidolic system and its height above the work plane. The characteristic angle of the anidolic system, or  $\theta$ , has an inverse relationship with the peak benefit’s distance from the window façade; the wider the angle, the closer the peak benefit (see Figure 4.10). The height of the anidolic system affects not only the distance of the peak benefit from the façade, but also its magnitude. Figures 4.11 and 4.12 show the effect of the same anidolic system at three different heights with no supplemental light from any other source.

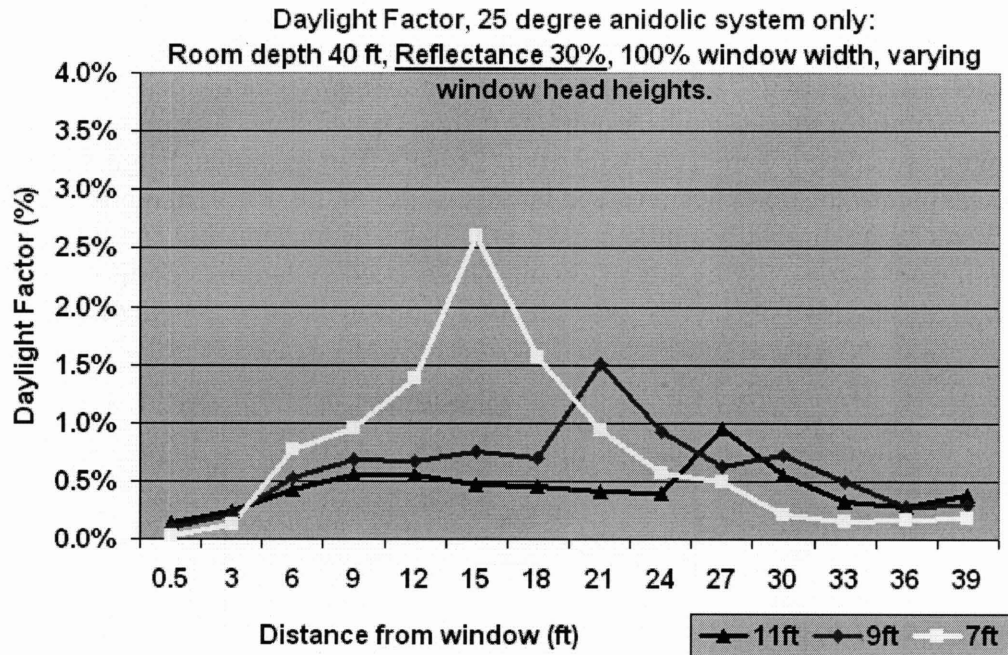


FIGURE 4.11: The effect of window head height on the DF distribution from an anidolic system in a room with very low wall and ceiling reflectance.

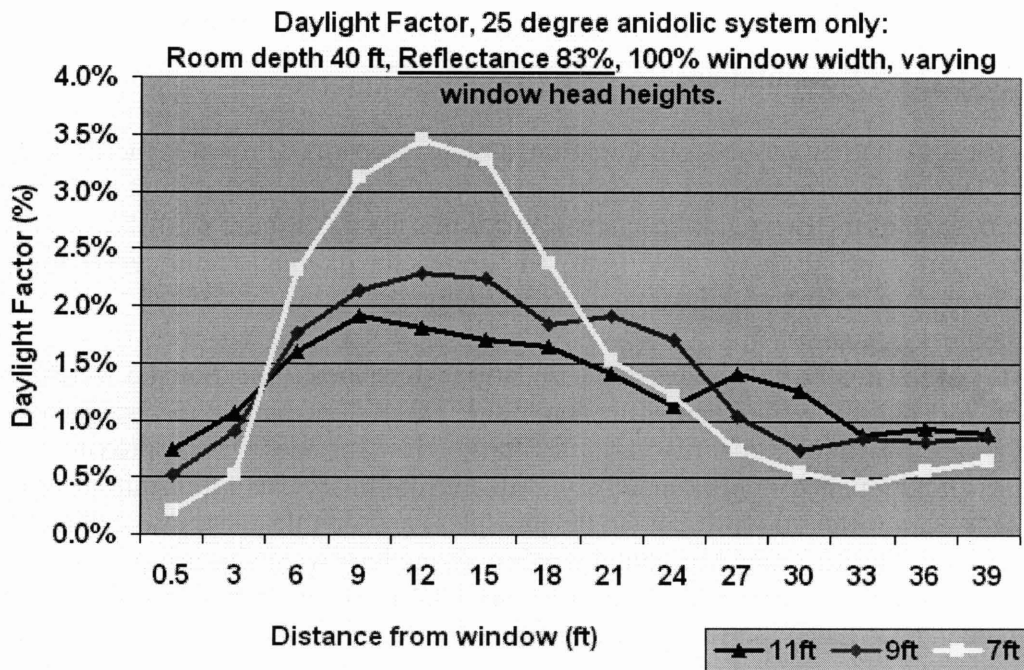


FIGURE 4.12: The effect of window head height on the DF distribution from an anidolic system in a room with very high wall and ceiling reflectance.

Because two of the variable values for room depth are quite large for unilateral daylighting (30 ft and 40 ft), the first anidolic system designed was one with a characteristic angle of  $25^\circ$ . At this experiment's maximum window head height (11 ft), the peak benefit of this system is around 27 ft from the window. The corresponding system measurements were an exit aperture ( $2a$ ) of 3 ft and a system length ( $L$ ) of 4.58 ft (although part of this length is recessed into the width of the wall). In hindsight, these measurements are probably a little large for the space in question, but can still serve as an interesting comparison to the other system. This second system was designed with a characteristic angle of  $30^\circ$ , an exit aperture of 2.4 ft, and a system length of 3.12 ft.

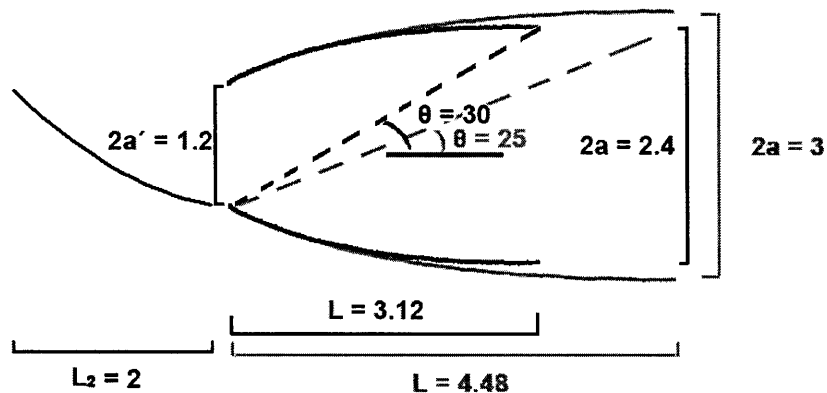


FIGURE 4.13: Schematics for the two anidolic systems used in this thesis.

#### 4.5 RADIANCE simulations

For each distribution variable combination, a plain, rectangular room is modeled using the RADIANCE software, and daylight factor profiles are calculated, first with, then without, each of the two anidolic systems described above. Figure 4.14 shows some sample room configurations, and Figure 4.12 shows the daylight factor curves for a specific room with and without an anidolic system.

In terms of the quantity variables, the simulations described in Section 4.3 were done without an anidolic system and with each of the two designed anidolic systems over the range of each particular quantity variable. Large glass surfaces were approximated as an array of smaller panes, approximately one square foot in area, and transmittances of 90% and 73% were meant to represent single pane glass and double pane, low-e glass respectively. Vertical and horizontal window frame bars were simulated every foot, and the bar thicknesses were 0.1 ft, 0.2 ft, 0.3 ft, and 0.4 ft (which correspond to the frame area percentages listed in the definition of variables). The effect of changing window area was studied by extending the bottom sill of the window up or down one or two feet at a time. Altitudinal urban masking was simulated by adding a cylindrical wall centered at the midpoint of the window façade (see Figure 5.7b). The cylindrical wall was 165 ft in radius and of a height which corresponded with the prescribed altitudinal masking angle, as measured from the window head height. The angular percent error between the

top and bottom of the window was 9% or less for the 100% window width and 15% or less for the 60% window width. The reflectance of the wall, and of the ground plane in front of it, was 20%, which is a widely accepted estimation for ground and surrounding reflectance (see Section 2.3). The purpose of the quantity variable simulations is to try to find definable trends related to the variable change which can be applied to any situation. Because of this, it is unnecessary to repeat the massive quantities of simulations done for distribution variable analysis.

The RADIANCE material definitions for each surface used in the simulations can be found in Appendix B, as can the geometry files for a sample anidolic system. The sky used in each simulation was a standard CIE overcast sky with a horizontal global illuminance of 10,000 lux, which is common when calculating daylight factor. The RADIANCE simulation parameters are listed in Table 4.2 below. In the case of both distribution and quantity variables, the parameters not listed may be assumed to be program default values. Most of these parameters have to do with direct light sources, and so it was felt that they were not applicable.

The number of ambient bounces listed (-ab) is uncommonly large for a normal radiance simulation. When implementing an anidolic system, however, one needs to make sure that after the light has bounced a couple times between the mirrors, there are still enough bounces left to make an adequate representation of the light distribution inside the room. Testing showed that ten bounces was even significantly different from eight or nine bounces. As for the ambient resolution (-ar), the scene size for the adjustable room is 67.5 ft, and divided by the ambient resolution of 128, that makes the scene resolution approximately 0.5 ft.

In the case of quantity variables, the ambient divisions and the ambient resolution were doubled, in the interests of increasing accuracy, and because fewer simulations could afford more simulation time. The window frame and urban masking simulations in particular required more resolution, because the space between the window frames were often smaller than half a foot, and because adding an exterior masking wall increased the scene size by at least a factor of two.

**TABLE 4.2: RADIANCE Parameter Values Used in Simulation**

<b>Distribution RADIANCE Parameter</b>	<b>Value</b>
-ab	10
-aa	0.1
-as	64
-ar	128
-ad	1024
<b>Quantity RADIANCE Parameter</b>	<b>Value</b>
-ab	10
-aa	0.1
-as	64
-ar	256
-ad	2048

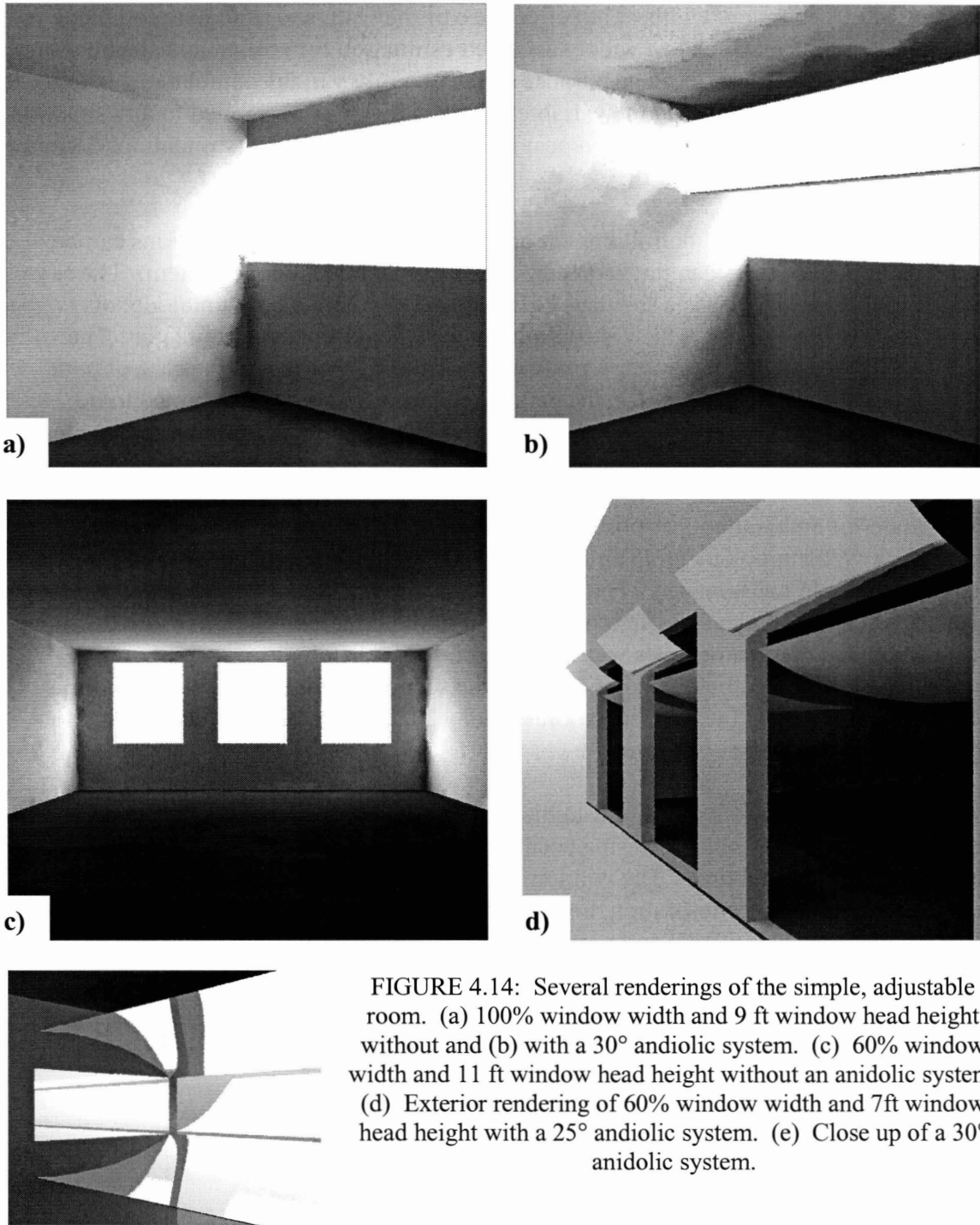


FIGURE 4.14: Several renderings of the simple, adjustable room. (a) 100% window width and 9 ft window head height without and (b) with a 30° andiolic system. (c) 60% window width and 11 ft window head height without an andiolic system. (d) Exterior rendering of 60% window width and 7ft window head height with a 25° andiolic system. (e) Close up of a 30° andiolic system.

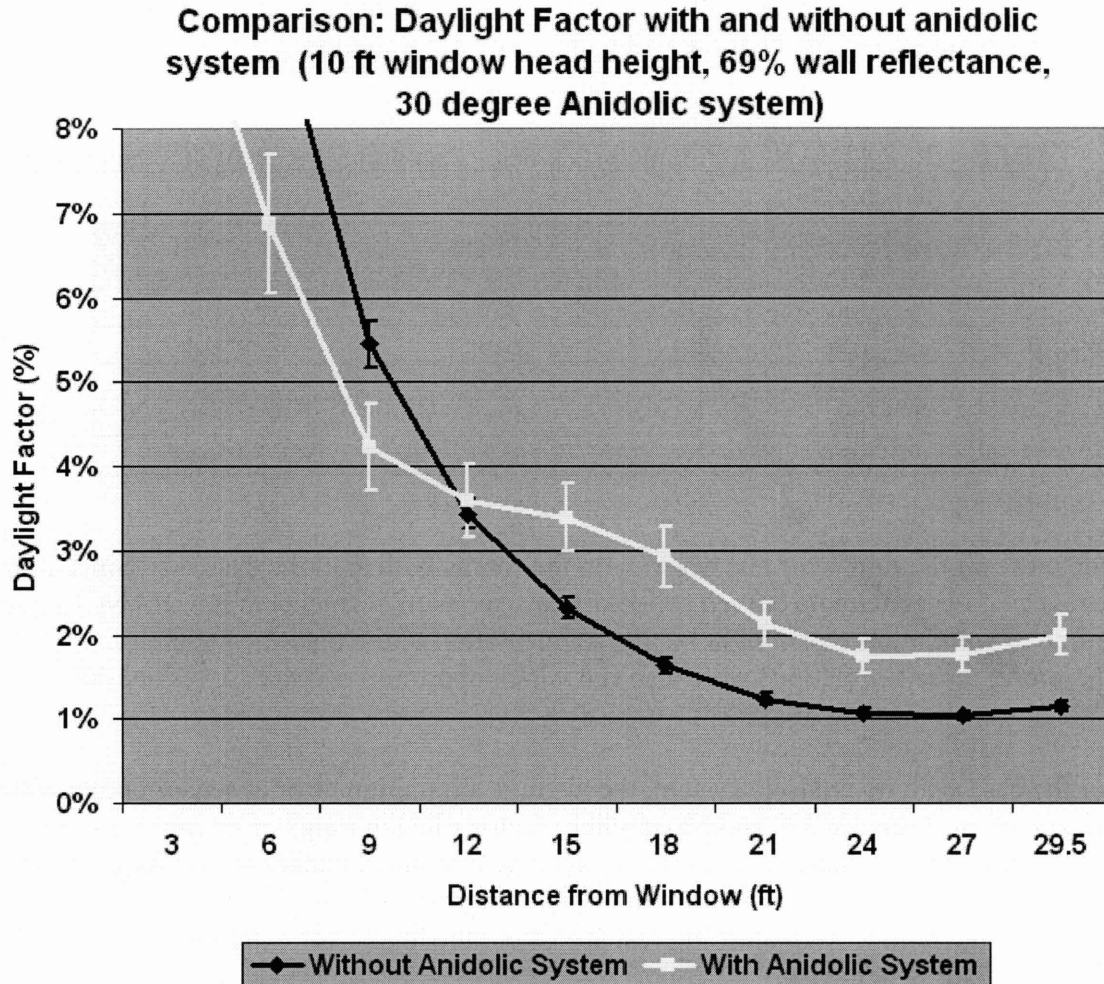


FIGURE 4.15: Daylight factor comparison before and after adding an anidolic system to a sample room. For explanation of error bars see Section 4.6.

#### 4.6 RADIANCE Simulation Error

Although some of the simulation parameters (such as “ambient bounces”) used exceed the values for “accurate” renderings, as given on the RADIANCE website [RAD web], others were kept slightly lower as a compromise to shorten calculation time. In order to quantify the possible error of these parameter choices, the parameters that were not already high accuracy were increased, and three simulations, representing a spread of possible room configurations, were calculated using the more accurate parameters. The room configurations tested were {100% window width, 9 ft window head height, 30% reflectance}, {75% window width, 7 ft window head height, 83% reflectance}, and {60% window width, 11 ft window head height, 55% reflectance}. All three rooms were 40 ft deep, in order to test the effects of different parameters on deeper spaces, and simulations were done for both situations with and without anidolic systems. A comparison of the recommended simulation parameters from the radiance website, and the ones used in

error analysis can be seen in Table 4.3. In the case of all parameters except for “-aa” (ambient accuracy), the higher the value, the more accurate it is.

TABLE 4.3: RADIANCE Parameter Values – “accurate” vs. error analysis values

RADIANCE Parameter	"accurate" recommendations	error analysis
-ab	2	10
-aa	0.15	0.1
-as	256	256
-ar	128	512
-ad	512	2048

One more simulation error test was run on the rooms with anidolic systems. Since it is necessary to approximate curved reflectors as a series of segments in RADIANCE, one source of simulation error might be this segmentation of the anidolic geometry. Therefore, three simulations were also run which approximated the curves at 1000 segments each, instead of 50.

For the case with no anidolic system, the average simulation error at sensor points with measurements between 1% and 5% daylight factor (the DF range of interest) was  $\pm 5\%$ . For the case with an anidolic system, the average combined parameter and segmentation error was  $\pm 12\%$ . Since the measure of good daylighting is a minimum daylight factor threshold, the points of greatest interest are where the high error extreme crosses the 2% daylight factor benchmark.

As discussed in Section 2.3, the error of a RADIANCE model as compared to real life can be as little as 5% to 10% or as much as 50% – the former as found by Mardaljevic’s simulations of the BRE dataset under accurate skies and the latter as found by Ng’s simulations of a Singapore office building under a CIE sky [NG 2001, MAR 1995, 2004]. Not only is this thesis using a CIE sky, but the rooms tested are minimal boxes rather than detailed and realistic models. This is an advantage in the fact that the results will apply to all situations equally (without reference to location, orientation, weather, or furnishings), but a disadvantage in the fact that the possible divergence between the RADIANCE model and a real room is difficult to predict (although it is probably closer to Ng’s findings than Mardaljevic’s because of the use of the CIE overcast sky and the lack of model detail). Fortunately, the results sought are not absolute illuminances, but recommendations as per a system’s applicability to a general situation. In light of this, the error shown on subsequent daylight factor curves will merely be the simulation parameter error (5% for no anidolic system and 12% for anidolic system) rather than some approximation of general simulation error. Furthermore, general simulation error tends to be heavy on the negative error, because most models overestimate illuminances. This thesis tends to be more interested in the positive error, thus providing one more reason to ignore general simulation error for the moment.

## 4.7 Data Analysis

The result of simulating every distribution variable combination is 1125 daylight factor profiles, which begs the question, how do we analyze this massive data set? One possibility is to give results as average daylight factor percent increases (such as are pictured in Figure 5.10a), but this gives no idea of the absolute level of daylighting, either before or after the anidolic system is installed. With this in mind, another 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. Certainly, daylight autonomy has the advantage of being truly quantifiable in terms of percent of year illuminance levels autonomy from electric lighting. One can also argue that it is important to look at the daylight glare index (DGI) and assess the quality of light, but this thesis uses daylight factor as a primary metric, so the easiest way to relate “good daylighting” to the results is to chose a minimum threshold daylight factor. As such, this thesis has adopted 2% daylight factor as that minimum benchmark, because it the number used by the Green Building Council’s LEED Rating System [LEED web]. For each variable combination, the expected improvement caused by the addition of an anidolic system is the ratio:

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

The daylight factor profile is acquired from the central axis of the room in question, and if it is assumed that this profile remains relatively constant along the width of the room, the ratio above is the expected increase of floor area with the addition of an anidolic system. These expected improvements can then be compared to those of other variable combinations in the medium of a contour chart or other graph (see Figure 5.1 and Appendix A).

Graphically, the expected improvement of the particular room represented by Figure 4.16 is the ratio of the light shaded area to the dark shaded area, which is defined by the points where the each curve’s positive error value crosses the 2% daylight factor line. The characteristic peak in the light daylight factor curve occurs approximately 15 to 18 feet from the window. 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 4.16 has a depth of 30, a window head height of 10 ft, a wall and ceiling reflectance of 69%, and a window width of 100%. The anidolic system used has a characteristic angle of 30°. The expected improvement for this configuration is 1.57, meaning that one should expect the original daylit workplane area (originally 56%) to increase its original value by another 57%. In other words,  $0.56 \times 1.57 = 87.9\%$ , which is the final area of the workplane above 2% daylight factor.

**Comparison: Daylight Factor with and without anidolic system (10 ft window head height, 69% wall reflectance, 30 degree Anidolic system)**

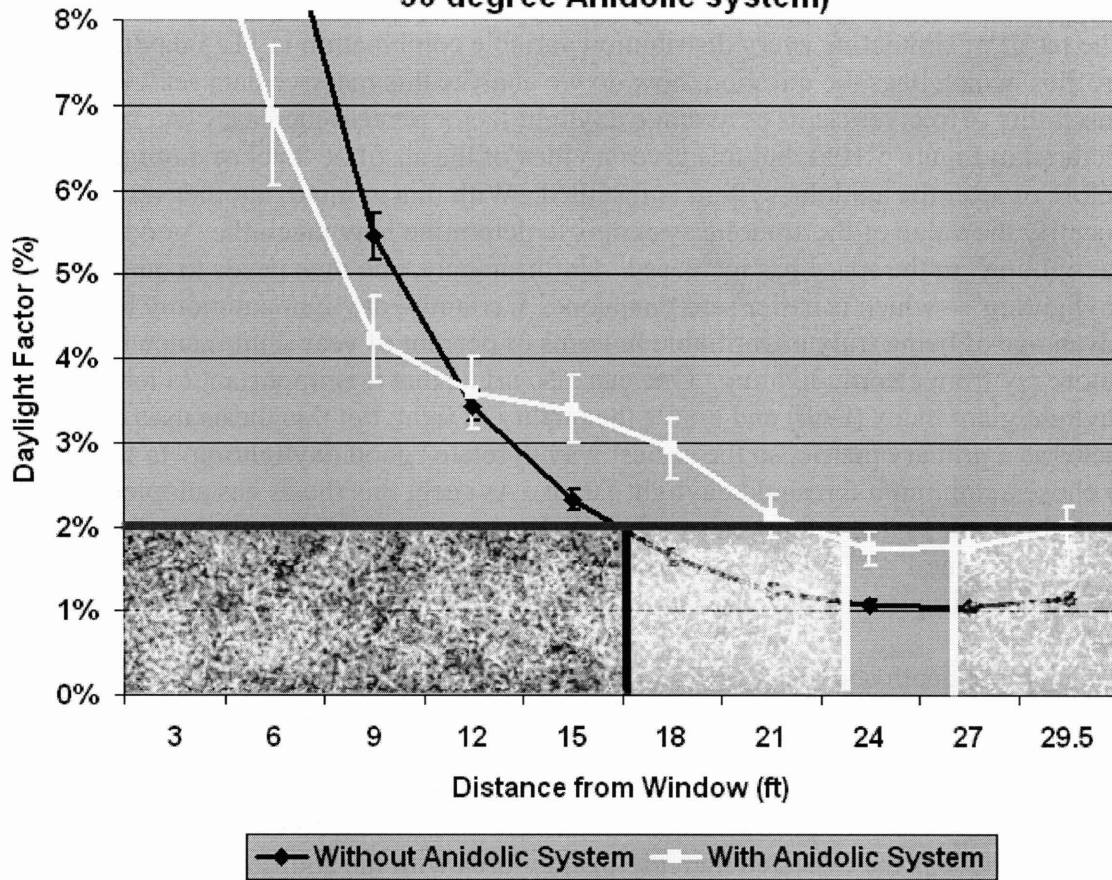


FIGURE 4.16: The same daylight factor curves represented by Figure 4.15. The Expected Improvement is the ratio of the light shaded area divided by the dark shaded area.

## 5 RESULTS

### 5.1 Distribution Variables: detailed contour graphs

To facilitate analysis, the expected improvement results (see Section 4.7) are displayed on contour graphs, where each point represents one specific combination of distribution variables. “Room depth” and one other distribution 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 workplane 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. The graphs representing rooms depths of 20 and 30 feet show these contours for absolute floor areas of 50%, 75%, and 95%, while the graph representing a room depth of 40 feet shows 30%, 40%, 50%, and 60%.

Figure 5.1a, for example, describes a room that is 20 ft in depth with an 8 ft window head height and single pane glass. The expected daylighting improvement caused by the addition of a 30° anidolic system is shown over the full spread of both total window width and interior reflectance. It is important to note that the graphs are not a floor plan of one room, but represent the expected improvement values from twenty-five different rooms with contour lines extrapolated between these values. For example, a room with 75% window width and 50% interior reflectance shows an expected improvement of 1.55, which means that the addition of the previously mentioned anidolic system should increase the daylit area of the room by 55%. The chart also tells us that this theoretical room, which would originally have had less than 75% of the floor area above 2% daylight factor, should be 100% daylit after the addition of this anidolic system. In other words, if this room remains exactly the same, it is well worth installing an anidolic system.

On the other hand, with a little creativity, we can see that merely painting the walls and ceiling white (and making sure that they are largely unobstructed) is another way to raise this particular room above 2% daylight factor. The spot on the contour graph corresponding with 75% window width and 83% interior reflectance has an expected improvement of 1.0. By noting the dotted contour lines, we can also see that the room was entirely above 2% daylight factor before an anidolic system was added. This is possible because the theoretical room in question is quite a shallow one, whereas one can see that it is still worth adding an anidolic system to a similar room which is 30 ft deep (see Figure 5.1b).

Beyond specific combinations of variables, the contour graphs (more of which can be seen in Appendix A) allow one to notice general trends. For instance, the two graphs in Figure 5.1 illustrate that a more consistent, though perhaps less dramatic, improvement value can be expected in the deeper room than in the shallower room. The two graphs in Figure 5.2 illustrate the need for higher internal reflectance to make an anidolic system worthwhile when the transmission of the window glass is lowered.

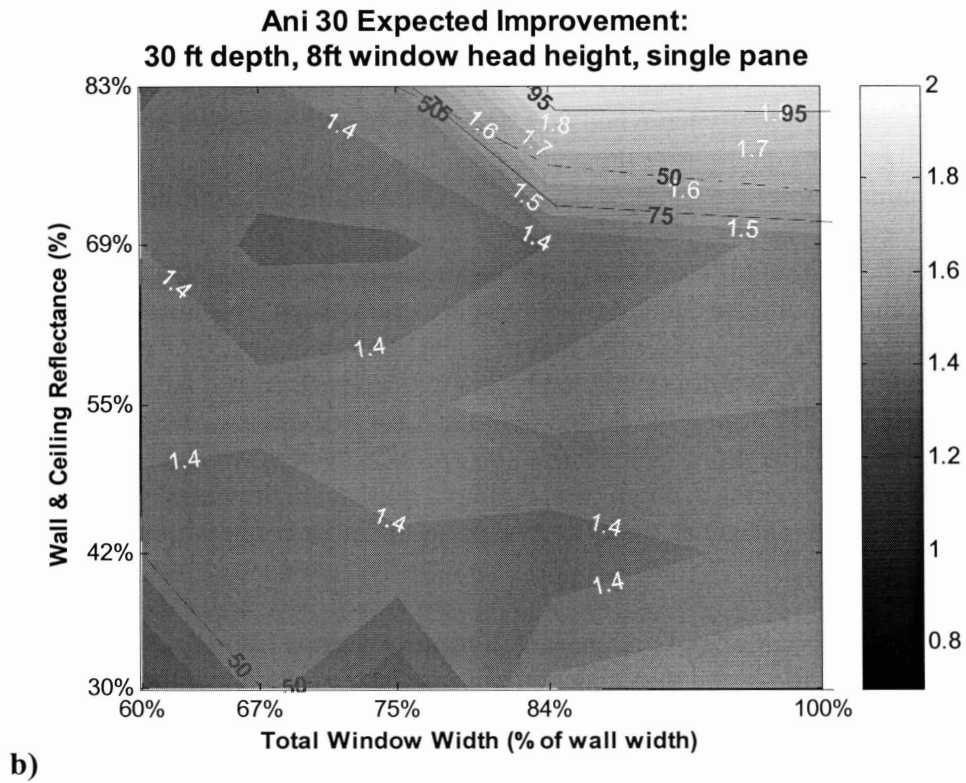
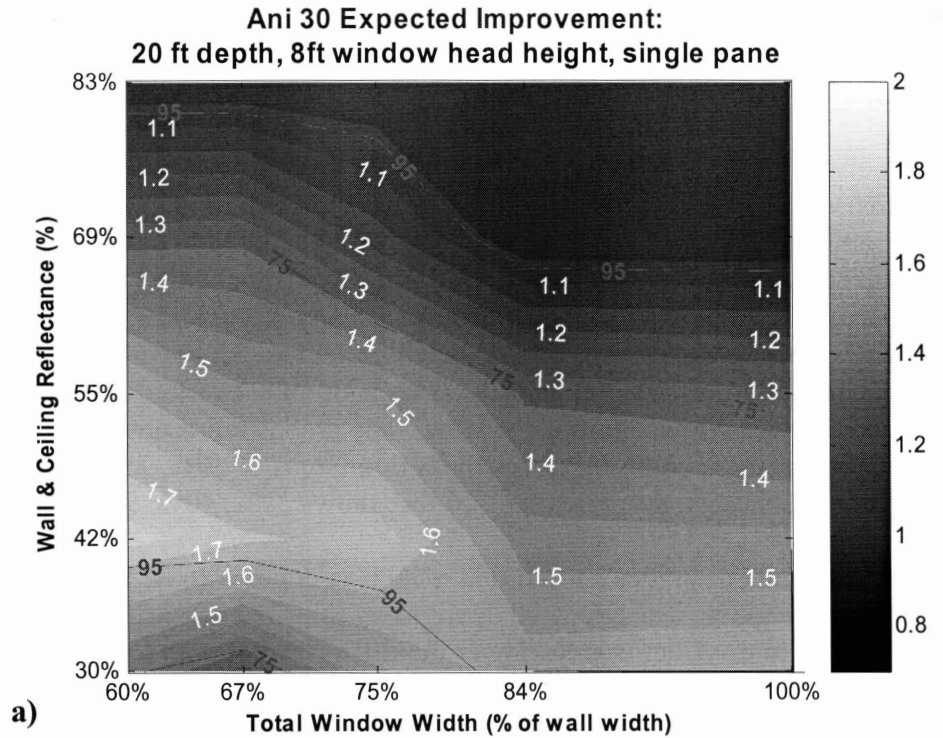


FIGURE 5.1: (a) A sample contour graph representing a room that is 20 ft in depth with an 8 ft window head height and single pane glass. (b) The same room represented in (a), but with a depth of 30 ft. More contour graphs are shown in Appendix A.

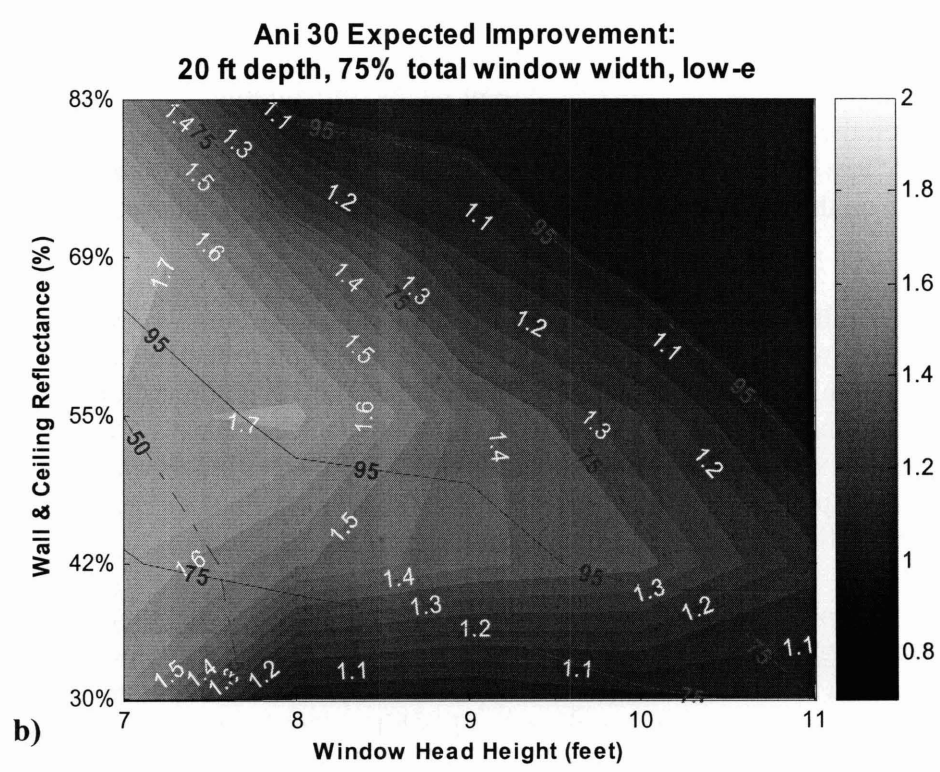
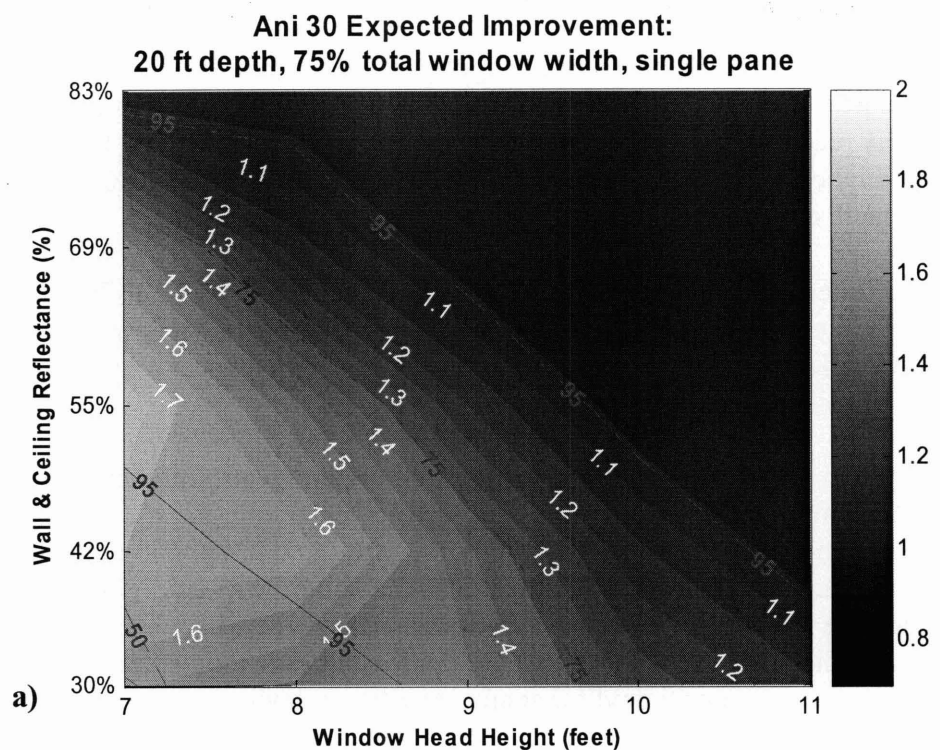


FIGURE 5.2: (a) A sample contour graph representing a room that is 20 ft in depth with a 75% total window width and single pane glass. (b) The same room represented in (a), but with double pane, low-e glass. More contour graphs are shown in Appendix A.

On close analysis of these results, several observations can be made in conjunction with the variable “room depth”. Forty feet was slightly too deep for these particular anidolic systems to handle the entire floor space; with an anidolic system, the amount of daylight floor area rarely reached or exceeded 60%. An expected improvement of 1.5 (50% gain) was about the highest achieved, but there was a fairly even gain of 25-40% daylight area over most variable combinations, which is still a significant increase.

The 30 and 20 ft deep spaces were able to get improvements of 1.75 to 2 (75-100% floor area gain) under the right circumstances, and 50 to 65% floor area 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 increases deeper daylight levels, 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 increase 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 reach the 2% benchmark. The second reason is caused by what can be called “the point of diminishing returns.” Applicable to the shallower rooms, this implies the original space is already so well daylit that any increase in daylight floor area would be literally truncated by the lack of floor area. This phenomenon becomes very noticeable when the space without anidolics is already over 75% daylit, (the upper part of the contour graph in Figure 5.1a 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 the benchmark for “good” daylight factor. An anidolic system might take a space for which the daylight factor is always above 2% and raise the daylight factor levels above 5%, which could be seen as a more desirable result, but would still be “no improvement” on this contour graph, as the original rooms had already reached the benchmark.

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.

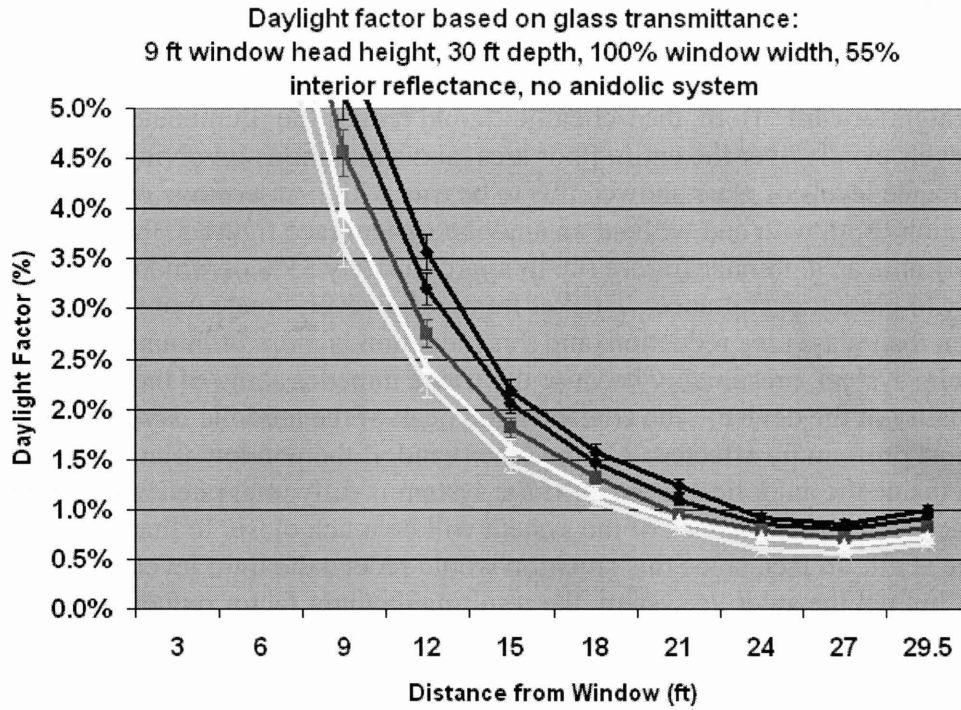
The variable values that give the best improvement are similar to what would be expected of good daylighting design, with a few exceptions. In accordance with good daylighting design, higher wall reflectance and greater window width produce better results. The only exception in these cases is when the 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.

## 5.2 Quantity Variables

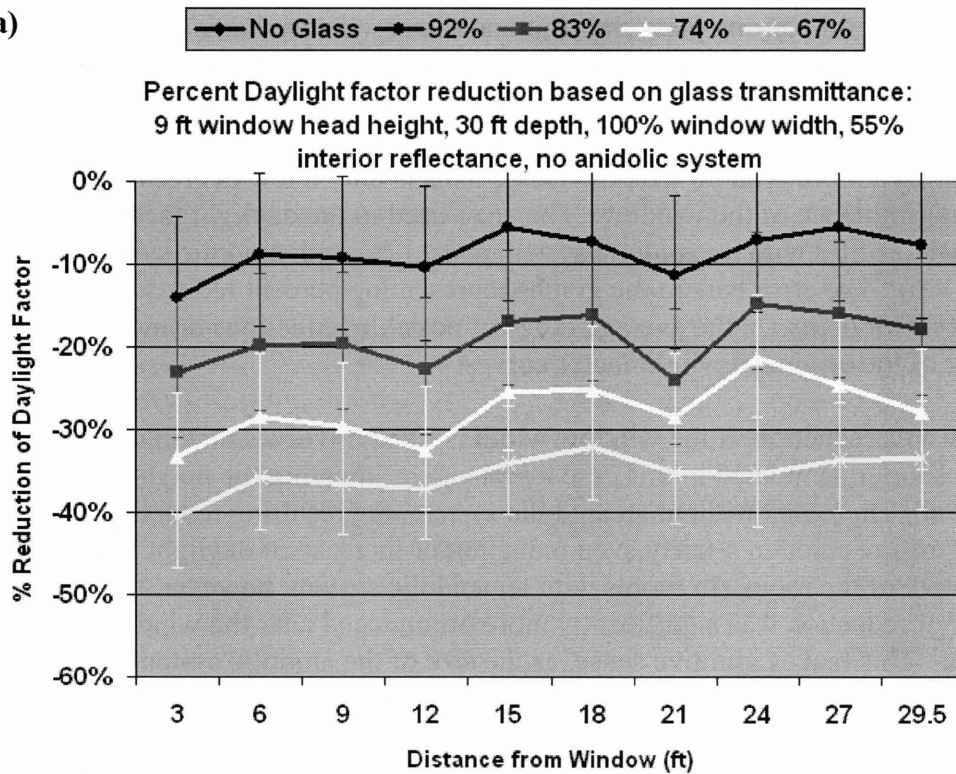
Of the four quantity variables studied, glass transmittance and window frame area are the most straightforward. Both, theoretically, should reduce the illuminance or daylight factor levels evenly over the entire floor area, and simulations involving varying transmittance levels of glass showed this to be true within an average of  $\pm 5\%$  deviation for situations both with and without an anidolic system (see figure 5.3b). In the case of window frame area, thinner frames (up to approximately 35% of window area) behave similarly to glass transmittance. Thicker frames, however, create more light level reduction than glass area reduction, and this reduction is more pronounced in the case of an anidolic system, presumably because the frame impedes some of the geometric functionality of the device. The characteristic peak of the anidolic daylight factor curve is the most profoundly affected. On the other hand, if the window frame is removed from the area inside the anidolic system, or if the system is fully integrated and becomes part of the façade, the performance of the system will be much closer to that of a window with no frame at all. In fact, since this situation would reduce the light levels from the view window but not the anidolic system, the resulting daylight factor reduction would be more like varying the window area.

Figures 5.3 through 5.6 show both the daylight factor curves and percent reduction of daylight factor for varying glass transmittances and window frame areas. For instance, in Figure 5.4 one can compare the daylight factor curve of 74% transmittance glass to a room with no glass, and then observe, in Figure 5.4b, that the percent reduction in daylight factor hovers around 29%, suggesting a daylight factor that is 71% of the curve representing a room with no window glass. This is only a few degrees different from the actual transmittance of the window. The error used in the daylight factor graphs is  $\pm 5\%$  for the DF profiles with no anidolic system and  $\pm 12\%$  with anidolic system included (see Section 4.6). The error bars in the graphs representing percent reduction or increase in daylight factor delineate the average range of possible reductions or increases based upon the error of the original daylight factor curves.

Window area reduction, if the window width is fixed, involves making the view window taller or shorter, simulated in this case by raising or lowering the height of the lower window sill. In rooms without an anidolic system, the resulting reduction or increase in window area resulted in a fairly even reduction or increase of daylight factor for the entire depth of the room. In rooms with an anidolic system, however, the daylight factor increase or reduction was significantly more pronounced near the window than deeper in the room. This makes intuitive sense, as the size of the anidolic system has not been affected, and the contribution of the view window to the daylight factor near the window façade is far greater than its contribution to the deeper spaces in the room. It must also be noted that the subsequent increase or reduction in average daylight factor is not a linear or 1-1 relationship with the increase or reduction of the window area. In fact, the percent change of daylight factor is smaller than the percent change of window area in all cases, and the increase or decrease in benefit starts falling off as the window area gets larger, thus establishing a kind of diminishing returns for window size (see Figure 5.7). From the results shown below, one can recommend a view window beneath the anidolic system

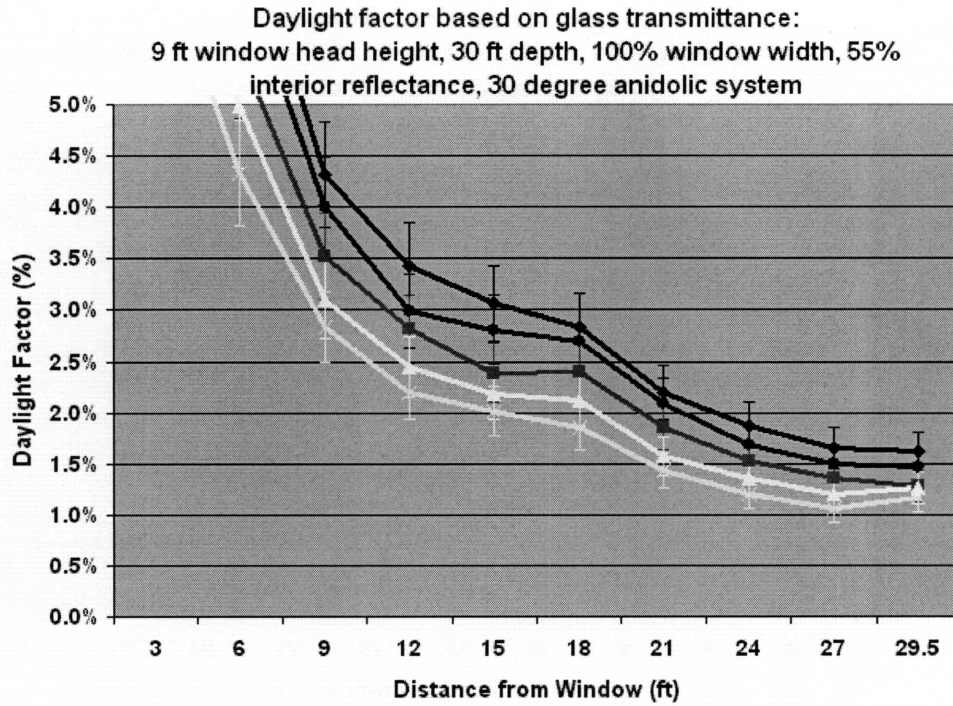


a)

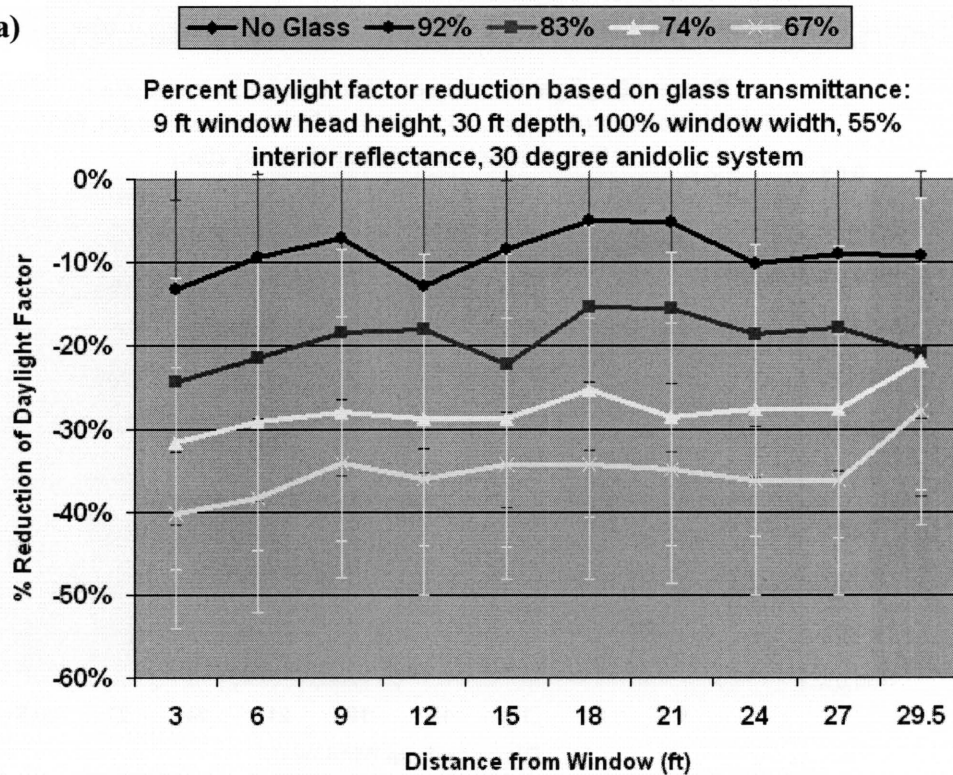


b)

FIGURE 5.3: These two graphs characterize the reduction of daylight factor due to glass transmittance in a room with no anidolic system. (a) shows the resulting daylight factor profiles, and (b) shows the % daylight factor reduction from a window with no glass.



a)



b)

FIGURE 5.4: These two graphs characterize the reduction of daylight factor due to glass transmittance in a room with a 30 degree anidolic system. (a) shows the resulting daylight factor profiles, and (b) shows the % daylight factor reduction from a window with no glass.

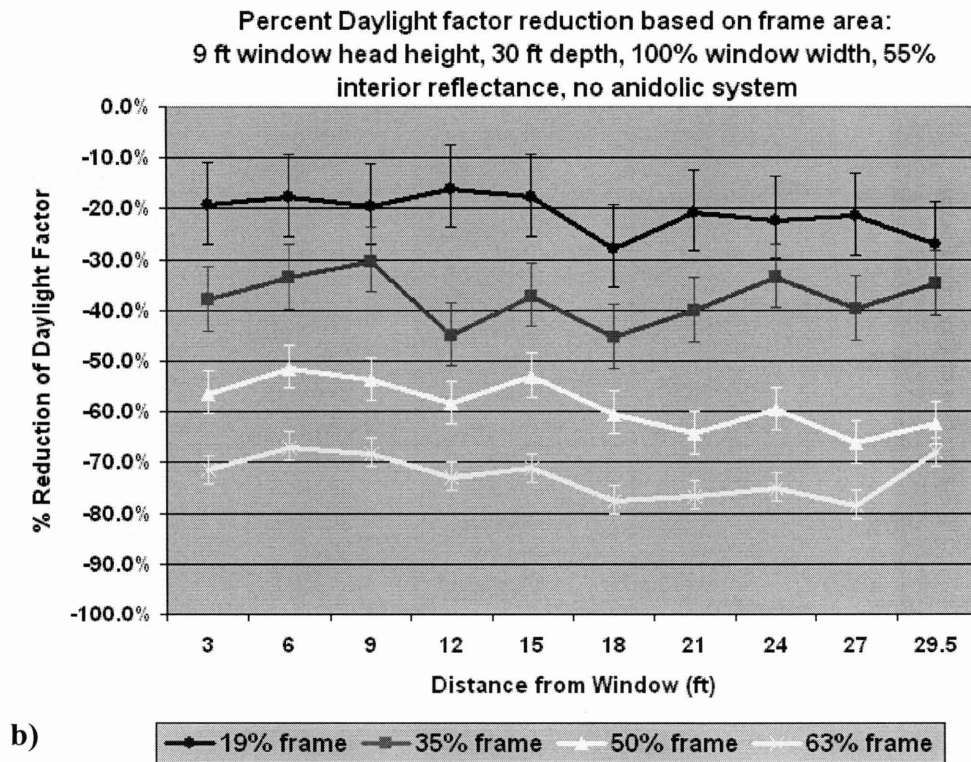
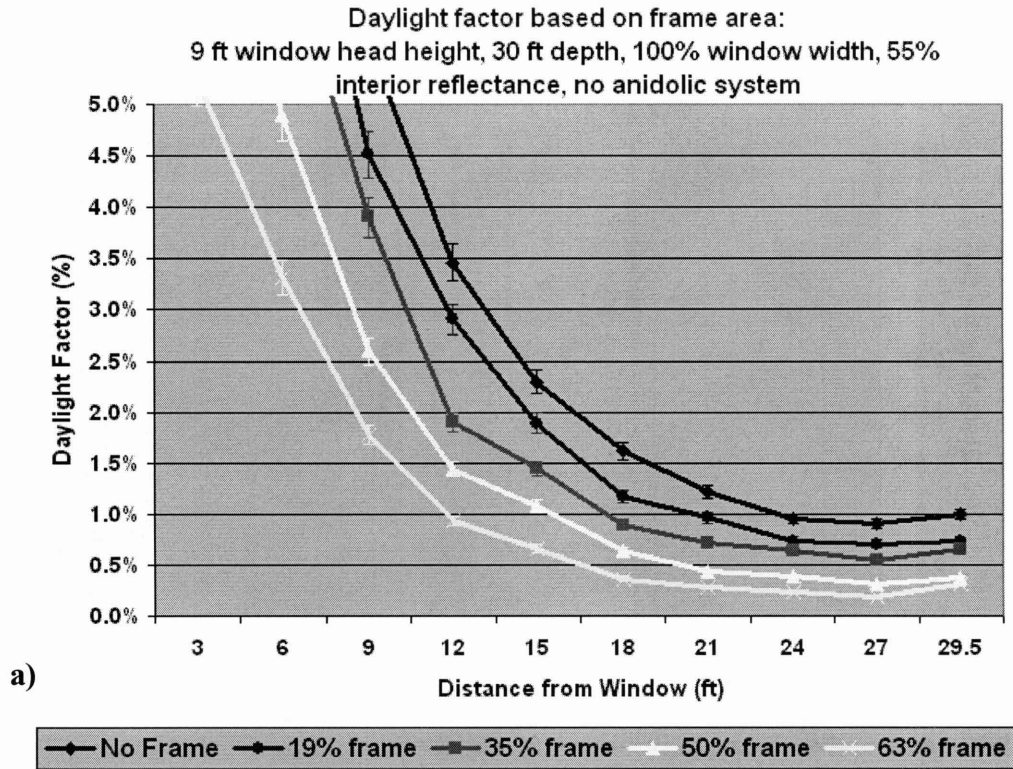


FIGURE 5.5: These two graphs characterize the reduction of daylight factor due to frame area in a room with no anidolic system. (a) shows the resulting daylight factor profiles, and (b) shows the % daylight factor reduction from a window with no frame.

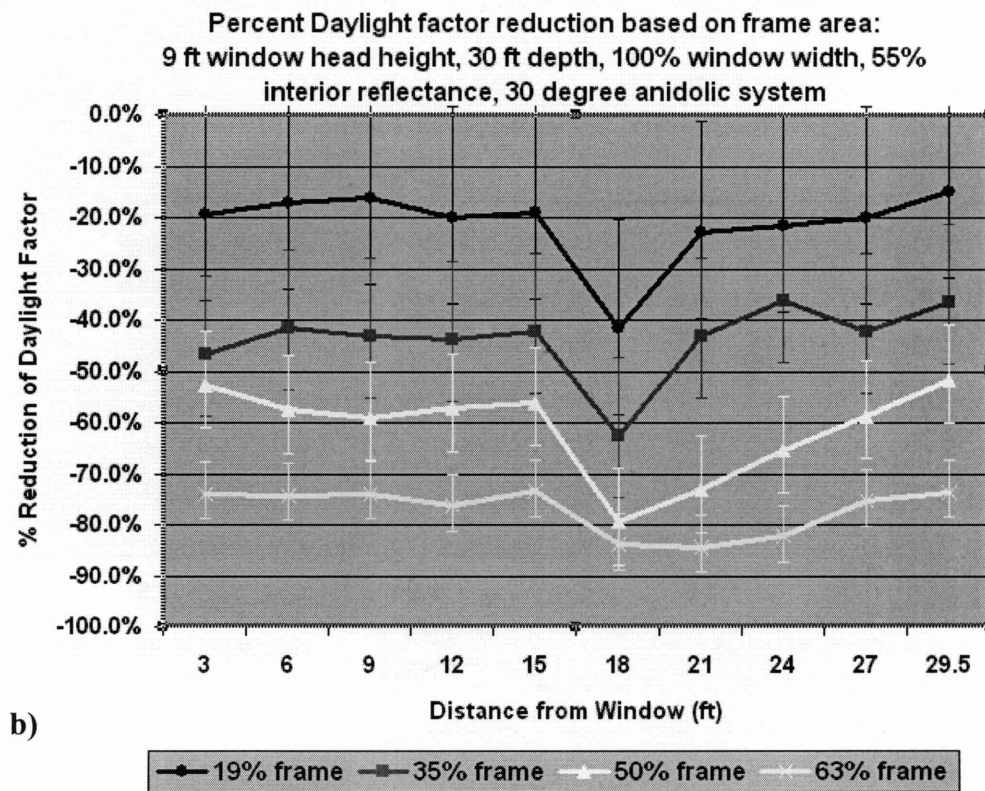
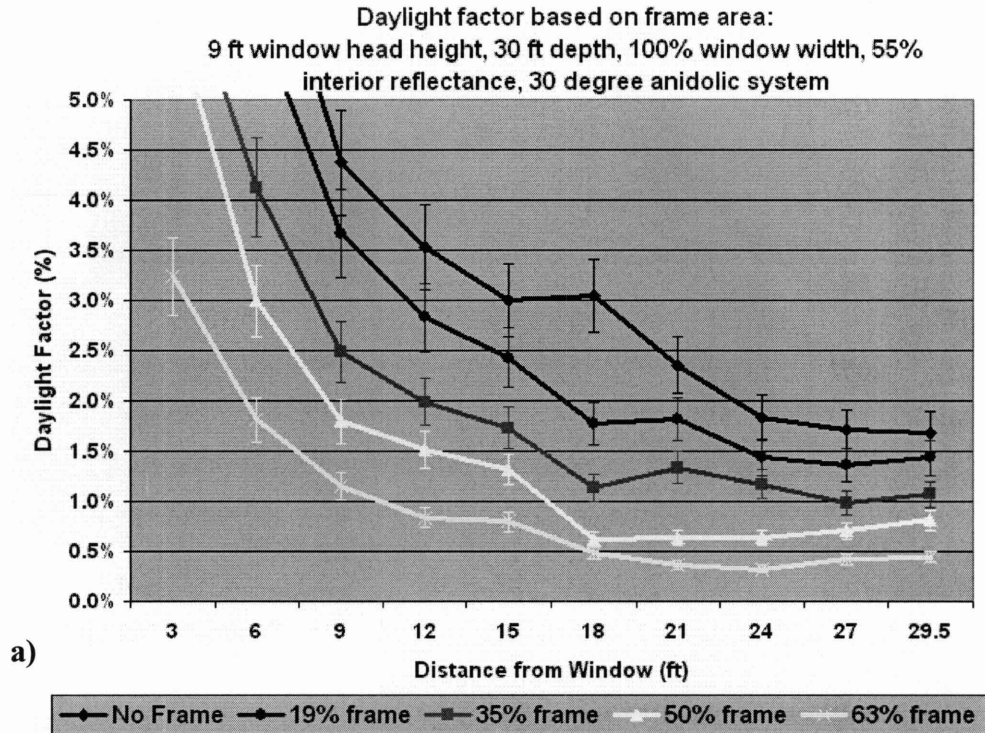
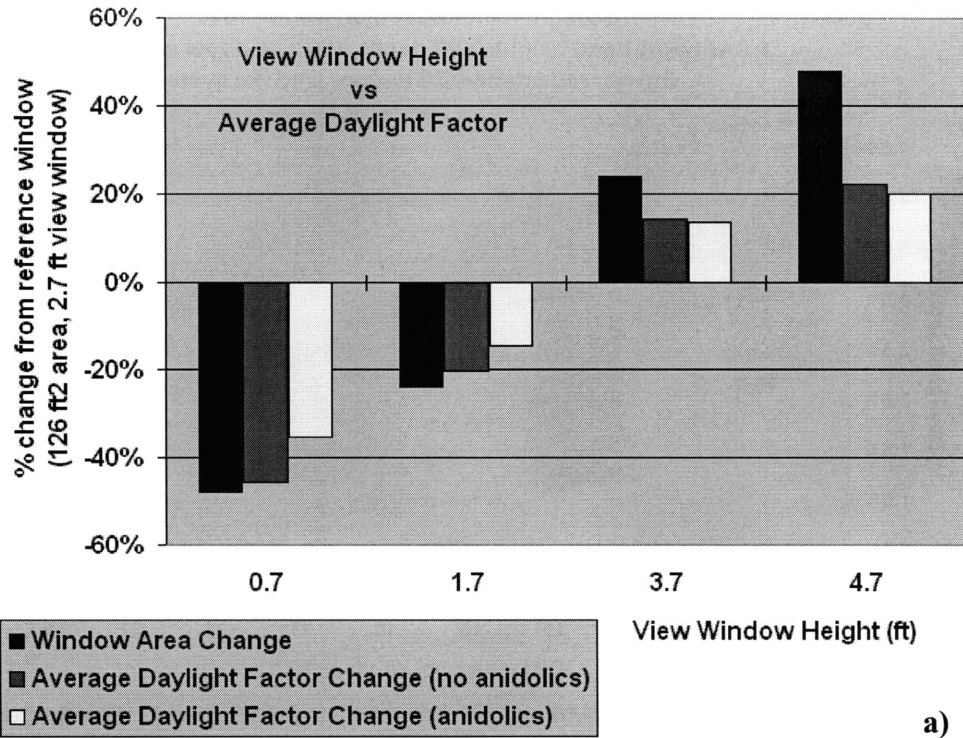
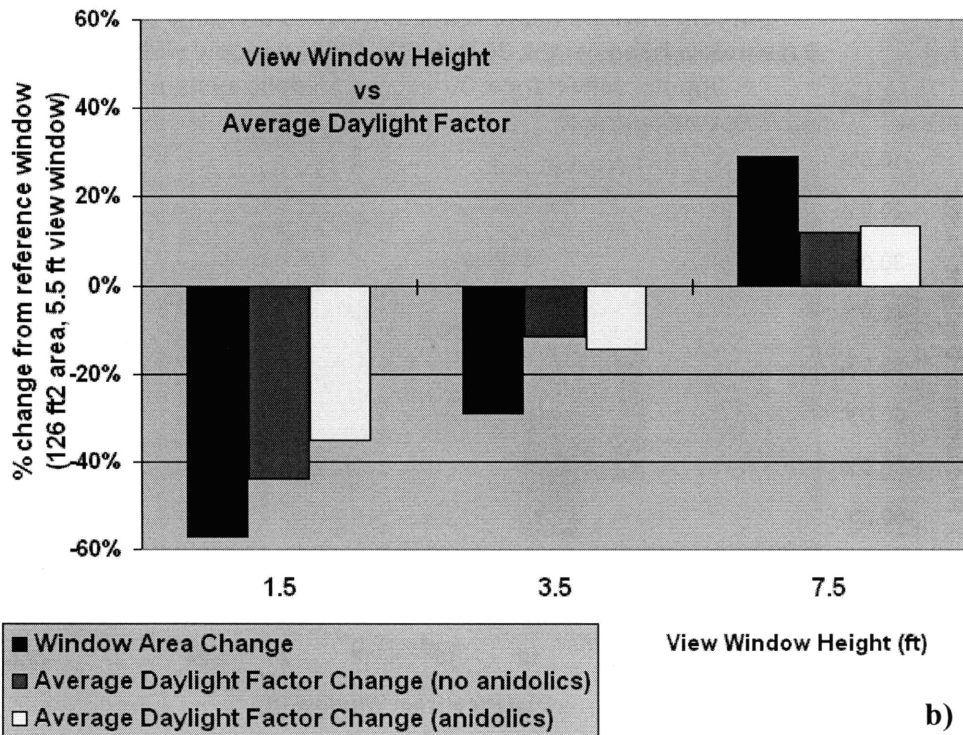


FIGURE 5.6: These two graphs characterize the reduction of daylight factor due to frame area in a room with a 30 degree anidolic system. (a) shows the resulting daylight factor profiles, and (b) shows the % daylight factor reduction from a window with no frame. Notice the impact of the frame on the peak of the anidolic daylight factor curve.



a)



b)

FIGURE 5.7: These two graphs compare the window area change to the average change in daylight factor. (a) represents a room of similar configuration to those represented in Figures 5.3 – 5.6 (100% window width) while (b) represents a similar room with 60% window width. Notice how, when the view window height on either window is greater than 3 ft, the same change in window area causes less change in overall daylight factor.

of at least 2.5 to 3 ft in height. When the window is made shorter than this, not only does the decrease in daylight factor begin to more closely mirror the decrease in window area, but the view outside becomes severely restricted, which causes problems in terms of the occupant's long-view and connection to the outdoors.

Urban masking, in this case altitudinal masking, is the last quantity variable studied in this thesis, and the most complex, because it is not a function of the building façade. Rather than affecting the amount of light transmitted through the façade, it affects the amount of light that reaches the façade by blocking a part of the sky dome. Although the distribution recommendations are based on models with no exterior masking, most building situations have some masking. Anidolic systems are, in some ways, ideally suited to urban or highly masked situations, because they gather light from the sky's zenith. In fact, up to a certain altitude, anidolic systems in masked situations provide a greater improvement than in situations without masking, because they do not depend upon a view of the horizon. Similarly to the issue of window area, however, the loss of light transmission through the view window might lower the overall daylight factor level such that the anidolic system cannot boost the daylight factor above the two percent benchmark. This means that even though the absolute daylight factor is always improved in cases of urban masking (see Figure 5.10a), the "expected improvement" of daylit floor area could be greater or worse than is shown in the contour graphs (Appendix A). It depends largely upon how well the room is designed for daylighting in the first place and how large the masking is. For instance, in Figure 5.11b, which has an interior reflectance of 83%, an altitudinal masking of 30 degrees would still allow for a large expected improvement, yet in that same room with a 30% interior reflectance, the peak daylight factor doesn't come close to 2%. It seems, therefore, that a masked building can enjoy the same or greater expected improvement as an unmasked building, but only when the original daylighting conditions were decent in the first place (i.e. brighter walls, shallower room, long window width, etc).

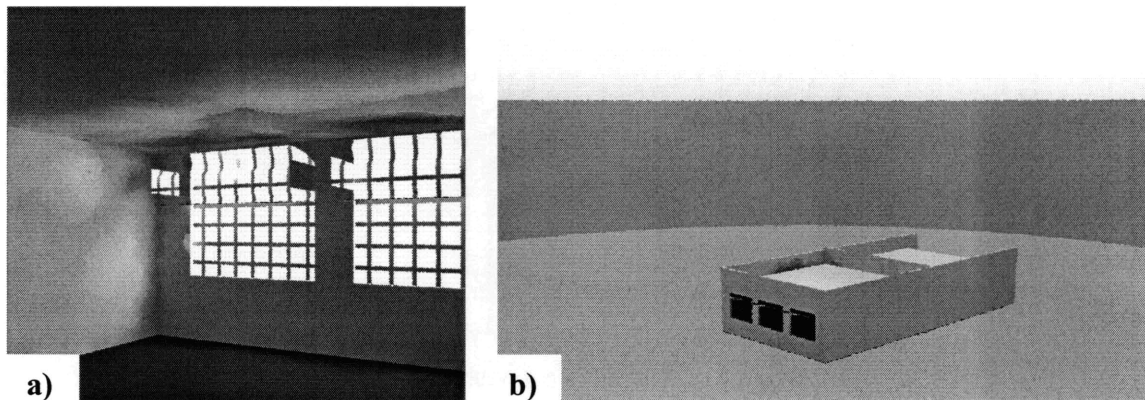
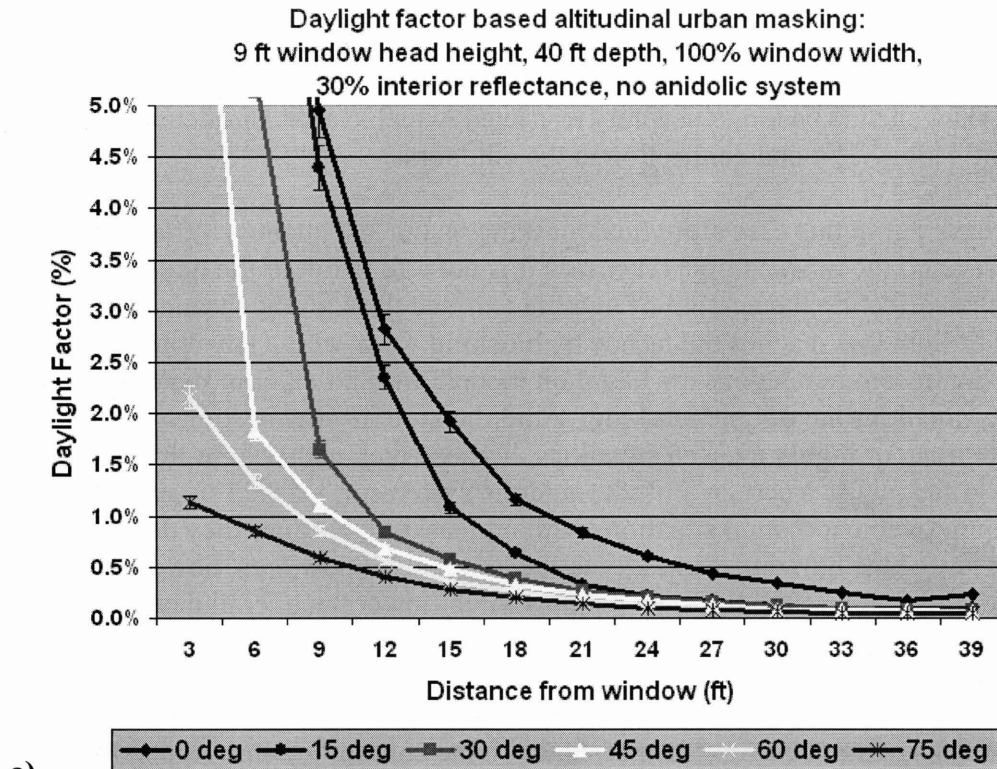
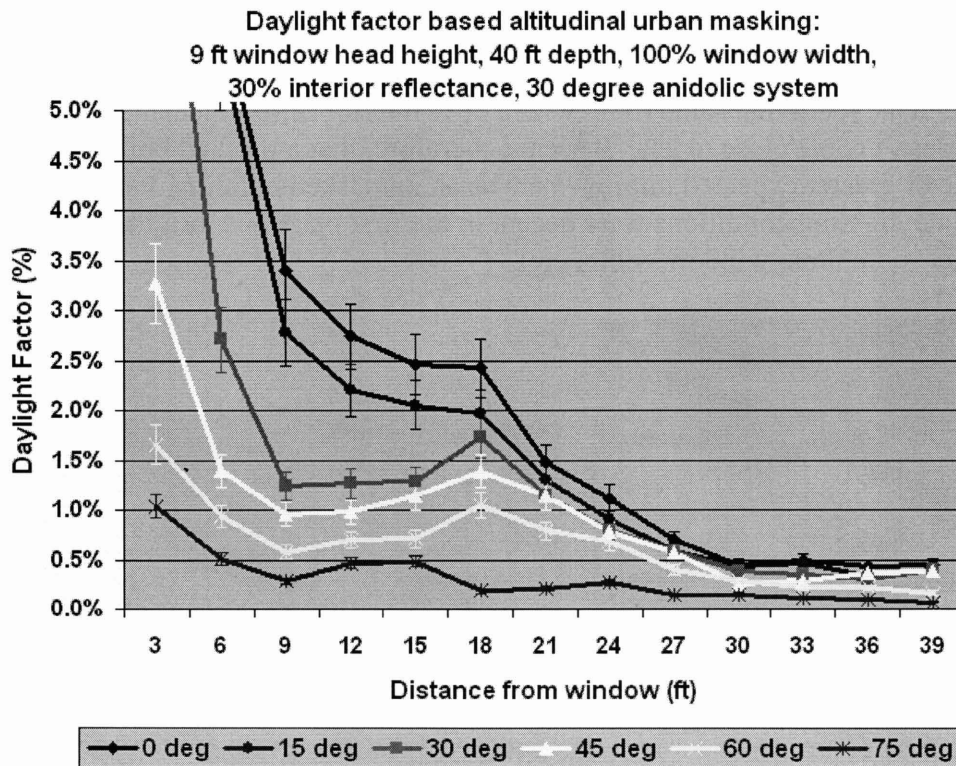


FIGURE 5.8: (a) Rendering of a room with 75% total window width and 19% window frame area with a 30 degree anidolic system. (b) Rendering of a similar room with no window frame area, but a cylindrical wall providing altitudinal urban masking.



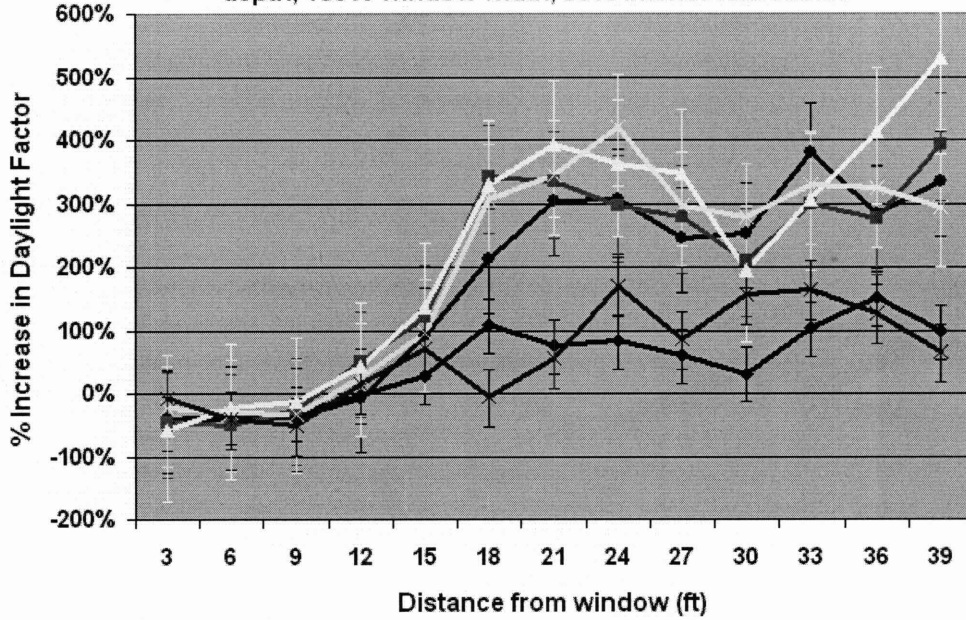
a)



b)

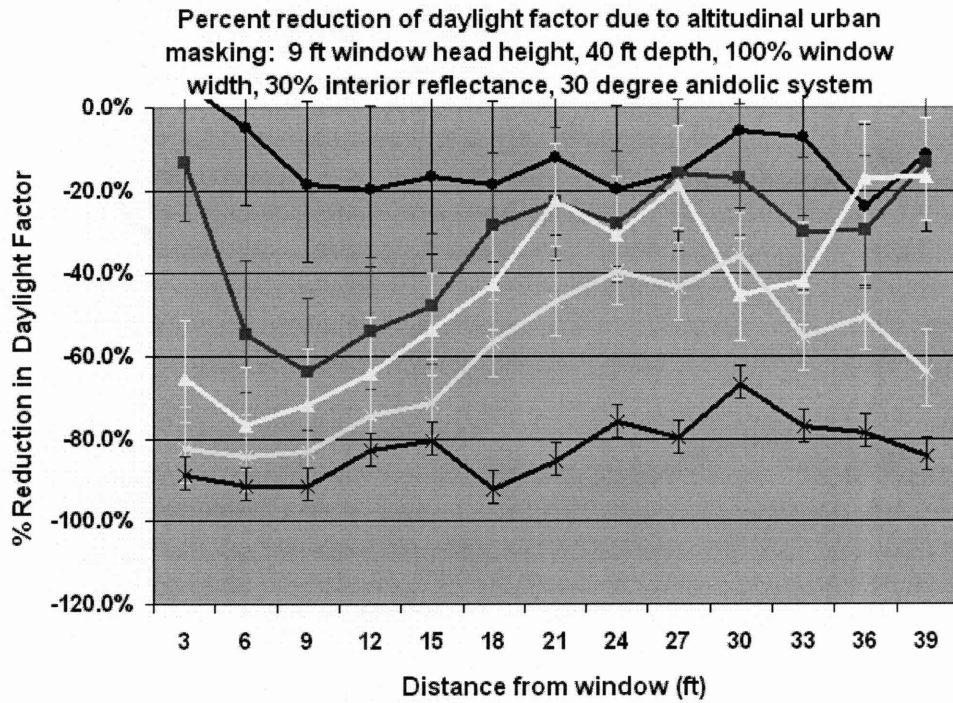
FIGURE 5.9: Daylight factors based on altitudinal urban masking both (a) without and (b) with a 30 degree anidolic system. The room represented has a depth of 40 ft, a window head height of 9 ft, a window width of 100%, and an interior reflectance of 30%.

Improvement of daylight factor due to 30 degree anidolic system based altitudinal urban masking: 9 ft window head height, 40 ft depth, 100% window width, 30% interior reflectance



a)

0 deg 15 deg 30 deg 45 deg 60 deg 75 deg



b)

15 deg 30 deg 45 deg 60 deg 75 deg

FIGURE 5.10: (a) The percent improvement of daylight factor due to the addition of the 30 degree anidolic system. (b) The percent reduction of daylight factor due to the increase in urban masking in the room with a 30 degree anidolic system and interior reflectance of 30%.

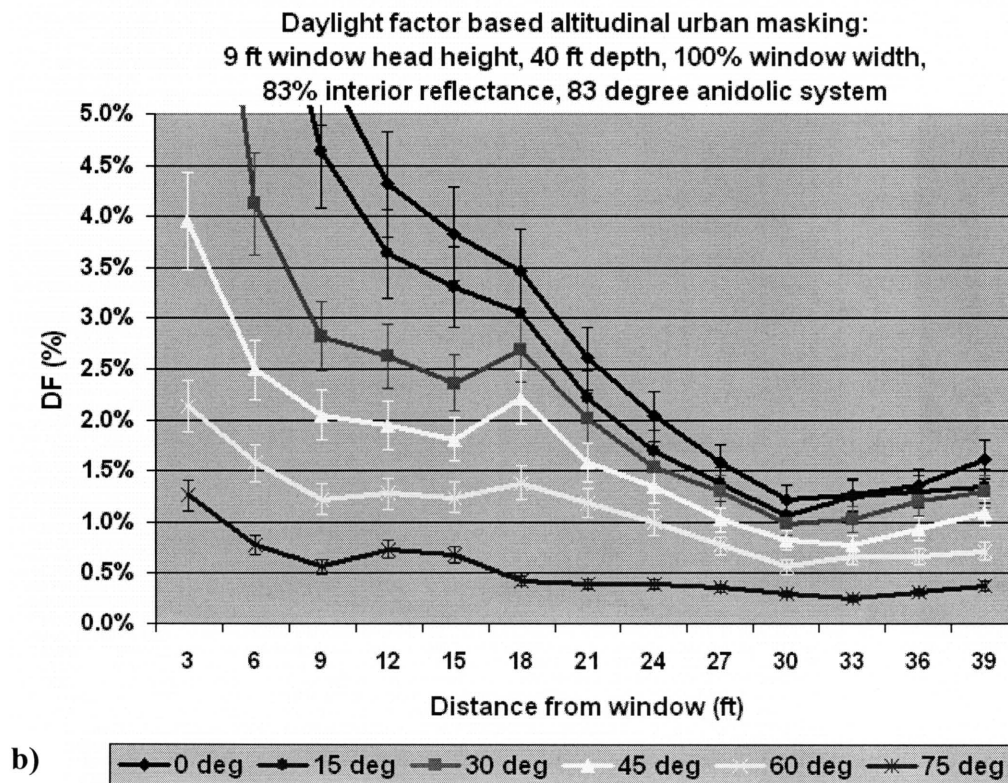
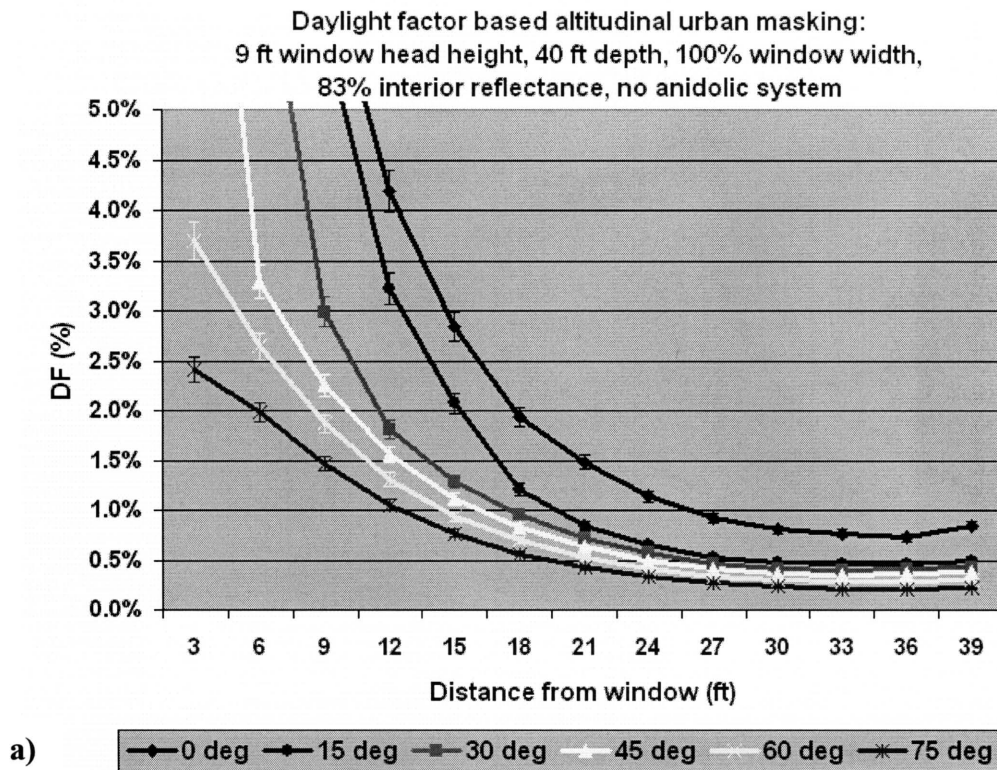
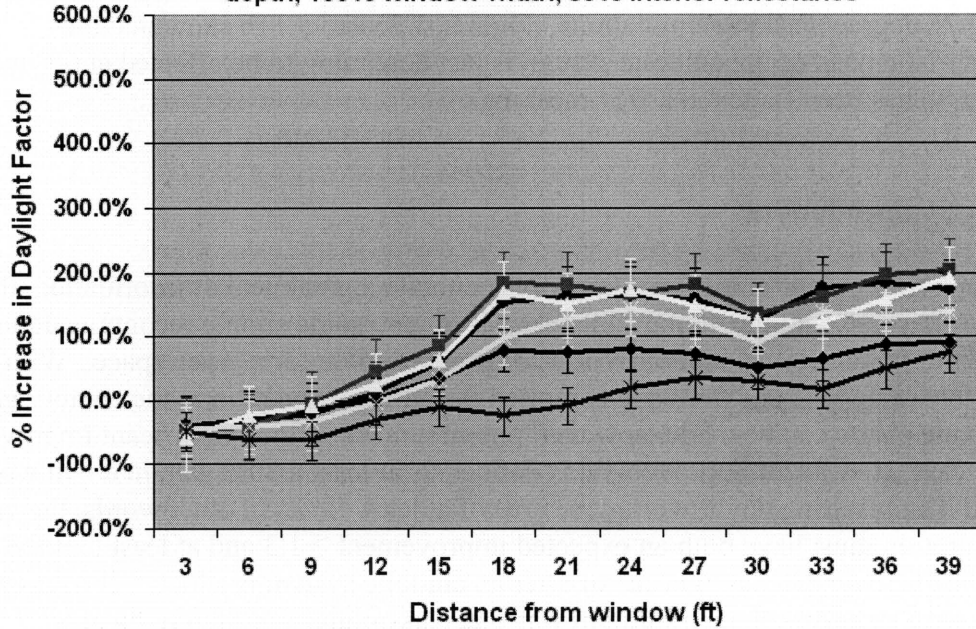


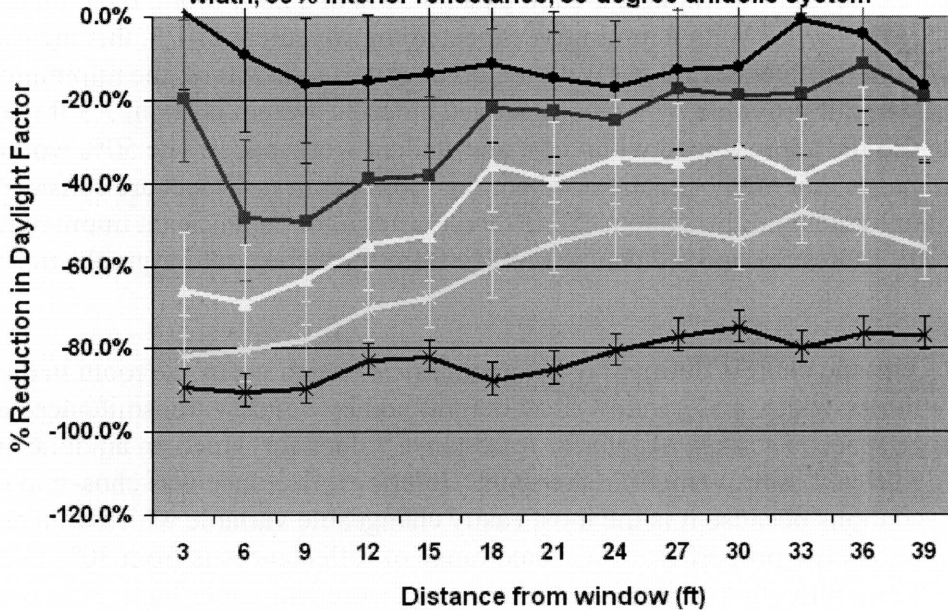
FIGURE 5.11: Daylight factors based on altitudinal urban masking both (a) without and (b) with a 30 degree anidolic system. The room represented has a depth of 40 ft, a window head height of 9 ft, a window width of 100%, and an interior reflectance of 83%.

Improvement of daylight factor due to 30 degree anidolic system based altitudinal urban masking: 9 ft window head height, 40 ft depth, 100% window width, 83% interior reflectance



a)

Percent reduction of daylight factor due to altitudinal urban masking: 9 ft window head height, 40 ft depth, 100% window width, 30% interior reflectance, 83 degree anidolic system



b)

FIGURE 5.12: (a) The percent improvement of daylight factor due to the addition of the 30 degree anidolic system. (b) The percent reduction of daylight factor due to the increase in urban masking in the room with a 30 degree anidolic system and interior reflectance of 83%.

There is a point at which anidolic systems stop being effective in urban situations, and that is when a significant portion of the anidolic system's sky view is blocked by the masking. In the case of the systems used in this experiment, this is apparent in both the 60 and 75 degree masking simulations. Figures 5.9b and 5.11b show that the characteristic peak of the anidolic system is just beginning to be affected at 60° masking, and that it has been flattened at 75° masking.

### 5.3 Recommendations

Although the contour graphs in Appendix A contain a great deal of information, they are difficult to parse, and the goal of this thesis is to give some simple recommendations on whether or not a zenithal anidolic collector is appropriate for a given space. With this in mind, the Tables 5.1 and 5.2 were compiled from the information in the contour graphs. Before the charts can be made, however, one first must define "significant improvement". In this case, significant improvement is defined as at least a 30% gain in daylit workplane area AND a resulting daylit workplane area of at least 50%. In other words, the variable configuration must have both an expected improvement  $\geq 1.3$  and at least half the floor area must be over 2% daylight factor after an anidolic system is added. The reason 50% was chosen as a workplane minimum was that classrooms are often lit by at least two banks of electric lights. If the room can be divided into two lighting zones and wired separately, only one set of lights would have to switch on if half the workplane was daylight. An improvement of 30% was chosen because anything less would seem too small in the case of shallower, 20 ft deep rooms. If, for example, an anidolic system increased the daylight workplane area to exactly 50% in a 20 ft room, the total daylit depth would be 10 ft. With a minimum expected improvement of 1.3, this means that the original daylit depth was 7.69 ft. With the given criteria, therefore, the minimum additional benefit provided by a recommended anidolic system is about 2.3 ft in depth, which is also the approximate width of a one student workspace. The 50% workplane criterion means that many situations where the room depth is 40 feet are considered not appropriate for an anidolic system. If different criteria for "significant improvement" are wanted, the Tables 5.1 and 5.2 can be remade from the same contour graphs in Appendix A.

Each space in the chart is defined by the geometric dimensions of the room in question (depth, window width, and window head height) and by window transmittance, and within each space is a range of interior reflectance values for which an anidolic system creates significant improvement in the room. Interior reflectance was chosen to convey recommendations because it is the most easily changeable variable which defines a room's photometric properties. The tested range of reflectances is from 30% to 83%, and while 83% (smooth white paint) is seen here as a theoretical upper limit, 30% is not a lower limit, and so the lower limit is sometimes described as "less than 30%" ( $< 30$ ). It would, however, be very odd for the average internal reflectance to be less than 30% unless the entire room was covered with chalkboards. If the appropriate range for an anidolic system is truncated at either the high or low end of reflectances, it may be assumed that above the given range, the room was already very well daylit, and below the

range, the system either had minimal effect (20 foot depth) or was inadequate to achieving the target expected improvement (30 or 40 foot depth).

It is possible that certain room configurations are not appropriate for an anidolic system no matter what reflectance is used. In this case, a small symbol appears in the box representing that geometry, and that symbol gives some information about why an anidolic system is not appropriate. If the room was already well daylit, for instance, a small figure of a sun appears in the box. If the anidolic system had minimal effect on the room (due, perhaps, to a combination of low wall reflectance and the characteristic peak of the daylight factor curve being deeper than the back wall of the room), it is represented by a sun partially obscured by a cloud. If the room with anidolic system fails to meet the criteria for “good daylighting”, it is represented by a small cloud. If the background of that cell is dark, it failed to produce the expected improvement at any reflectance, and if it is lighter grey, the expected improvement was met in some cases, but the target floor area was not.

As for quantity variable recommendations, the only examples integrated into the two charts are the transmittances of single pane glass (90%) and double-pane low-E glass (73%). In general, it is best to get the highest transmission of glass possible, while still allowing for the thermal performance of windows, and glass that has a lower transmittance than double pane low-E glass is not recommended. It is suggested that all window frame be removed from the apertures of an anidolic system. If it cannot be removed, thin window frames may be thought of as part of glass transmittance according to the formula:

$$\text{Total transmittance} = [1 - \% \text{ frame area}] \times [\% \text{ glass transmittance}]$$

This total transmittance should be thought of as an upper bound transmittance, because it does not take into account any detrimental effects on the geometric performance of the anidolic system. The greater the percent frame area blocking the anidolic system (especially as concerns horizontal frame elements), the less accurate the total transmittance estimate will be.

If window frames are removed from the aperture of the anidolic system but not the rest of the window, it makes more sense to treat them as a reduction in total window area. Assuming a constant window width for the sake of the anidolic system, window frame area can be approximated as a reduction in view window height, where the view window is the part of the window not occupied by an anidolic system:

$$\text{Adjusted view window height} = \frac{[\text{view window area}] \times [1 - \% \text{ frame area}]}{\text{total window width}}$$

In this case, the total window width should be an absolute measurement, rather than the percentage which is used in the distribution variable “total window width”. The view window area should also be an absolute number, so that the view window height is an absolute measurement.

As shown in Figure 5.7 above, severe reductions of view window height cause daylight factor reductions to follow window area reductions more closely, whereas if a significant view window height is maintained, then increases and reductions in window area have less of an impact on overall daylight factor. Therefore it is recommended that the view window be no less than 2.5-3 feet tall. This recommendation can also be made in reference to occupant comfort, because a larger view window provides more connection to the exterior and an opportunity for long focus and eye relaxation.

Urban masking is present in almost every architectural situation. For cases of very low masking levels (less than  $15^\circ$  altitude), the recommendation charts should still be generally applicable. For masking up to  $45^\circ$ - $50^\circ$  altitude, the improvement provided by an anidolic system becomes dramatic enough that they can be considered worthwhile in spaces well designed for daylighting (high reflectance levels, wide and tall windows, shallower spaces). Above this level of masking, depending on the system configuration, the masking starts to significantly interfere with the performance of the anidolic system.

**TABLE 5.1: Anidolic Application Recommendations for a 30° Anidolic System**

*Recommendations given as a range of internal reflectance.*

**Anidolic System:  $\theta = 30^\circ$**

Window Head Height	Window Width					Room Depth
	60%	67%	75%	84%	100%	
11ft	<b>&lt; 30 - 35</b>	<b>&lt; 30 - 40</b>	<b>&lt; 30 - 50</b>	<b>&lt; 30 - 40</b>	<b>&lt; 30 - 35</b>	20 ft
10ft	<b>40 - 55</b>	<b>35 - 55</b>	<b>&lt; 30 - 55</b>	<b>&lt; 30 - 40</b>	<b>&lt; 30 - 35</b>	
9ft	<b>&lt; 30 - 70</b>	<b>30 - 75</b>	<b>&lt; 30 - 65</b>	<b>&lt; 30 - 60</b>	<b>&lt; 30 - 55</b>	
8ft	<b>&lt; 30 - 83</b>	<b>&lt; 30 - 75</b>	<b>&lt; 30 - 75</b>	<b>&lt; 30 - 75</b>	<b>&lt; 30 - 75</b>	
7ft	<b>70 - 83</b>	<b>65 - 83</b>	<b>55 - 83</b>	<b>40 - 80</b>	<b>70 - 83</b>	
11ft	<b>70 - 83</b>	<b>60 - 83</b>	<b>50 - 83</b>	<b>55 - 83</b>	<b>55 - 83</b>	30 ft
10ft	<b>50 - 83</b>	<b>65 - 83</b>	<b>40 - 83</b>	<b>&lt; 30 - 83</b>	<b>40 - 83</b>	
9ft	<b>45 - 83</b>	<b>30 - 83</b>	<b>35 - 83</b>	<b>&lt; 30 - 83</b>	<b>&lt; 30 - 83</b>	
8ft	<b>60 - 83</b>	<b>45 - 83</b>	<b>50 - 83</b>	<b>&lt; 30 - 83</b>	<b>&lt; 30 - 83</b>	
7ft	<b>70 - 83</b>	<b>60 - 83</b>	<b>50 - 83</b>	<b>&lt; 30 - 83</b>	<b>&lt; 30 - 83</b>	
11ft	<b>&lt; 30 - 55</b>	<b>40 - 75</b>	<b>70 - 83</b>	<b>55 - 83</b>	<b>83</b>	40 ft
10ft	<b>40 - 75</b>	<b>70 - 83</b>	<b>70 - 83</b>	<b>75 - 83</b>	<b>83</b>	
9ft	<b>55 - 83</b>	<b>70 - 83</b>	<b>70 - 83</b>	<b>75 - 83</b>	<b>75 - 83</b>	
8ft	<b>&lt; 30 - 83</b>	<b>70 - 83</b>	<b>70 - 83</b>	<b>75 - 83</b>	<b>75 - 83</b>	
7ft	<b>70 - 83</b>	<b>70 - 83</b>	<b>70 - 83</b>	<b>75 - 83</b>	<b>75 - 83</b>	

**LEGEND:**

<b>&lt; 30 - 55</b>
<b>40 - 75</b>
<b>55 - 83</b>
<b>&lt; 30 - 83</b>

**90% Transmittance (single pane glass)**

Room was already sufficiently daylight  
 Room does not meet daylighting criteria  
 Small impact low refl, sufficient daylight high refl  
 Low recommended internal reflectance  
 Medium recommended internal reflectance  
 High recommended internal reflectance  
 All internal reflectances recommended

**73% Transmittance (double pane low-e glass)**

**Quantity Variable Recommendations:**  
**Glass:** No less than 73% transmittance.  
**Frame:** Thinner frames, remove from anidolic aperture  
**Area:** View window at least 2 - 3 ft tall  
**Masking:** Anidolic system may be worth in better daylight rooms with up to 50 degrees masking. Higher masking impedes system.

**TABLE 5.2: Anidolic Application Recommendations for a 25° Anidolic System**

*Recommendations given as a range of internal reflectance.*

*Anidolic System:  $\theta = 25^\circ$*

Window Head Height	Window Width						Room Depth
	60%	67%	75%	84%	100%	100%	
11ft							20 ft
10ft							
9ft	55	40 - 55	40 - 50	< 30 - 40	< 30 - 35	40 - 55	
8ft	45 - 70	40 - 70	35 - 65	< 30 - 55	< 30 - 55	35 - 75	
7ft	40 - 83	30 - 75	< 30 - 75	< 30 - 70	< 30 - 70	< 30 - 83	
11ft	75 - 83	65 - 83	60 - 83	45 - 83	50 - 80	60 - 83	30 ft
10ft	75 - 83	65 - 83	60 - 83	45 - 83	40 - 83	60 - 83	
9ft	70 - 83	65 - 83	60 - 83	50 - 83	40 - 83	55 - 83	
8ft	60 - 83	60 - 83	45 - 83	35 - 83	< 30 - 83	45 - 83	
7ft	55 - 83	50 - 83	45 - 83	< 30 - 83	< 30 - 83	40 - 83	
11ft							40 ft
10ft							
9ft			83	50 - 83	50 - 83	80 - 83	
8ft			70 - 83	50 - 83	40 - 83	70 - 83	
7ft				75 - 83	60 - 83	65 - 83	

73% Transmittance (double pane low-e glass)

**LEGEND:**

	< 30 - 55
	40 - 75
	55 - 83
	< 30 - 83

**90% Transmittance (single pane glass)**

Room was already sufficiently daylight  
 Room does not meet daylighting criteria  
 Small impact low refl, sufficient daylight high refl  
 Low recommended internal reflectance  
 Medium recommended internal reflectance  
 High recommended internal reflectance  
 All internal reflectances recommended

**Quantity Variable Recommendations:**

**Glass:** No less than 73% transmittance.  
**Frame:** Thinner frames, remove from anidolic aperture  
**Area:** View window at least 2 - 3 ft tall  
**Masking:** Anidolic system may be worth in better daylight rooms with up to 50 degrees masking. Higher masking impedes system.

## 6 VALIDATION

### 6.1 Applying the tables

#### 6.1.1 *Boston Classroom Example*

Because real classrooms come in all sizes and shapes, the variables which describe them might fall between the categories in Tables 5.1 and 5.2. In cases such as these, the reader must make assumptions and choices as per which value is most applicable. As an example, the Boston classroom modeled in Section 4.2, will be located on Table 5.1.

Although this classroom was built in the 1960's, a time when most of the rest of the country was building windowless schools, it more closely resembles a classroom from the 1930's in dimension. As was commented on in section 3.1, Boston tends to have rather traditional architecture, and it is one of the cities that cannot be reliably expected to follow national trends closely. The classroom is 24ft deep and 35.5 ft wide with 10.5 ft ceilings. It has 10 six foot tall windows which, without the thick casements between them, have a total width of 75% of the wall width. The window head height (after accounting for the upper frame) is about 9.25 ft. The window glass is single pane, and the window frame area (not including the casements between the windows) is 19%. The reflectance of the upper part of the side and back walls is white paint, with a reflectance of 83%, and the visible portion of this is 34% of the total area of the side and back walls and ceiling. The lower part of the wall is yellow with 57% reflectance and takes up 13% of the total area. The ceiling, though white, is a very rough acoustic finish, so the reflectance of this is approximated as 75%, and the surface area is 49% of total. The chalkboards are dark green with a reflectance of 28%, covering 4% of the total area. Altogether, this makes the average reflectance of the walls 72%. This does not take into account doors, furniture which might obscure the walls (of which there was very little), and other finishes, but it is probably a good enough approximation.

The above description puts us most definitely in the column for 75% window width and single pane glass, if the window frame is taken out (if left in, the resulting total transmittance is, fortuitously, 72.9%). The window head height is also much closer to 9 ft than 10 ft, so the only real dilemma is whether to look at the 20 ft or the 30 ft deep category. Although a more exact expected improvement could be obtained from the 30 ft contour graph in Appendix A, Table 5.1 can give an idea. In this case, the 20 ft category gives a reflectance range of less than 30% to 50% as appropriate for an anidolic system. Beyond 50%, judging by the number of sun icons which appear in the 20 ft category, one must assume that the room is already pretty well daylight. The 30 ft category, on the other hand, gives a range of 40% to 83% as appropriate for an anidolic system. The approximate internal reflectance of the classroom in question, 72% falls well within this range. If the window frame is left untouched (73% transmittance), the recommended reflectance range at 20 ft depth is less than 30% to 55%, and at 30 ft depth, it is still 40% to 83%. This gives us a similar situation as the 90% transmittance case.

In short, Table 5.1 says that at 20 ft depth, it is not worth installing an anidolic system, but at 30 ft depth it is. At 24 ft depth, it is probably worth it for two reasons. First, categorizing the 20 ft room as “too good” does not mean that it is 100% daylit – the way “good daylighting” is characterized here, up to 5 ft of that 20 feet could still be less than 2% daylight factor. Second, the anidolic system would still raise the illuminance level near the back of the rooms and provide a little bit of shading next to the window, evening out the daylight factor profile. In general, however, the case is borderline and could be decided either way, according to how conservative the reader wishes to be.

Daylight factor simulations on this classroom model reveal that, if no blinds obscure the windows, the room with no anidolic system remains above 2% daylight factor until 17 ft from the window (70% of the floor area). When a 30° anidolic system is installed without touching the window frame, the daylit depth increases to 22.6 ft, for an improvement of 33%. If the window frame inside the anidolic aperture is removed, the daylit depth increases to 100%, which is a 40% improvement over the original room (see Figure 6.1).

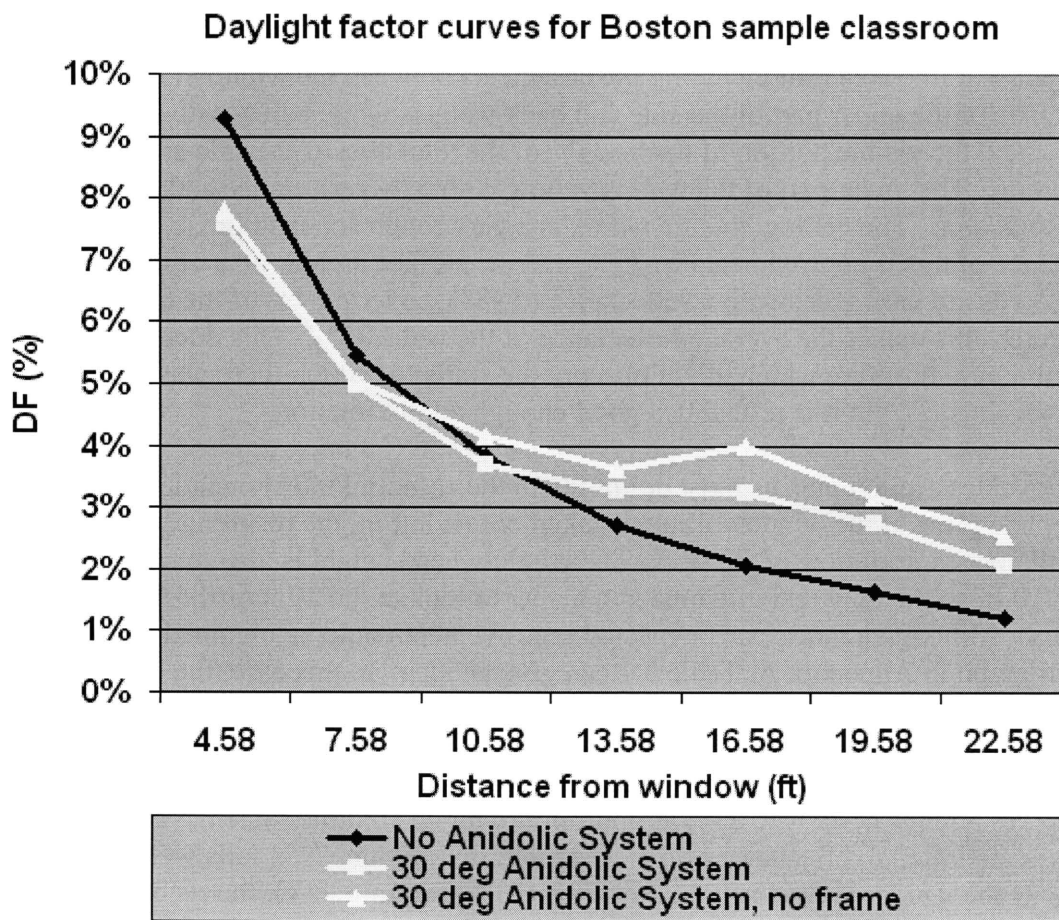


FIGURE 6.1: Daylight factor curves for the Boston sample classroom without an anidolic system, with a 30° anidolic system leaving the window frame intact, and with a 30° anidolic system removing the window frame.

### 6.1.2 Bronx Classroom Example

Another model was made based on an anonymous classroom in the Bronx. This classroom, which was built in the earlier part of the century (1920's-30's), is 33 ft wide by 21 ft deep with 12 ft ceilings. The three windows are deeply recessed with rather thick frames, and the total window width is not more than 54% of the façade wall. Thanks to some darker surfaces, the average internal reflectance is around 60%. The windows are single pane glass, and, not including the thick posts between the windows, the frame area is just over 35%.

Because of the thick frame area, it should certainly not be left in to obscure the anidolic aperture. The recommendation for 20 ft depth, 60% window width, 10 ft window head height, and single pane glass suggests that an anidolic system is not worth installing above 40% interior reflectance, presumably because the room is already too well daylit. As is obvious from Figure 6.6, this is not the case, probably for some of the reasons mentioned above. When the error described in Section 4.6 is taken into account, the area of the room above 2% daylight factor just passes 50%, which is an improvement of only 7% over the original daylight factor curve. The back of the room is indeed improved, but not up to 2% daylight factor. This was an unexpected result, but there may be some reasons for it. One of the things held constant in all simulations was that a flat, smooth ceiling was 1 ft taller than the window head height and directly above the anidolic exit aperture. It is possible that the ceiling in this classroom, though it is the lightest color of paint in the room, contributed less to the daylighting of the room because it was several feet above the anidolic system and was obstructed by beams. Also, there is a concentration of dark reflectances at the level of the work plane, and the walls and window frames have at least twice as much depth to them as the simple-model simulations did.

In short, this is an example that does not agree with Table 5.1, probably because the simple models used to make the table were too deviant from this classroom. This points

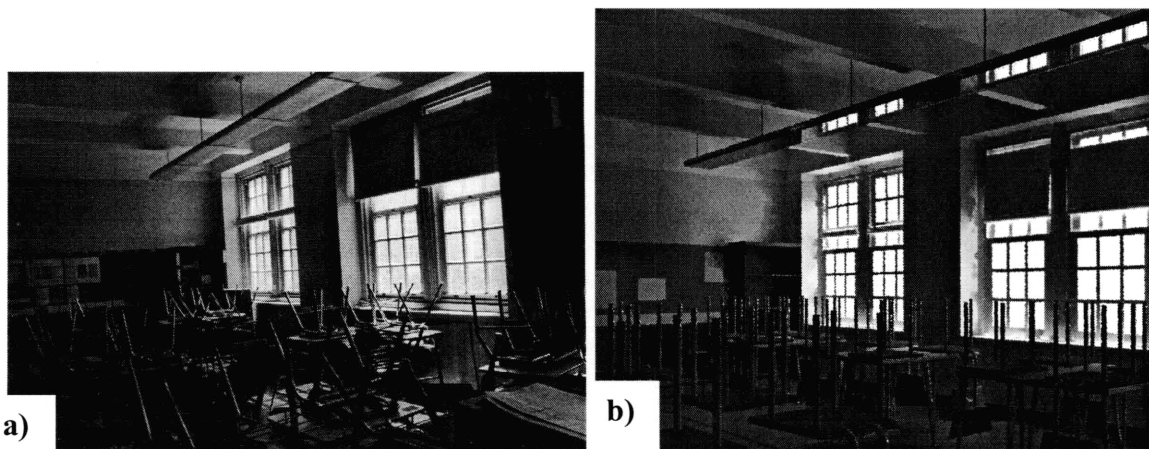


FIGURE 6.2: Photograph and rendering of a classroom in the Bronx in its original state, including shades (photograph taken by the author).

to a limited applicability of these tables if the spaces in question deviate too much from the assumptions made by the simple models. At this point, the exact reason for the Bronx classroom's lack of performance is unknown, but it was probably related to the theoretical reasons given in the paragraph above.

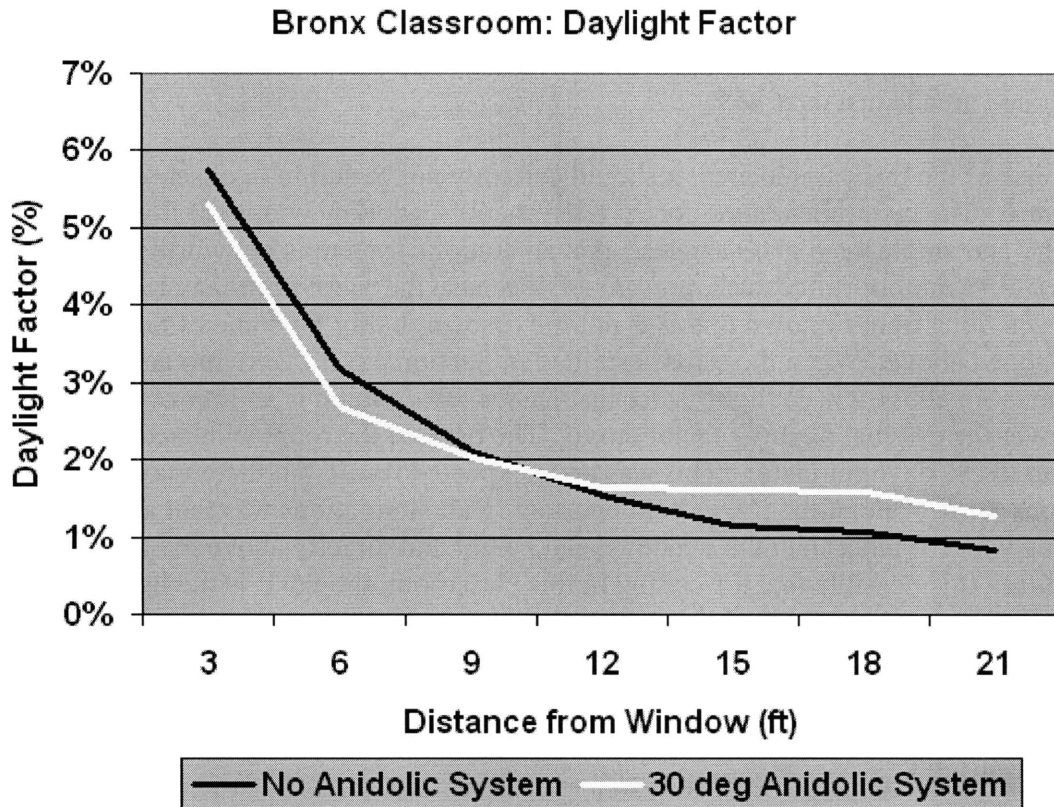


FIGURE 6.3: Daylight factor curves for the Bronx classroom with and without an anidolic system.

### 6.1.3 MIT Classroom Example

A model based on a series of MIT classrooms from building 26 was made in conjunction with a brief exploration study of anidolics in façade renovation (see Section 7). These rooms face southwest, and the afternoon direct light causes the Venetian blinds to stay drawn in many rooms 24 hours a day. Because of this, two scenarios are available for study: one in which there are no blinds on the windows, and one in which the blinds remain drawn and fixed at a 45 degree angle.

The room in question has a width of 28 ft, a depth of 24 ft, and a height of 12 ft. The window head height is not currently 12 ft, but the study concluded that it would be easy to make it so with little renovation, therefore the window head height is considered to be 12 ft. The window width is approximately 95% of the room, and the windows themselves are 9 ft tall. The current tinted, single-pane glass was, for this study,

considered to have been replaced by double pane, low-e glass (73% transmittance). The wall reflectance is about 60%, except for one side wall, which is covered from floor to ceiling in blackboards (estimated 5% reflectance). Aside from a few posts, there is no window frame area. A 30 degree anidolic system was designed for installation.

First, let us consider a scenario in which there are no blinds. According to Table 5.1, it is not worth installing an anidolic system in a room that is 20 ft deep, because the room is already too well daylit, but in a room that is 30 ft deep, it is worth it in the range of higher reflectances. Again, the reader must make a choice. Because the windows are so tall as well as broad, in the case where no blinds are deployed, it is more likely that the room will be very bright, therefore, according to this set of criteria, it is not worth it to install an anidolic system. This can be seen in Figure 6.4.

Observation, however, shows us that blinds are often drawn in these windows in reality. Therefore, in the second scenario, the top two feet of the window are covered, and blinds are drawn on all the rest, leaving only a 1.5 ft tall view window clear at the bottom. The blinds are set to an angle of 45 degrees, but they effectively reduce the view window height to 1.5 ft, which is not recommended. In this case, there is no doubt that an anidolic system would greatly improve the space, but with such a reduced (and low) view window, it is possible that even the anidolic system may not be able to raise very much of

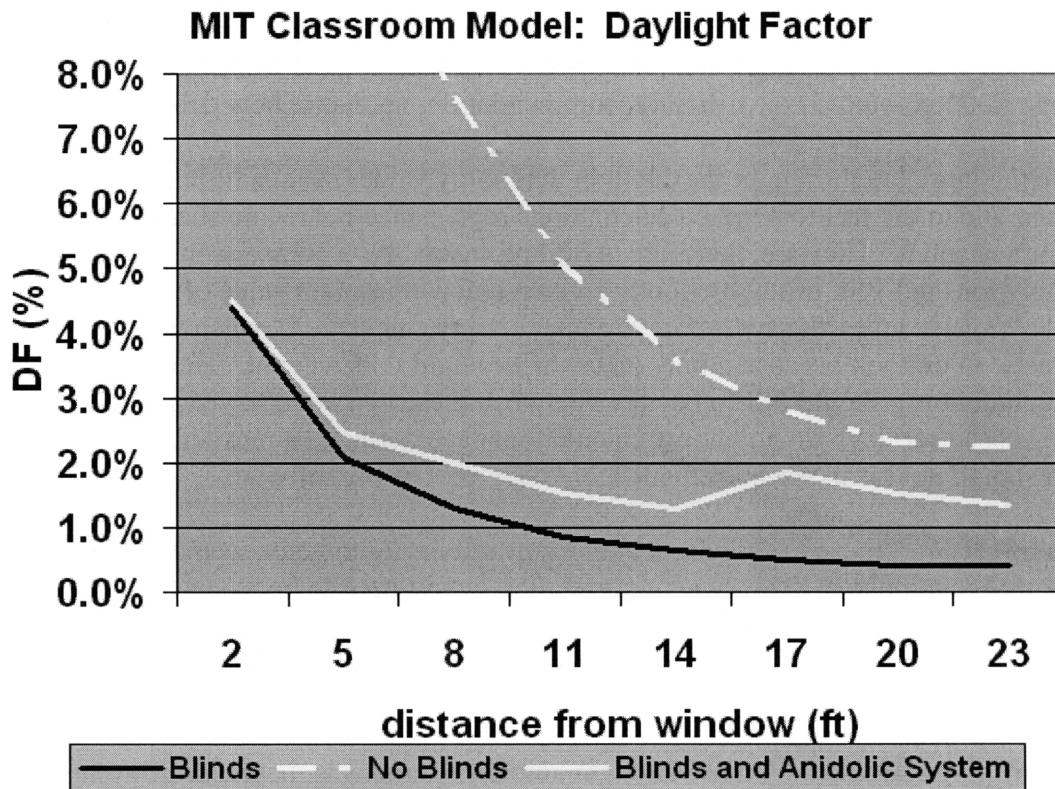


FIGURE 6.4: Daylight factor curves for the MIT classroom with no blinds, with blinds, and with blinds plus an anidolic system.

the floor area above the requisite 2% daylight factor. In fact, this turns out to be the case, as seen in Figure 6.4.

This example, though it agrees with Table 5.1 (which was created without reference to blinds use), highlights one of the weaknesses of daylight factor, which is that it is a worst-case scenario. In the case where blinds are drawn, the anidolic system makes a huge improvement in the daylight factor, but it is shown as “no improvement,” because it doesn’t reach the 2% daylight factor cutoff. Although the classroom would probably be too dim on heavily overcast days, it is likely to reach acceptable illuminance levels on days which are brighter (sunny or intermediate days). It is in situations like this that it seems most necessary to relate the daylight factor results to daylight autonomy, because DA would take into account the number of cloudy and sunny days in a particular climate.

## **6.2 Daylight Autonomy with DAYSIM**

This thesis used daylight factor as the main measure of daylight quantity largely for practical reasons (see Section 4.2), but it has been shown to be less accurate in predicting actual illuminances (see Section 2.3). Therefore, a few daylight autonomy comparison measurements were made using the program DAYSIM. These simulations were done with a reference illuminance value of 500 lux, as that is the most recent IESNA recommendation for illuminance levels in the classroom (Figures 6.5 and 6.6). (This illuminance value is quite high, and many people are comfortable working in conditions of 300 to 400 lux, but it is the official recommendation, no matter how debatable.)

Despite the large lux minimum the daylight autonomy values seem a little high, and this is mainly due to the fact that, in the calculations represented below, no shading strategy is taken into account. They are, therefore, a bit optimistic. As a comparison, the daylight autonomy for the EPFL prototype room is given a new minimum value of 300 lux and plotted alongside an earlier type of daylight autonomy calculation, which was very pessimistic in outlook because it only takes diffuse light into account. The reality of the daylight autonomy should fall somewhere between these two boundary cases. All buildings used for daylight autonomy calculations face north, so direct sun in the anidolic system should not be an issue for the RADIANCE part of the software.

As can be seen in Figure 6.8, daylight autonomy and daylight factor seem to have an exponential relationship. This type of correlation would need to be repeated for each city and building orientation. Too few calculations have been done to draw any concrete correlation between these two metrics, but at the very least, Figure 6.8 shows that such a concrete correlation might be possible.

The other thing suggested by these daylight autonomy graphs is that anidolic systems give the greatest improvement by far under cloudy skies. Each daylight autonomy which was calculated using DAYSIM shows a much smaller improvement than its daylight factor counterpart, where as the “pessimistic” daylight autonomies from EPFL (see Figure 6.7) shows a vast improvement in daylighting.

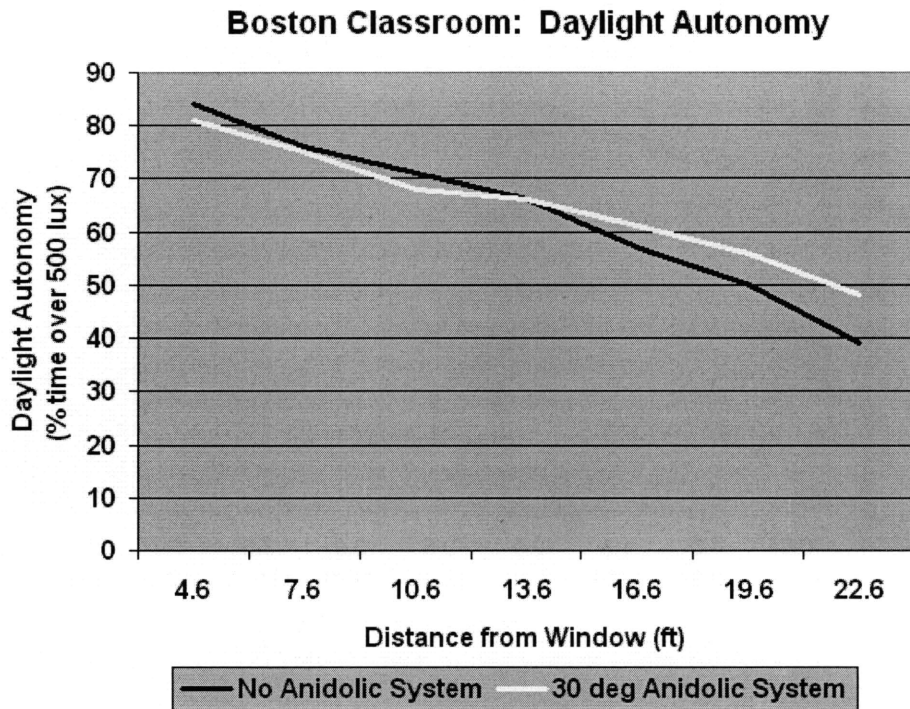


FIGURE 6.5: Daylight autonomy calculation (DAYSIM) for the Boston classroom, with a reference value of 500 lux.

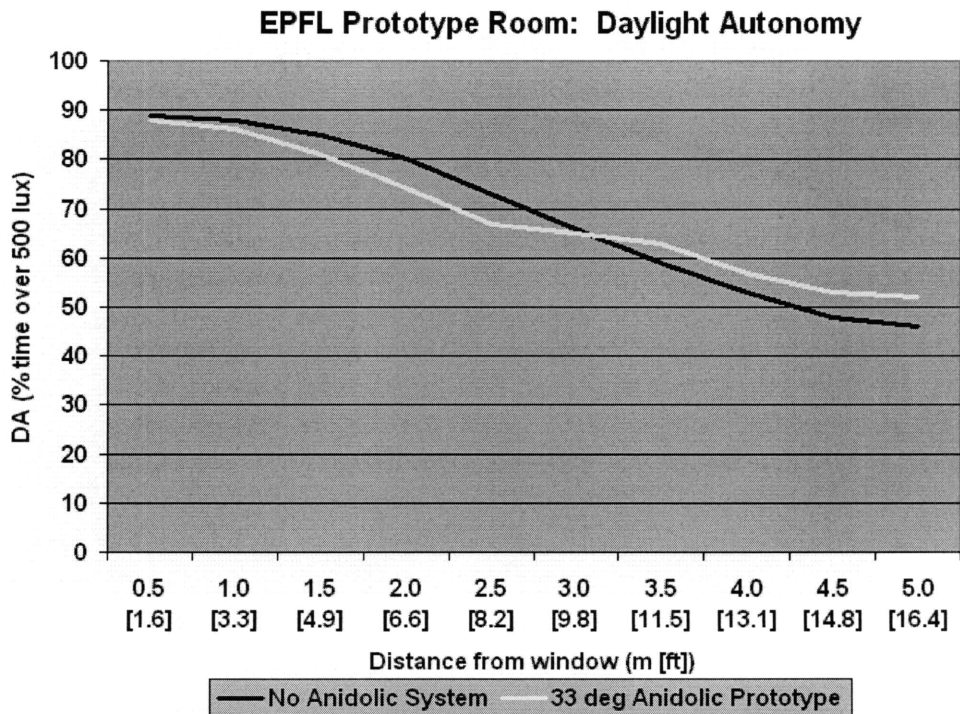


FIGURE 6.6: Daylight autonomy calculation (DAYSIM) for the EPFL anidolic prototype room, with a reference value of 500 lux.

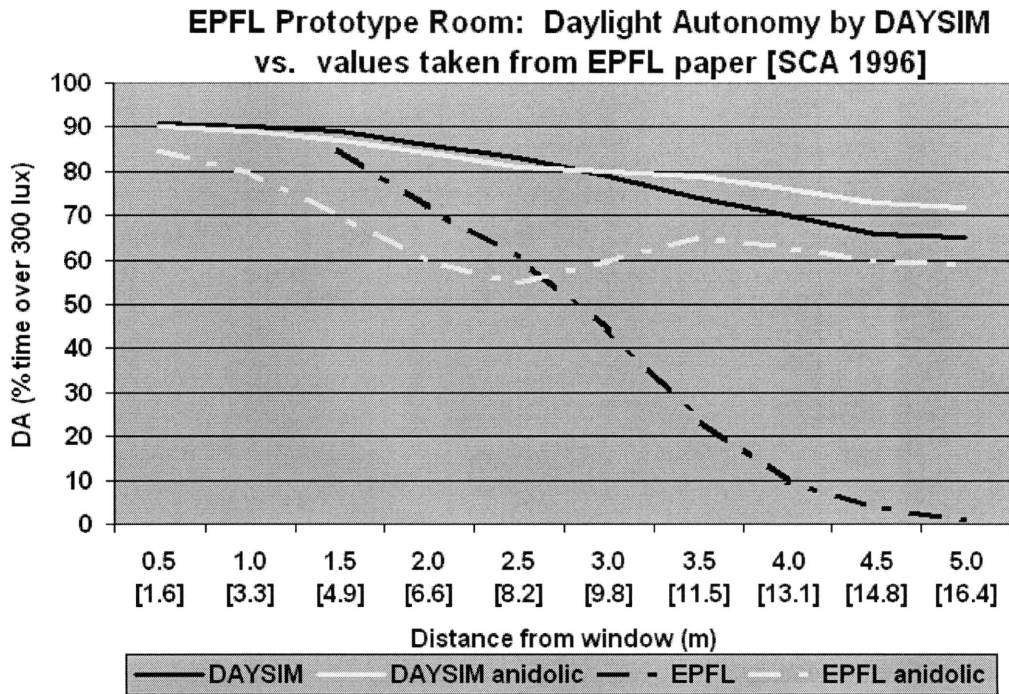


FIGURE 6.7: Comparison between the optimistic type of DA calculation from DAYSIM and pessimistic type of DA calculation from [SCA 1996]. These two sets of curves can be thought of as an upper and lower bound for daylight autonomy. The minimum illuminance value for both calculations is 300 lux.

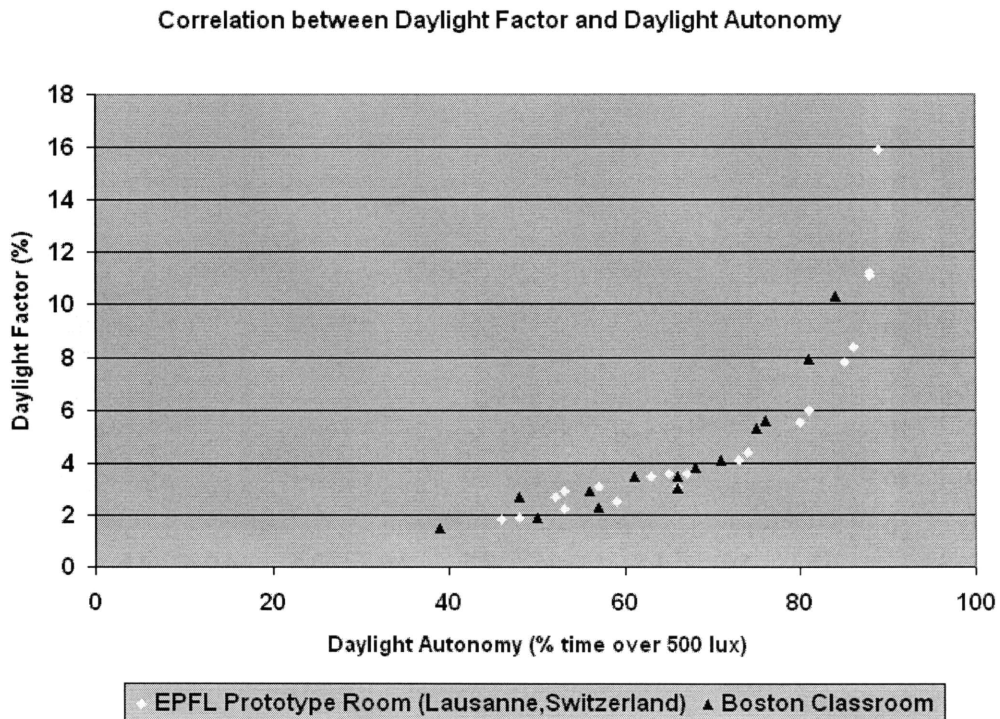


FIGURE 6.8: Correlation plot between daylight factor and daylight autonomy.

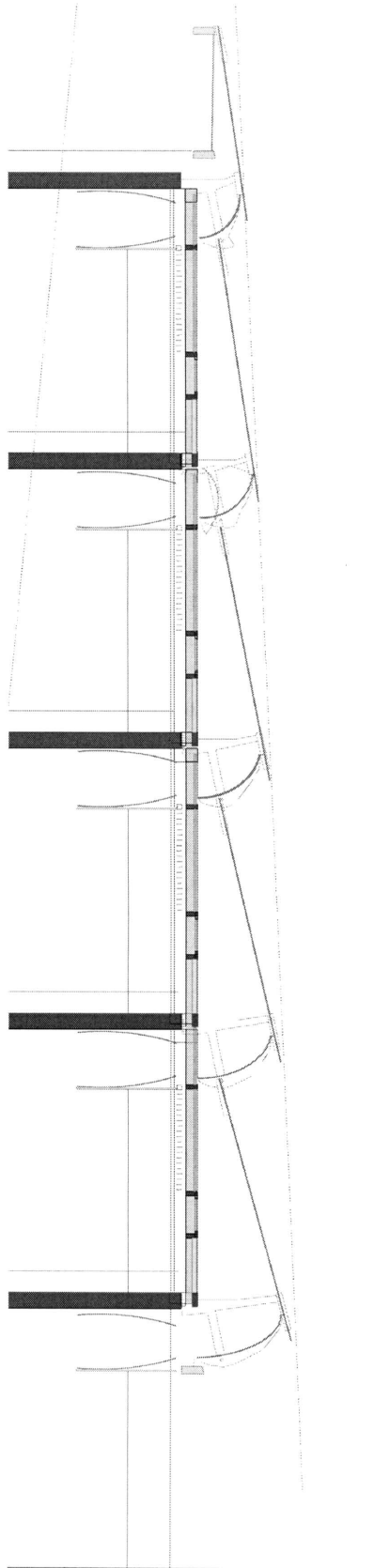
## 7 DISCUSSION

This thesis is an attempt to simplify a vast amount of information. Because the set of physical variables which affect daylighting is so large, however, any attempt to simplify it may cause inaccuracy – most especially if the simplified data set deviates too greatly from reality. The more differences there are between a real classroom and the minimal classroom models which were used to produce tables 5.1 and 5.2, the less it is likely that the recommendations will be accurate. For example, the daylight factor curve of the Bronx classroom was quite a bit lower than the recommendation tables predicted, but the ceiling was further from the top of the window and the walls were twice as thick as those of the simplified models. Furthermore, the darkest reflectances in the room were unevenly spaced, and were concentrated at the level of the work plane. These characteristics may have contributed to the lack of agreement between the daylight factor simulations and the tables in Section 5.

One noteworthy tendency is for RADIANCE simulations to overestimate daylight factors and illuminances [NG 2001, MAR 1995, 2004]. There is also a similar tendency concerning the simplified rooms used to create the tables in Section 5, in the sense that the simplified rooms seem to give higher daylight factor and illuminance results than more detailed or cluttered rooms. In a future version of these recommendation tables, both tendencies should be researched and possibly added into the equation as a correction factor.

Another issue that must be researched further is the correlation between daylight factor and daylight autonomy. Although daylight factor was chosen for logistical and practical reasons, there is no doubt that there are many advantages to providing recommendations which can be related to daylight autonomy and other similar metrics. It would be impractical to produce the same set of data given in this thesis by means of daylight autonomy calculations alone, due to enormous calculation time and an explosion of the number of variables to consider (i.e. sky type, orientation, location, time of day, time of year, operation hours, etc). However, if a correlation can be established between daylight factor and daylight autonomy (such as is suggested in Figure 6.8), then daylight factor could provide a base from which rough daylight autonomies could be extrapolated. Included in this theoretical daylight autonomy analysis, there should also be some allowance for occupant use of blinds (such as is possible with the program DAYSIM [REI 2004]). As could be seen in the classroom photographs, even north-facing windows often had blinds at least part way drawn, and this would make a great difference in the daylight autonomy. The daylight autonomy calculations given in the previous section are rather high, partly because they do not take blinds into account.

Energy savings and economic analyses are also more easily tied to daylight autonomy than daylight factor. Daylight autonomy literally predicts how many hours of the year one may turn off or dim the lights, while daylight factor gives only a ratio of indoor to outdoor illuminances – and one that is not valid in any but the most overcast skies.



One final issue that needs further research is the question of how to best integrate an anidolic system into the building façade. Several possibilities were researched at EPFL (see Section 2.2), but it is a topic that deserves further study and creative energy. As a thought experiment, the author collaborated with Edward Rice, a fellow degree candidate interested in daylighting and building façades, to come up with some ideas as to how anidolics may be incorporated into the façade. One of the major concerns about anidolic integration is how to allow the exterior collector a view of the sky and yet protect it from the elements. One answer is to have a step-like façade in which each floor was slightly shorter than the one below it, but that would reduce the floor area of the building. Providing the collector with a self-cleaning coating and leaving off the glass covering was another thought. The idea is that the surface of a window – or in this case, the reflective collector – is coated with a material whose nanostructure and chemical nature does not permit dirt to cling to it. The loose dirt and dust is then washed away with each rainfall. Titanium Dioxide applied in a 15 nanometer film is one such coating which is already used on window glass manufactured by Pilkington [TWI 2004].

The one idea that was explored further was to have a second, zigzagging plate-glass skin protecting the exterior collectors (see Figure 7.1). The collectors themselves could also rotate on an axis to cover the aperture of the anidolic system if direct sun started to cause glare. This kind of extra façade could possibly be attached to the brackets of an existing steel curtain wall, or perhaps to the floor slab itself, during a full façade renovation. This anidolic double skin was attached to a RADIANCE model of a mid-century steel and concrete building at MIT and rendered under cloudy and sunny skies. Results are shown in Figure 7.2.

FIGURE 7.1: One possible anidolic façade.

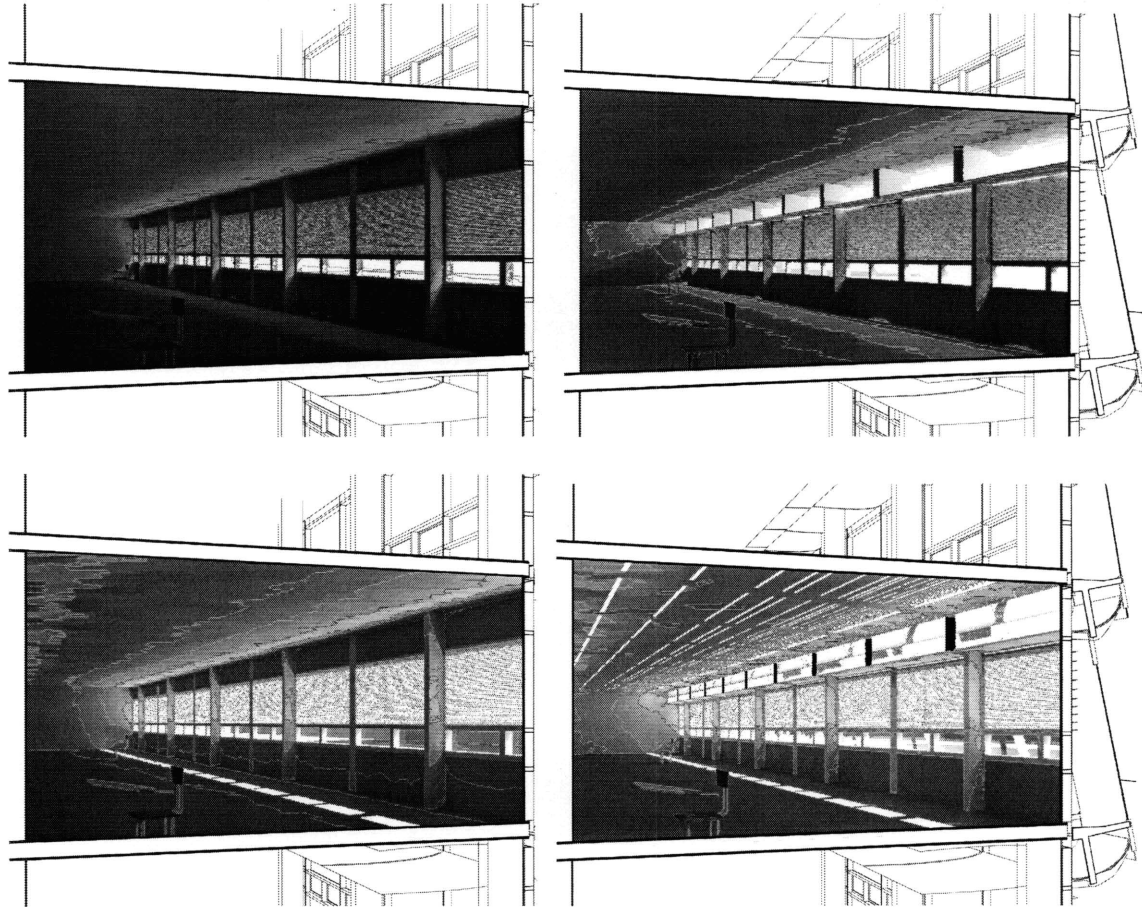


FIGURE 7.2: An elongated classroom with and without the anidolic double-skin façade in two sky conditions. From the top left, going clockwise: No anidolic system under cloudy sky, anidolic system under cloudy sky, anidolic system under sunny sky, no anidolic system under sunny sky. The horizontal beams on the ceiling in the bottom right hand picture are the result of direct sun on a curved mirror system which is approximated in segments.



## 8 CONCLUSION

This thesis is an attempt to reduce large amounts of information about a relatively new complex fenestration system into simple guidelines which would be useful to architects and builders. By giving these guidelines in a form dependant upon the physical constraints of a space, this information is hopefully made useful to those practitioners considering building renovation as well as those considering new construction. Existing buildings, it is assumed, may be in greater need of complex fenestrations to improve daylighting, as many passive daylighting alternatives may be impossible without substantially altering the building structure.

This thesis was successful in the way that it outlined a method to reduce these massive amounts of data to a simple and readable form, such that it would be accessible to practitioners with no special lighting software skills. The limitations of this thesis center around the use of daylight factor as the primary metric, with insufficient ties to daylight autonomy – and also that the author was forced to make certain assumptions about the building set with which she was working. These assumptions make tables 5.1 and 5.2 less useful in situations where the space in question deviates significantly from the simple model assumptions.

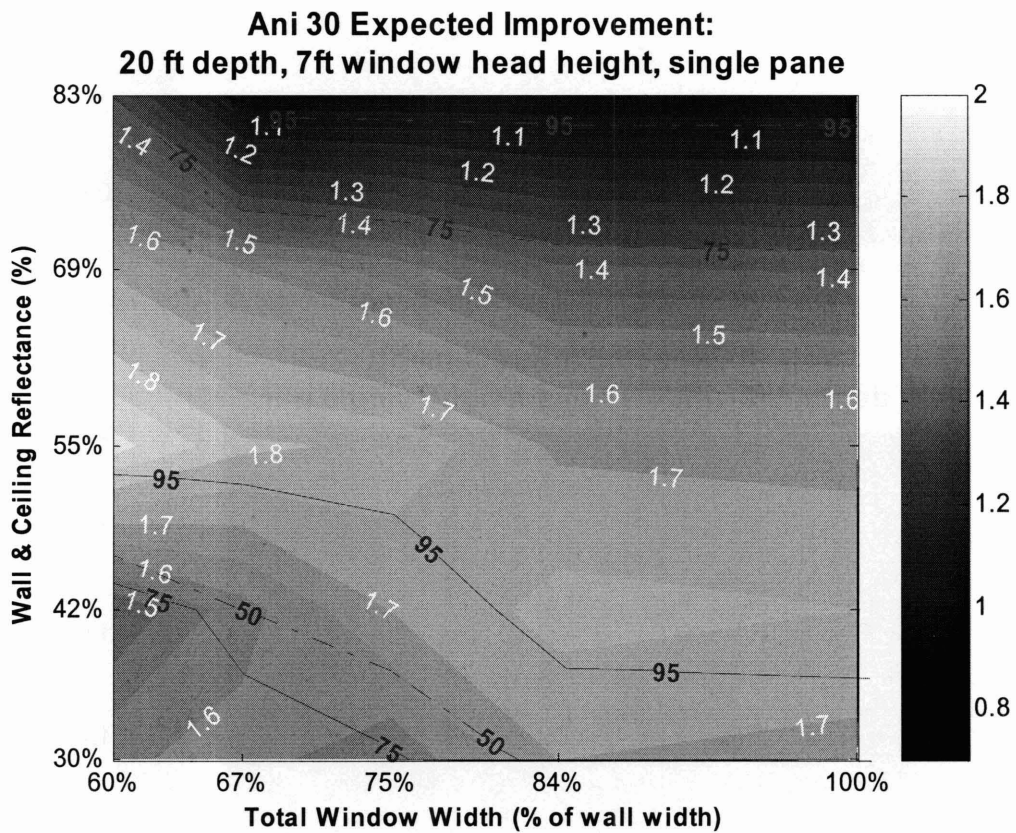
Anidolic systems are a valuable addition to the daylighting toolbox, but any tool is only as useful as the hands which operate it, and a tool which no one knows how to operate soon grows rusty from lack of use. A real need exists, therefore, not only to keep producing new daylighting systems and analytical tools, but to give practitioners the means to learn to use them.

The guidelines given in this thesis, although certainly not ready for widespread publication, are a good start, but there is much still to be done. The fact that more complex models did not always agree with the daylight factor recommendations serves to point out some of the weakness in the daylight factor method. Daylight autonomy should be correlated with daylight factor, as should studies on Glare Index and a brief economic analysis. It is the authors hope that a future version of Tables 5.1 and 5.2 will inspire greater use of anidolic devices, that other similar guidelines may be created for other complex fenestration systems, and that all such guidelines will be constantly revised and improved. Daylight is a worthy aspect to add to any architectural design, and research in this area should not only expand the realm of existing knowledge, but it should also light the way, so to speak, for the use of this knowledge in the world.

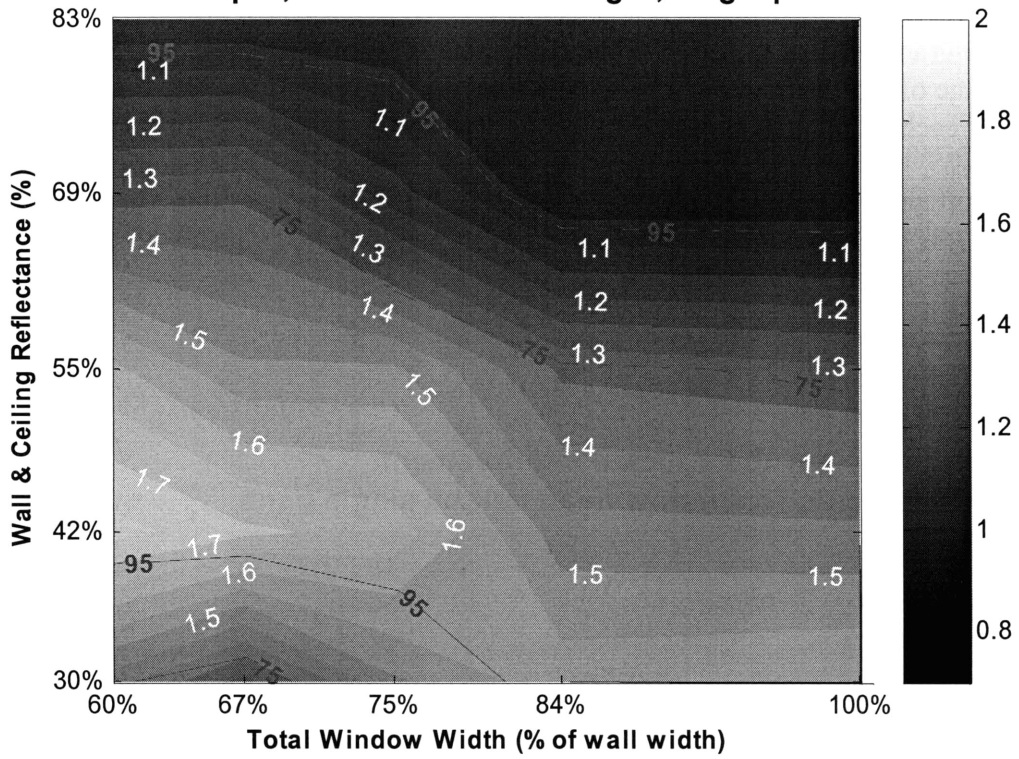


**9 APPENDIX A: Contour Graphs – Total Window Width vs. Reflectance**

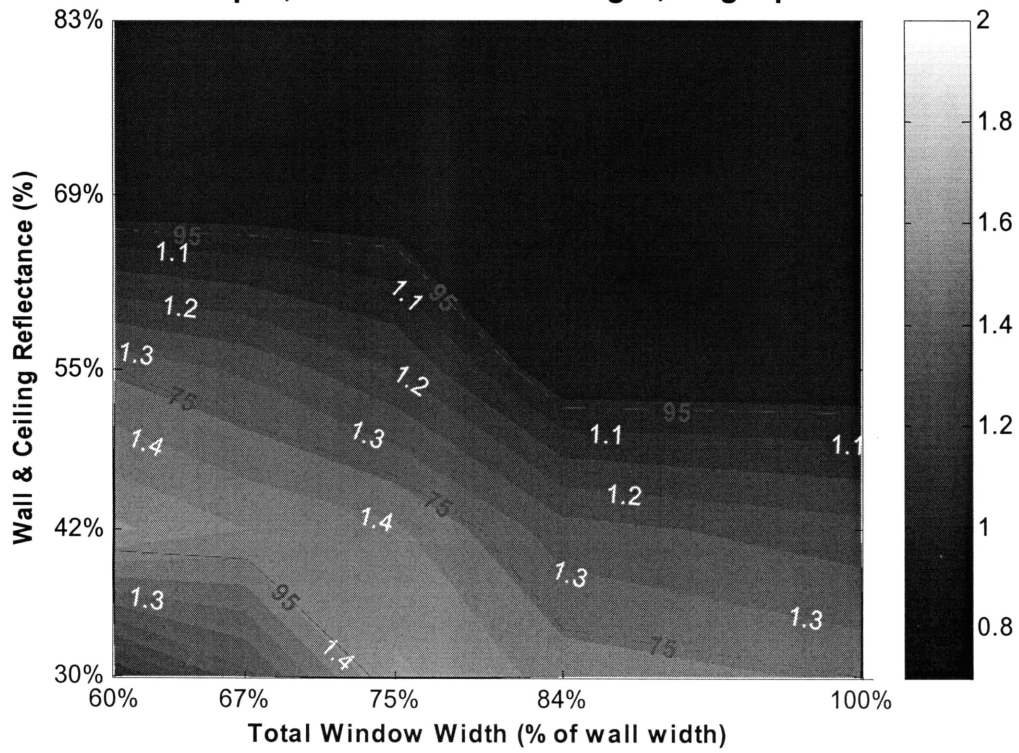
The contour graphs in this appendix show the spread of expected improvement values over the range of total window widths and internal reflectance values. The variables held constant for each graph are characteristic angle of anidolic system (30° or “Ani 30” and 25° or “Ani 25”), depth of room, window head height, and glass type (“single pane” is 90% transmittance and “low-e” is double pane low-e, or 73% transmittance). These are the contour graphs from which Tables 5.1 and 5.2 were compiled (see also Figure 5.1). For more of an explanation see the text in Section 5.1.



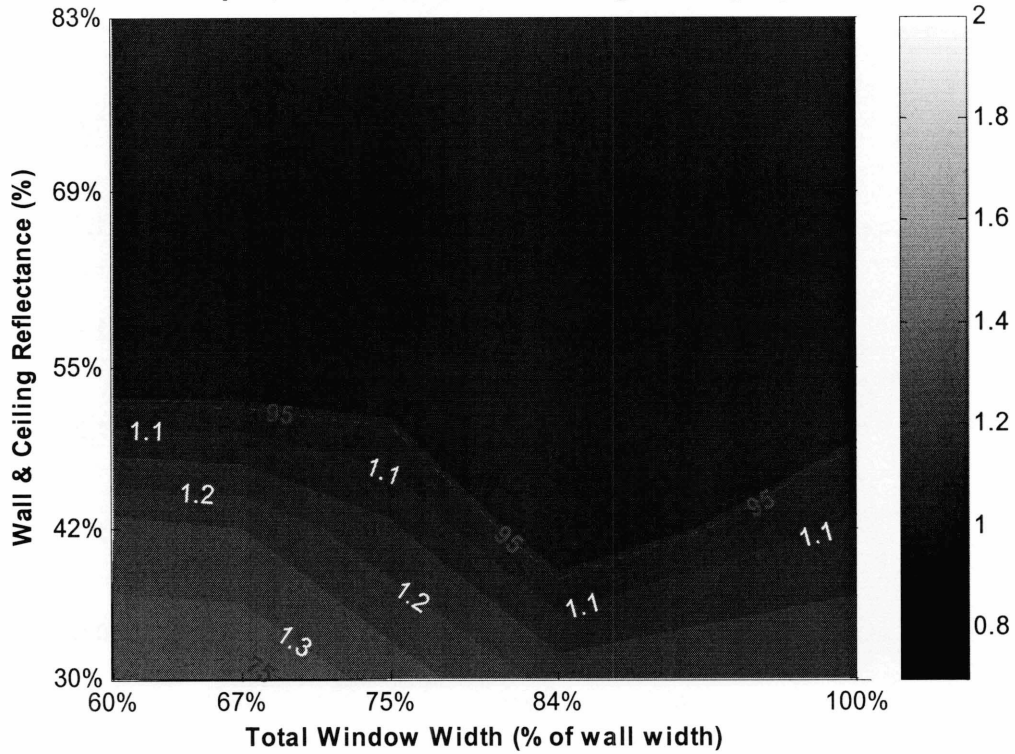
**Ani 30 Expected Improvement:  
20 ft depth, 8ft window head height, single pane**



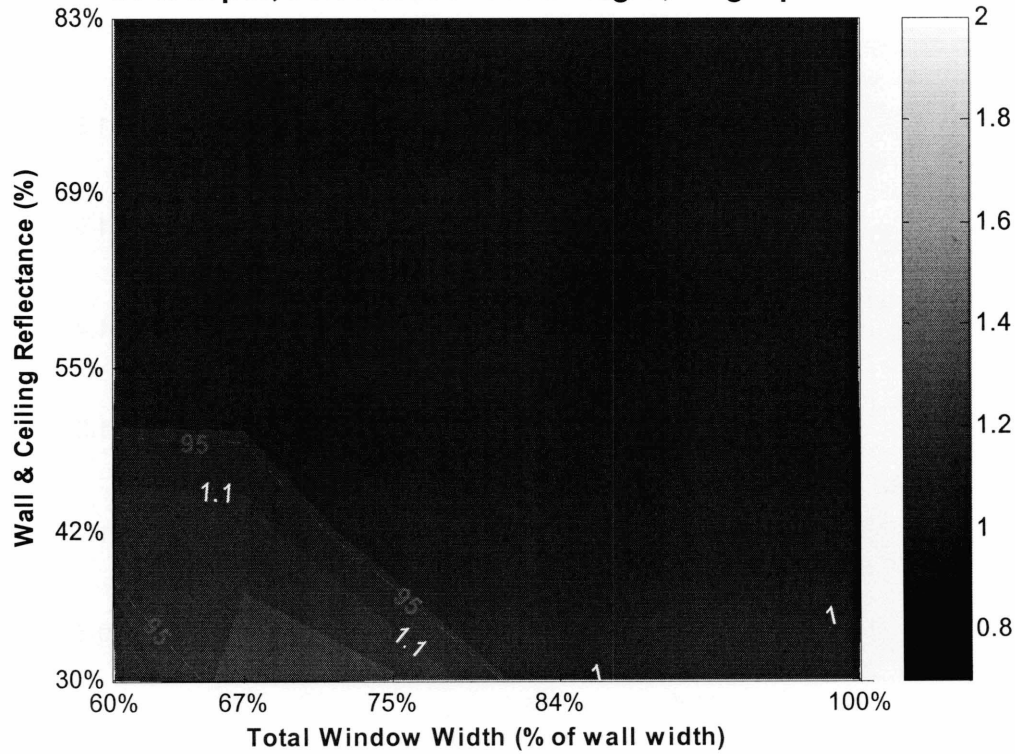
**Ani 30 Expected Improvement:  
20 ft depth, 9ft window head height, single pane**



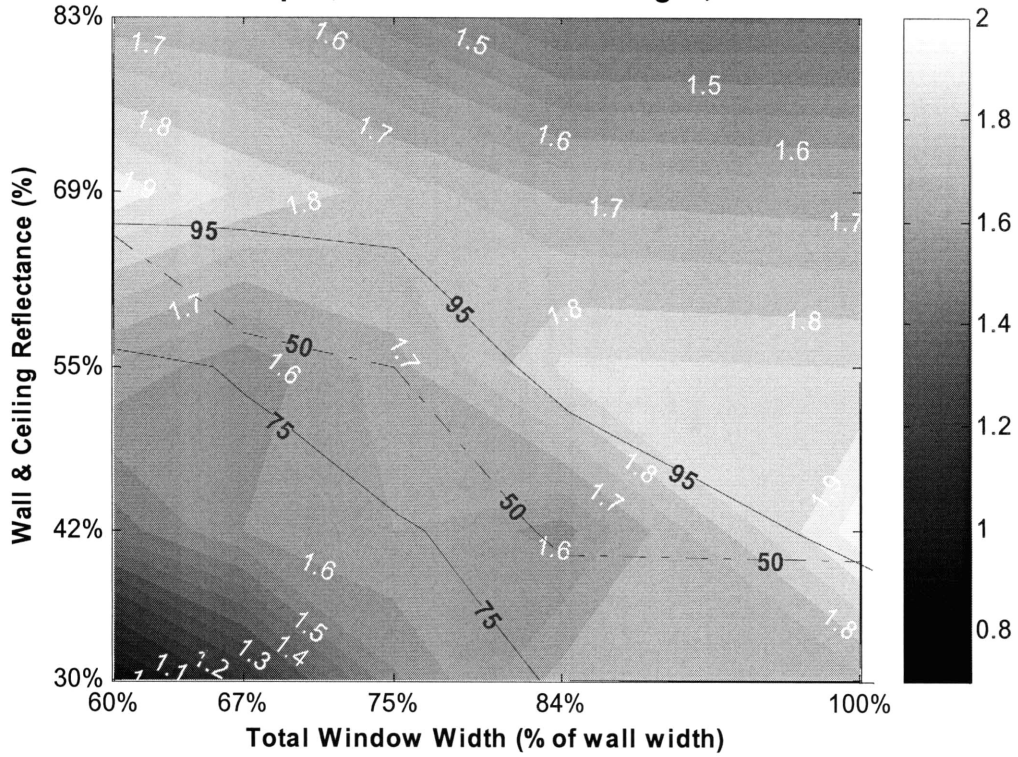
**Ani 30 Expected Improvement:  
20 ft depth, 10ft window head height, single pane**



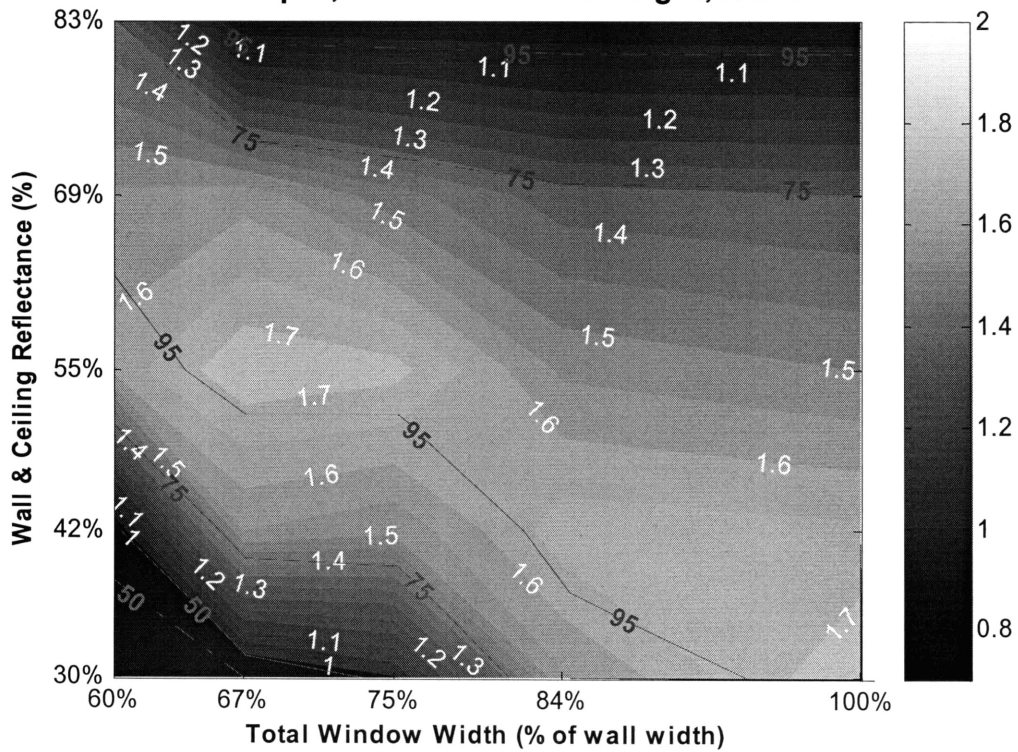
**Ani 30 Expected Improvement:  
20 ft depth, 11ft window head height, single pane**



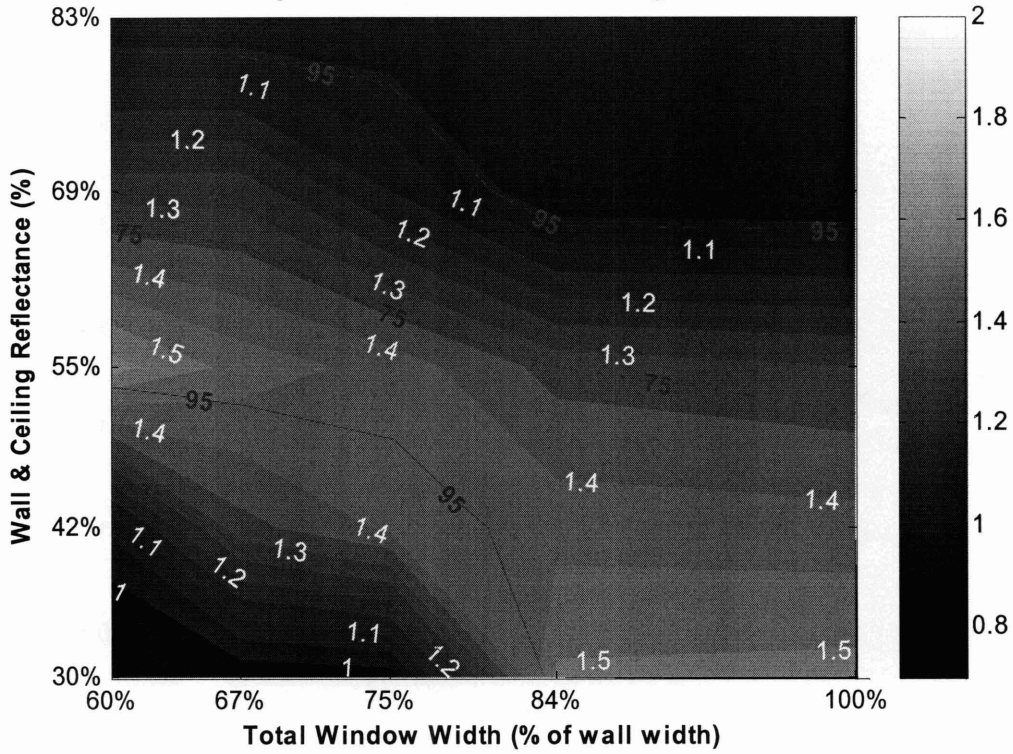
**Ani 30 Expected Improvement:  
20 ft depth, 7ft window head height, low-e**



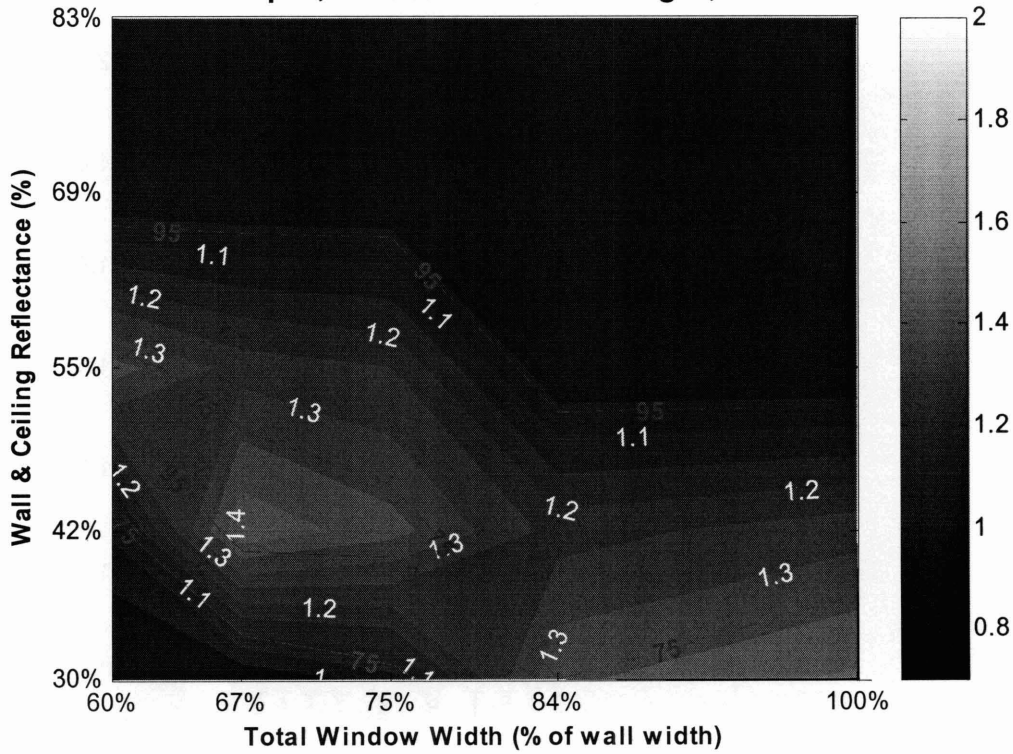
**Ani 30 Expected Improvement:  
20 ft depth, 8ft window head height, low-e**



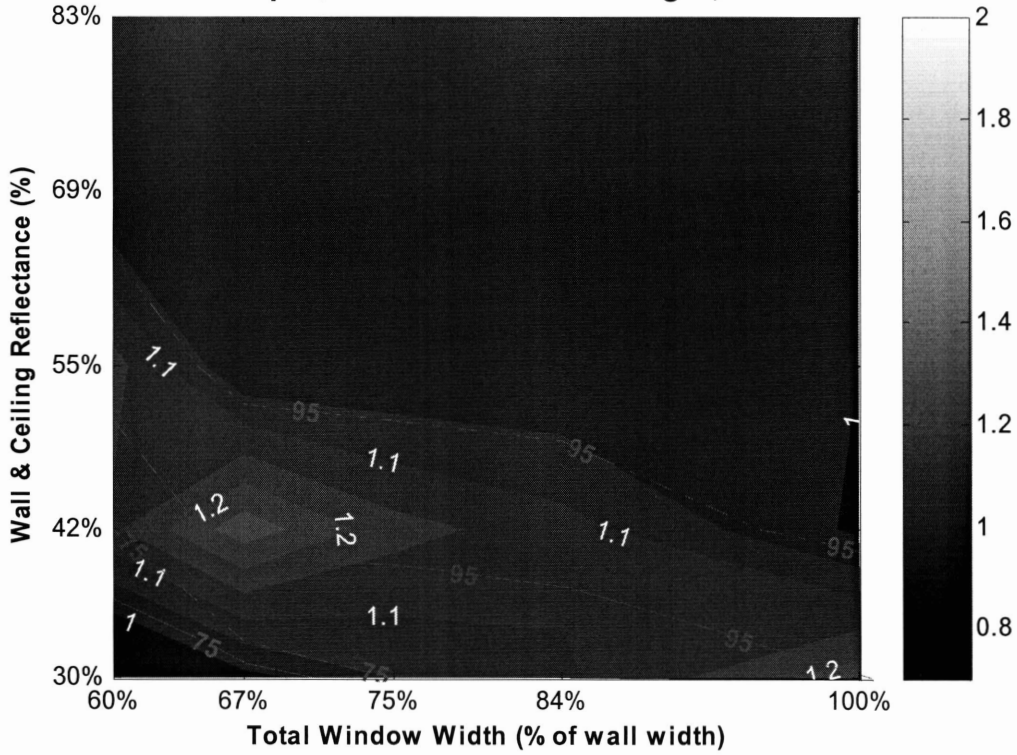
**Ani 30 Expected Improvement:  
20 ft depth, 9ft window head height, low-e**



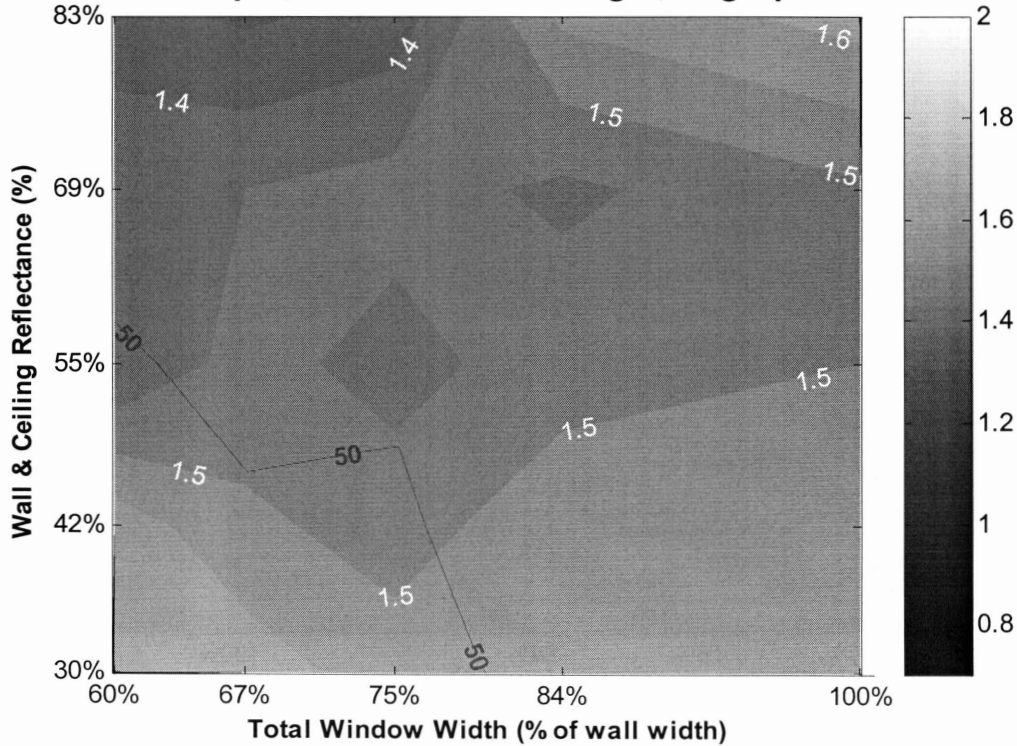
**Ani 30 Expected Improvement:  
20 ft depth, 10ft window head height, low-e**



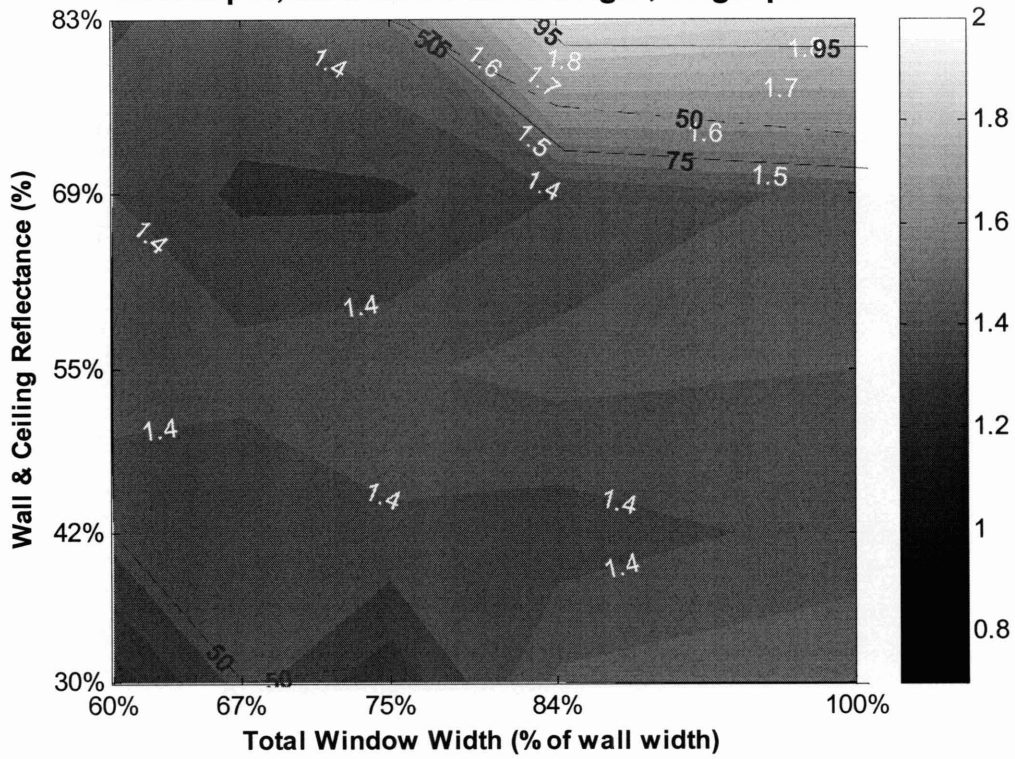
**Ani 30 Expected Improvement:  
20 ft depth, 11ft window head height, low-e**



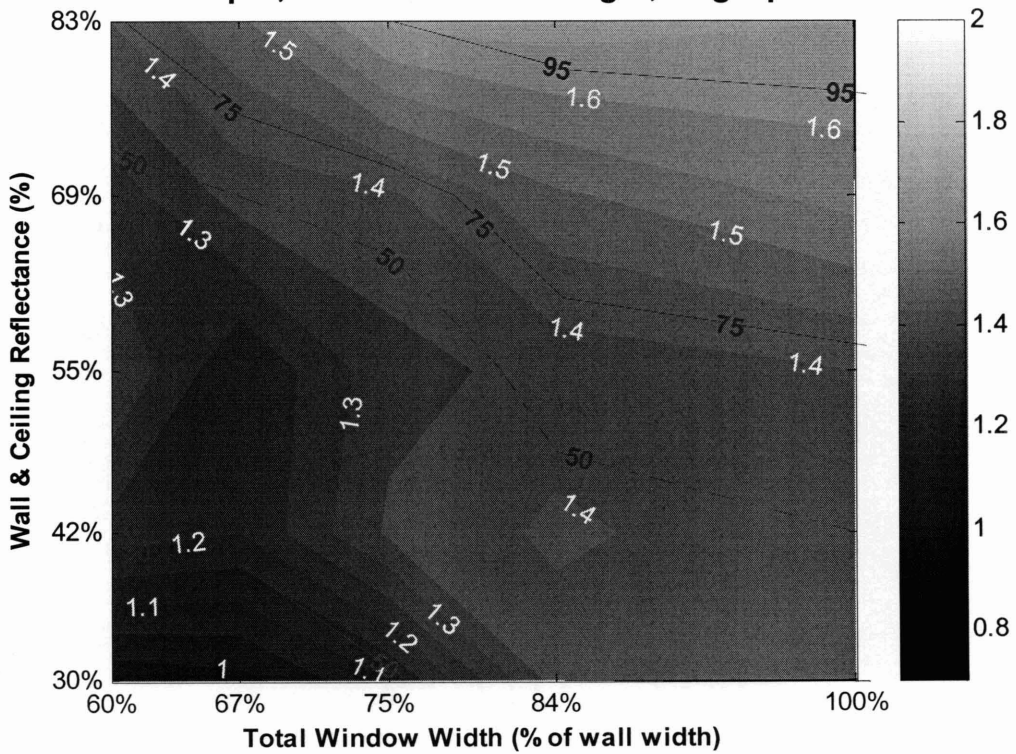
**Ani 30 Expected Improvement:  
30 ft depth, 7ft window head height, single pane**



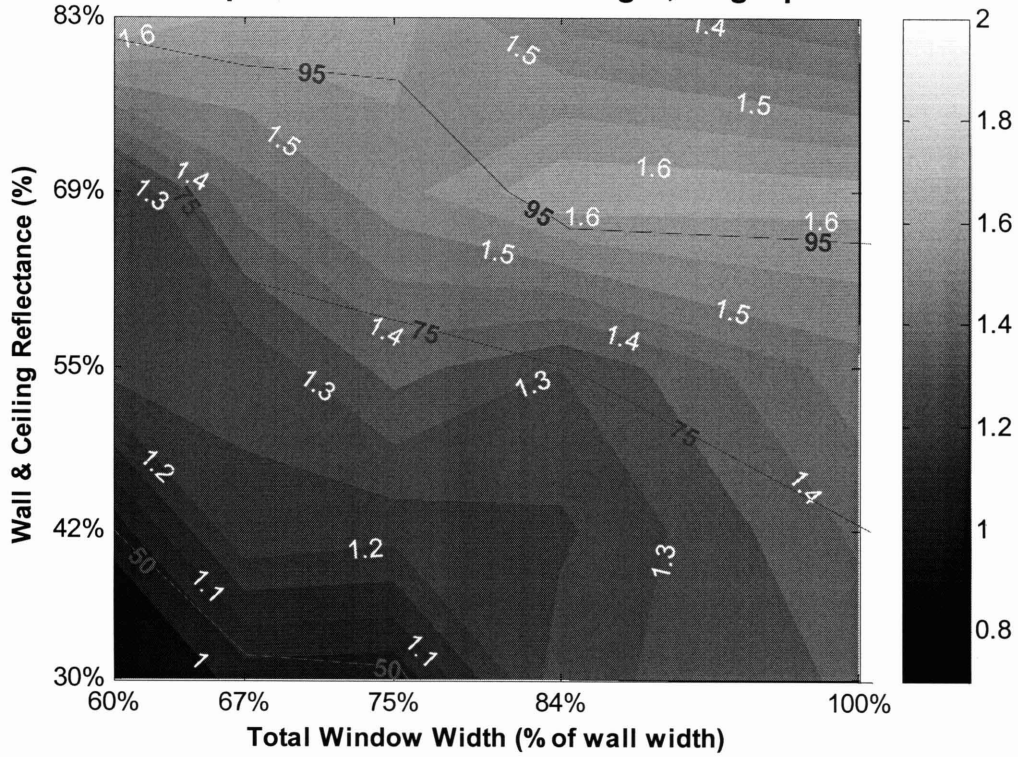
**Ani 30 Expected Improvement:  
30 ft depth, 8ft window head height, single pane**



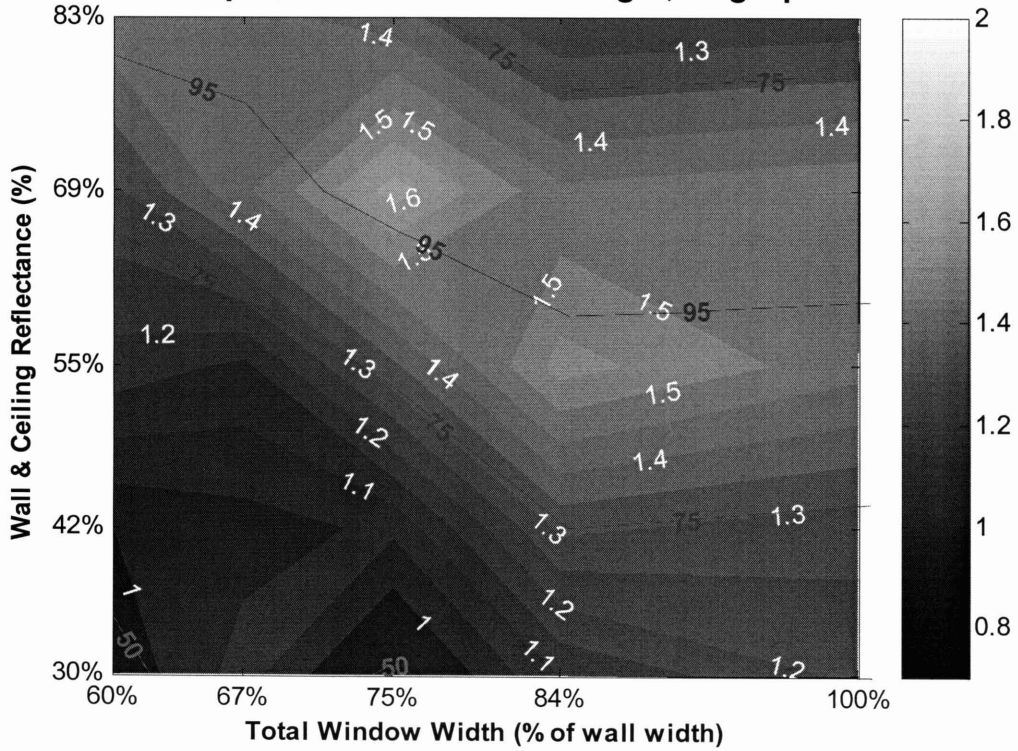
**Ani 30 Expected Improvement:  
30 ft depth, 9ft window head height, single pane**



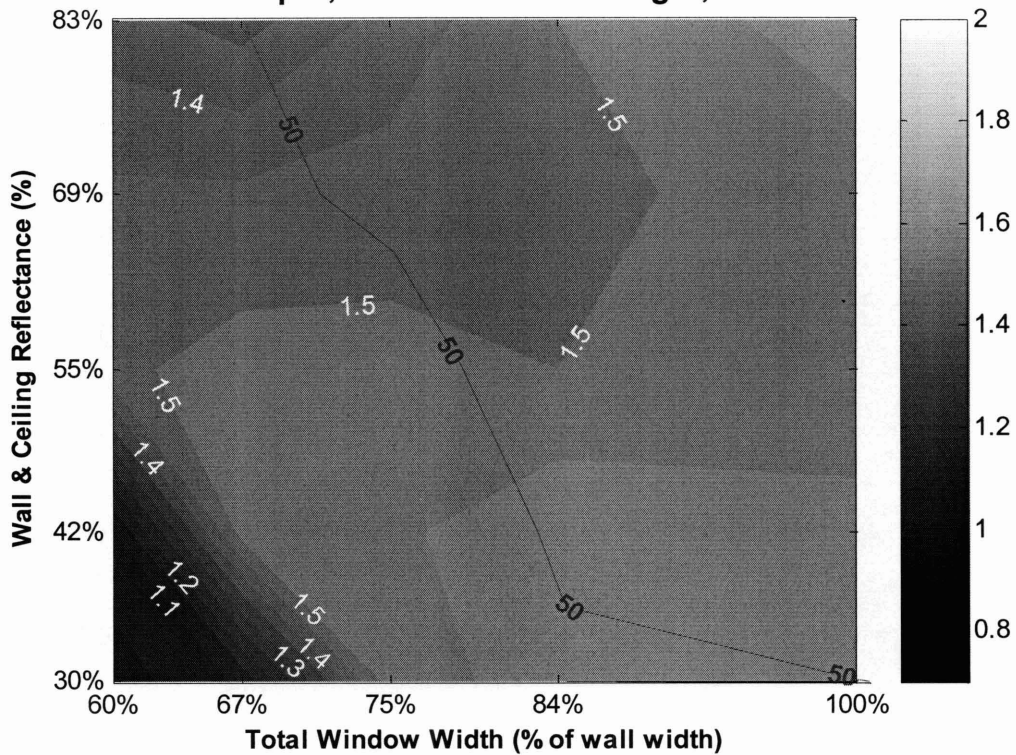
**Ani 30 Expected Improvement:  
30 ft depth, 10ft window head height, single pane**



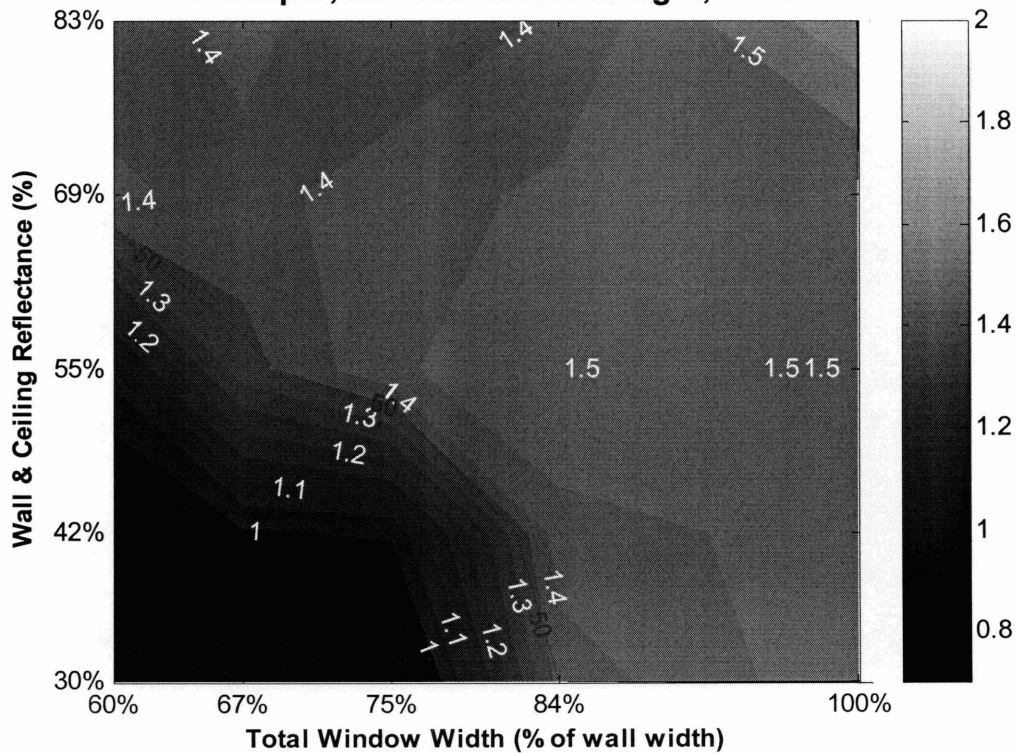
**Ani 30 Expected Improvement:  
30 ft depth, 11ft window head height, single pane**



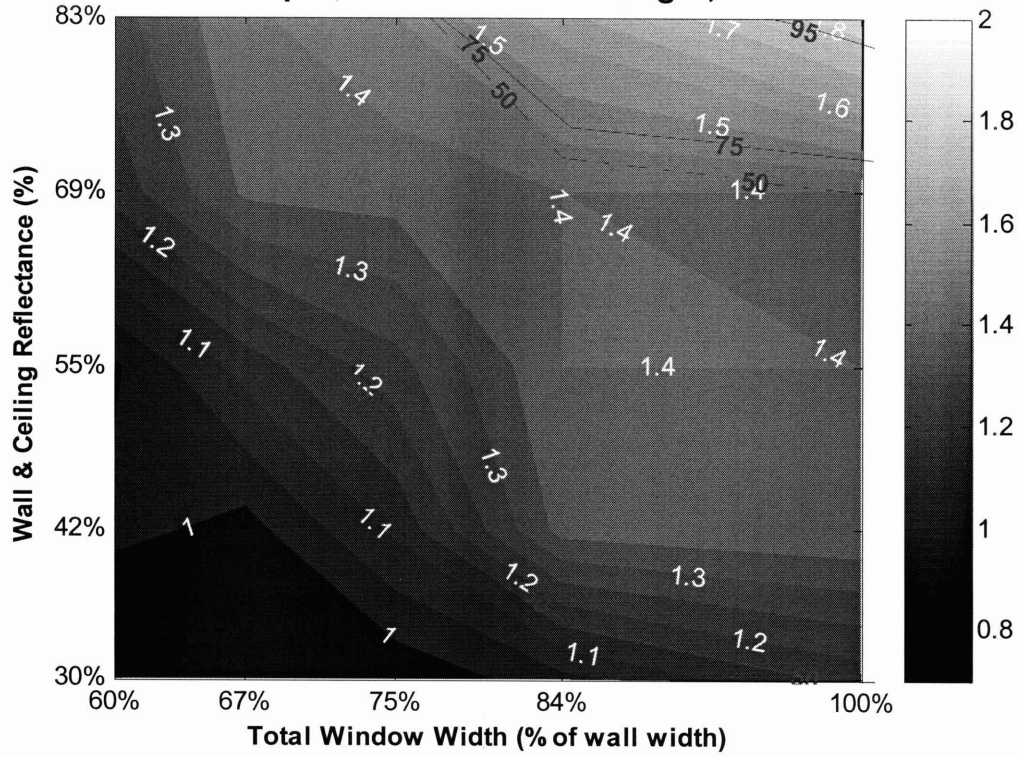
**Ani 30 Expected Improvement:  
30 ft depth, 7ft window head height, low-e**



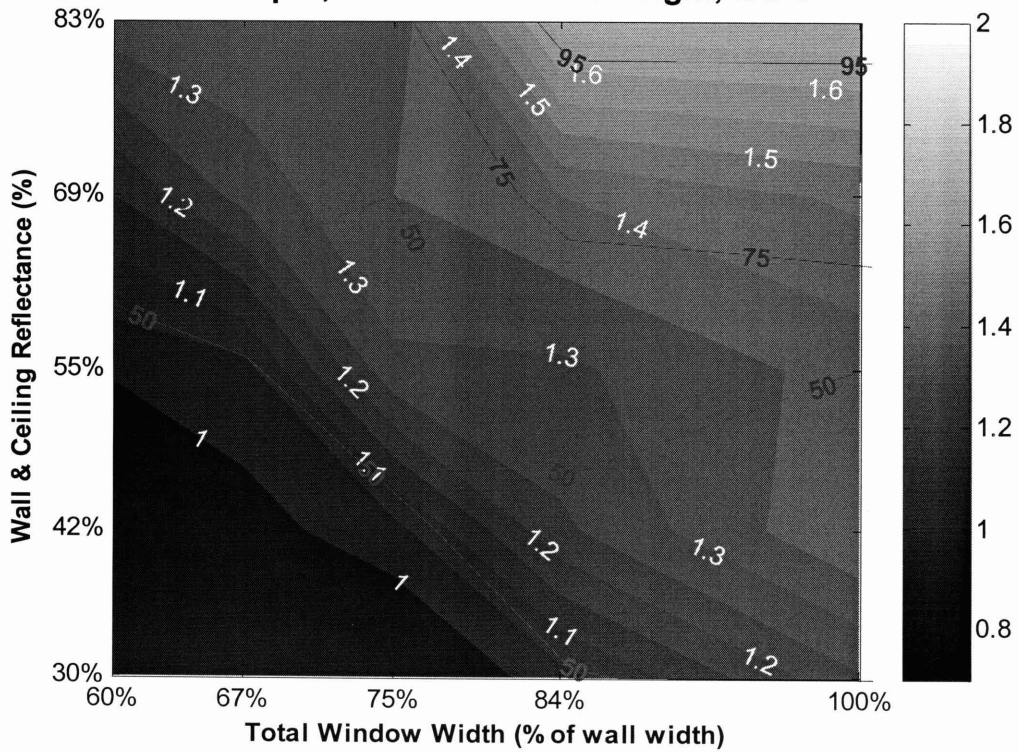
**Ani 30 Expected Improvement:  
30 ft depth, 8ft window head height, low-e**



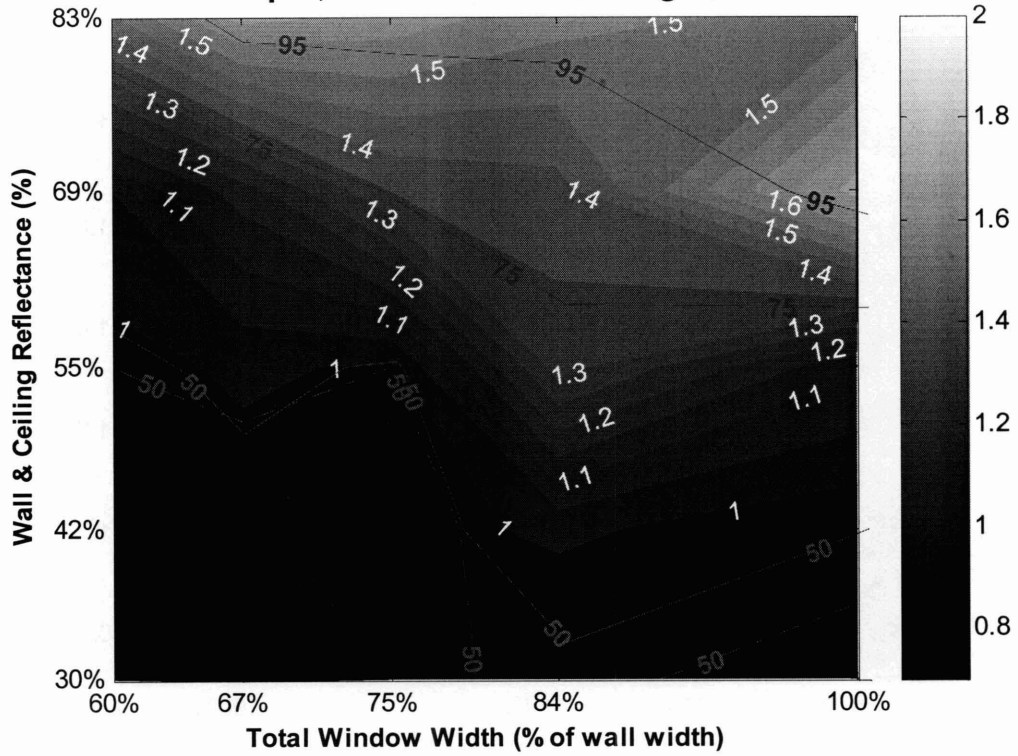
**Ani 30 Expected Improvement:  
30 ft depth, 9ft window head height, low-e**



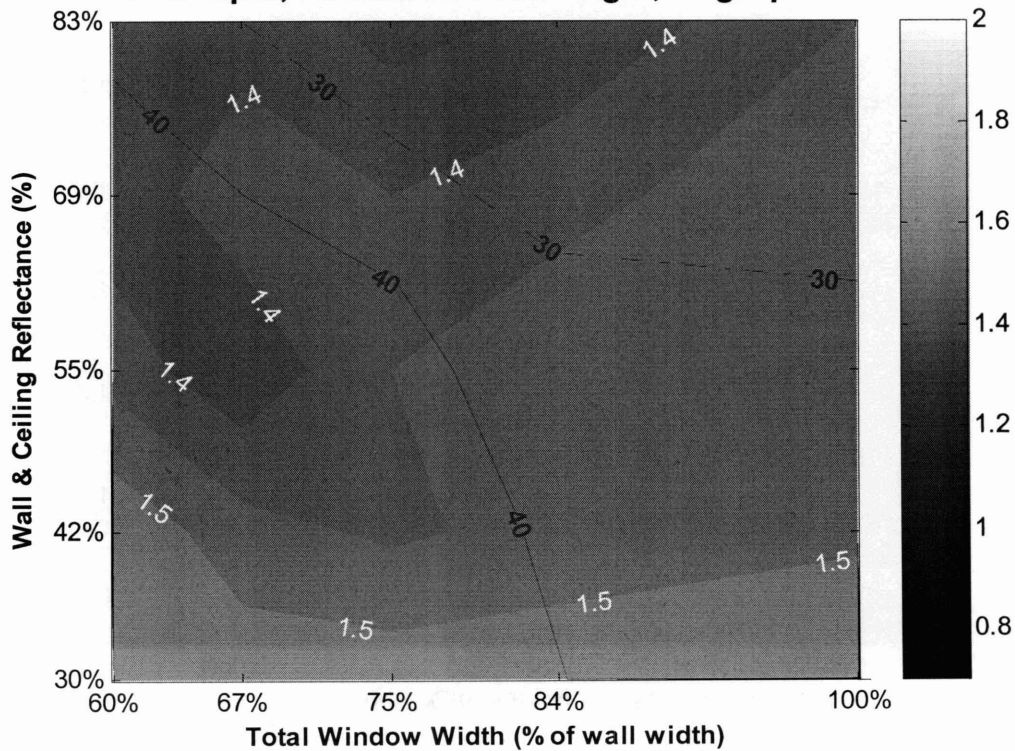
**Ani 30 Expected Improvement:  
30 ft depth, 10ft window head height, low-e**



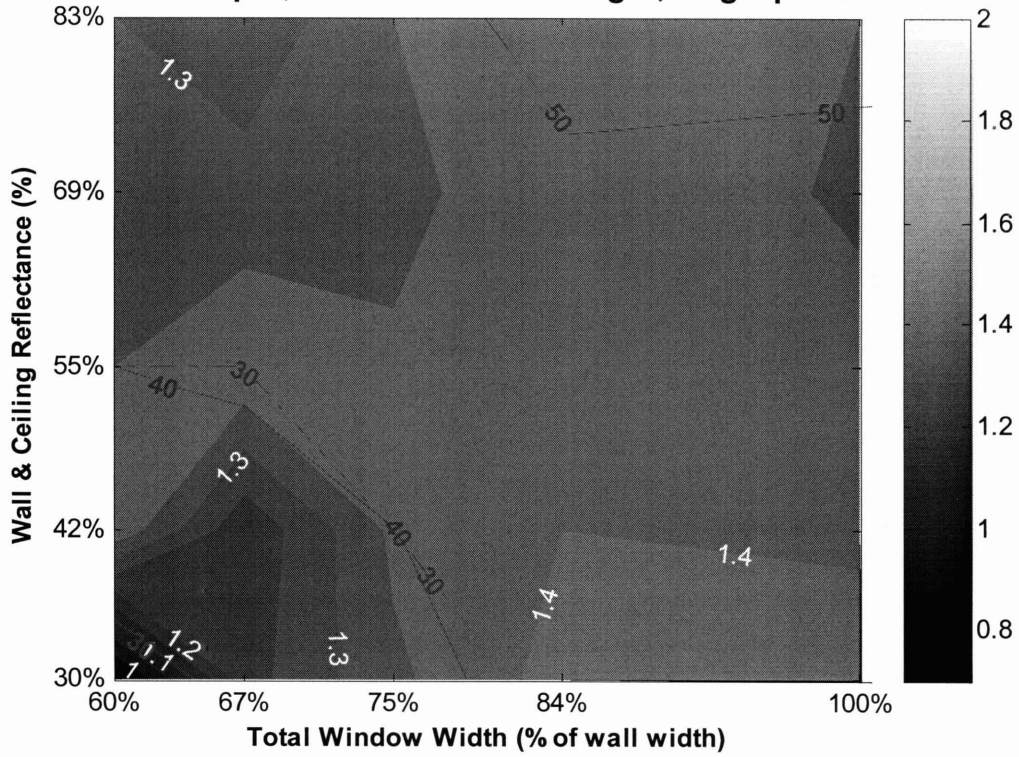
**Ani 30 Expected Improvement:  
30 ft depth, 11ft window head height, low-e**



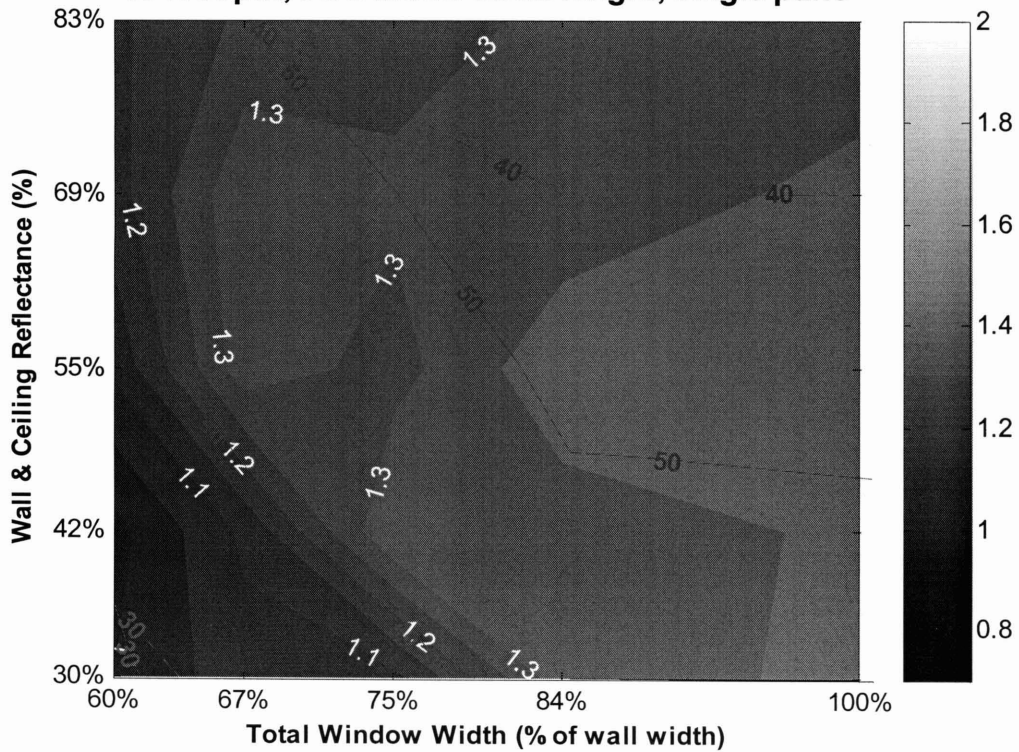
**Ani 30 Expected Improvement:  
40 ft depth, 7ft window head height, single pane**



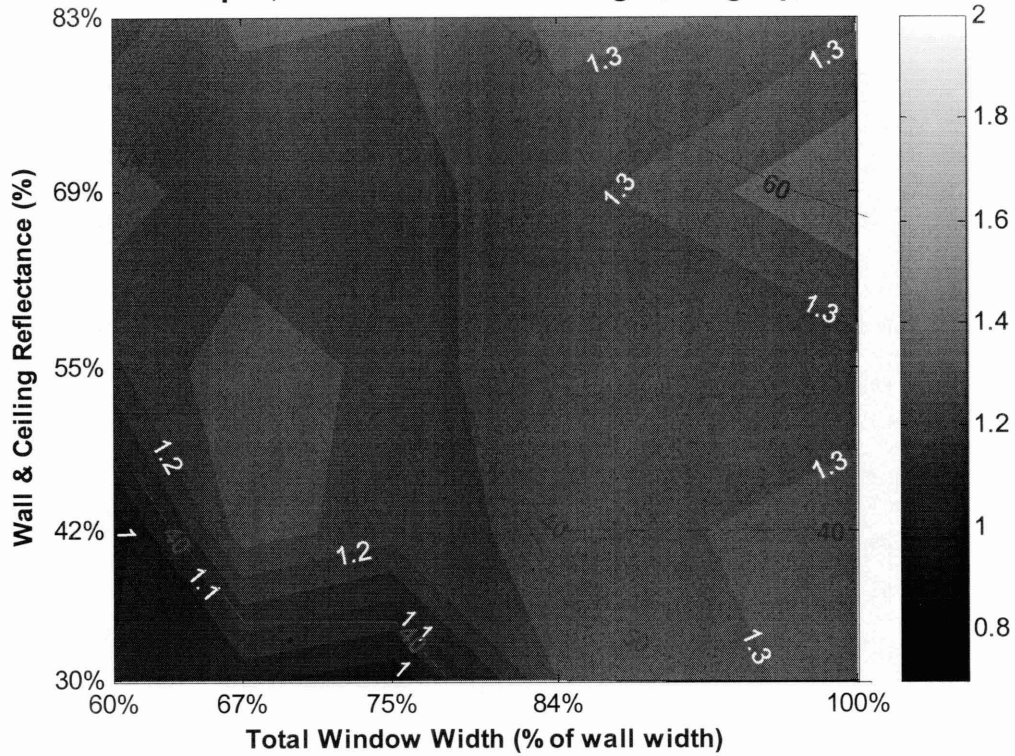
**Ani 30 Expected Improvement:  
40 ft depth, 8ft window head height, single pane**



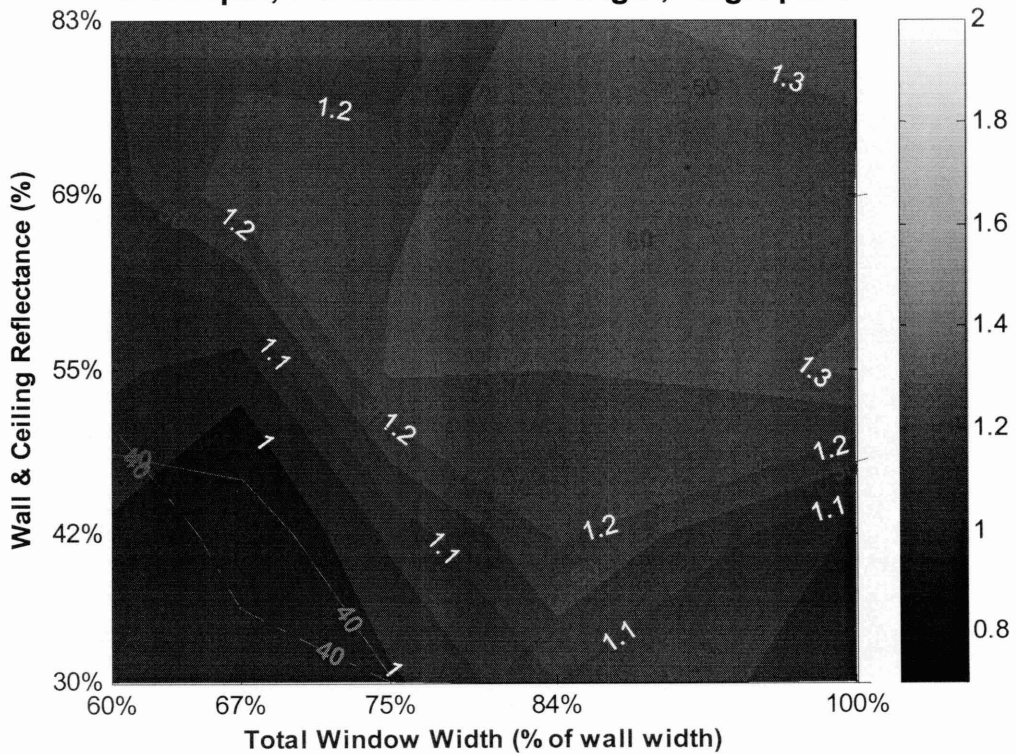
**Ani 30 Expected Improvement:  
40 ft depth, 9ft window head height, single pane**



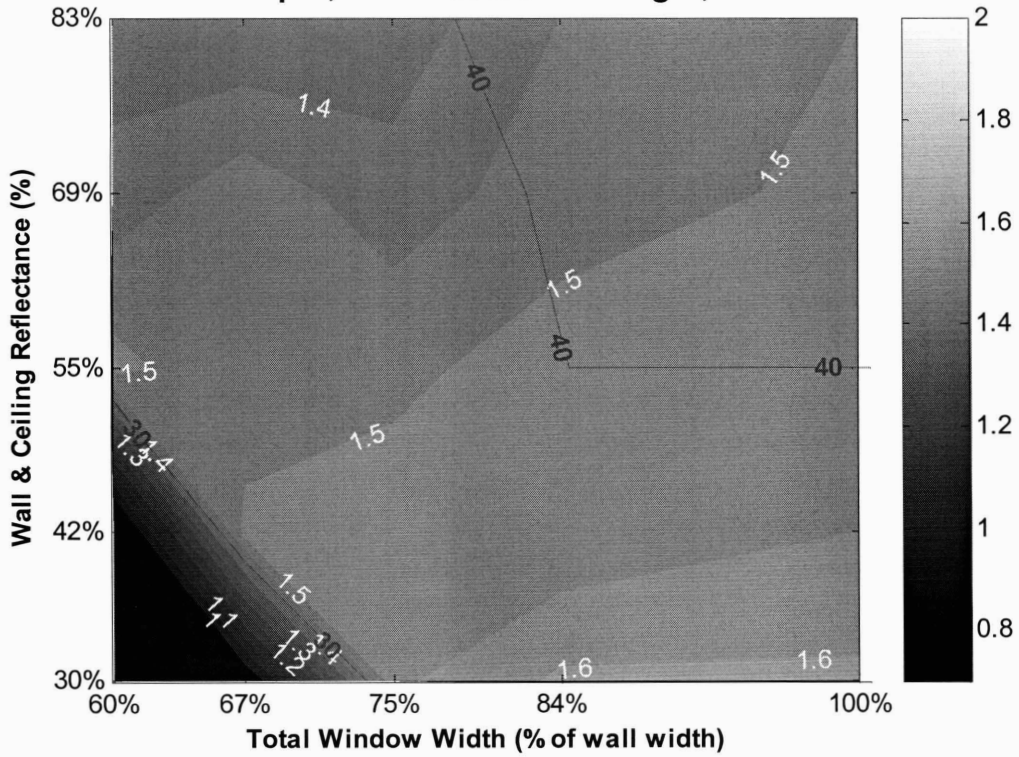
**Ani 30 Expected Improvement:  
40 ft depth, 10ft window head height, single pane**



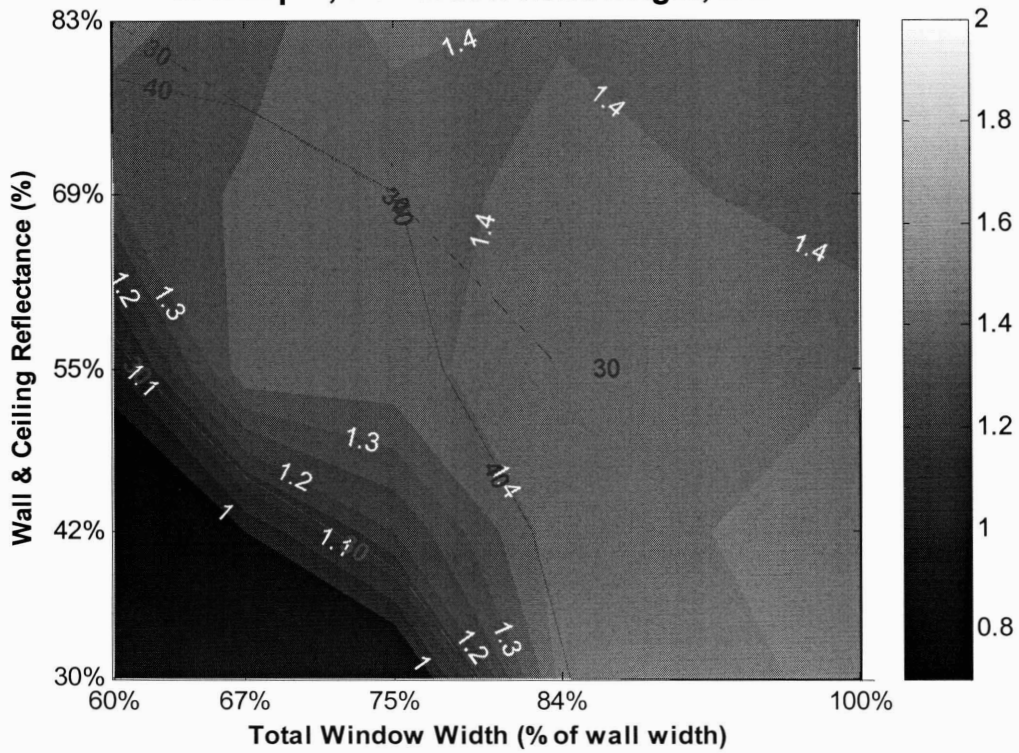
**Ani 30 Expected Improvement:  
40 ft depth, 11ft window head height, single pane**

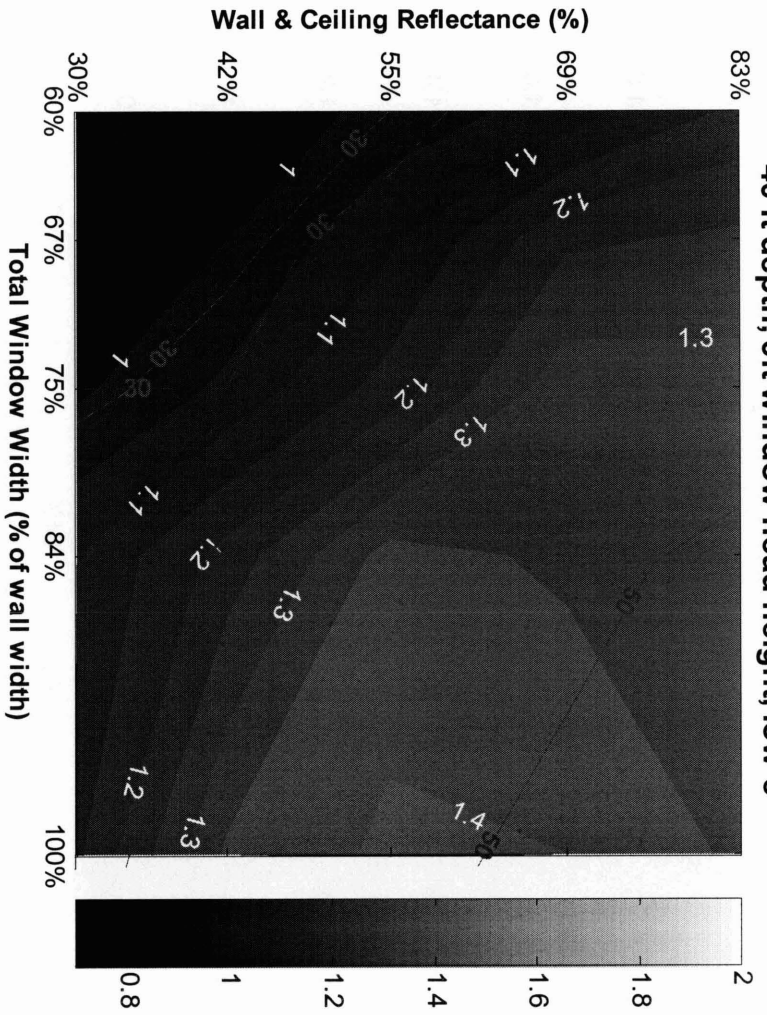


**Ani 30 Expected Improvement:  
40 ft depth, 7ft window head height, low-e**

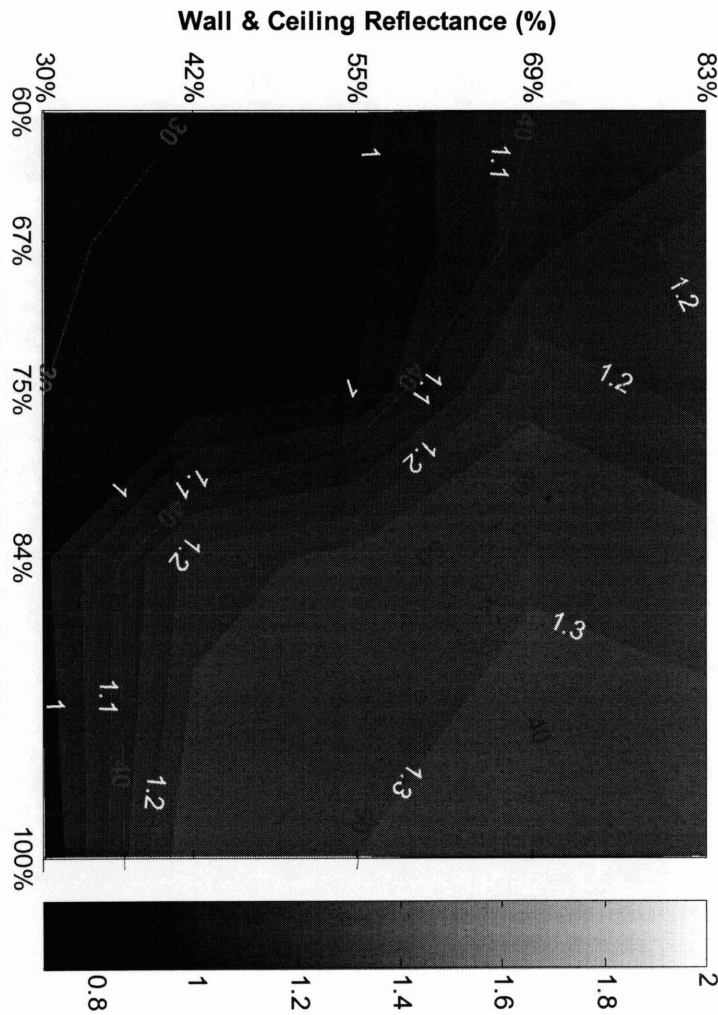


**Ani 30 Expected Improvement:  
40 ft depth, 8ft window head height, low-e**

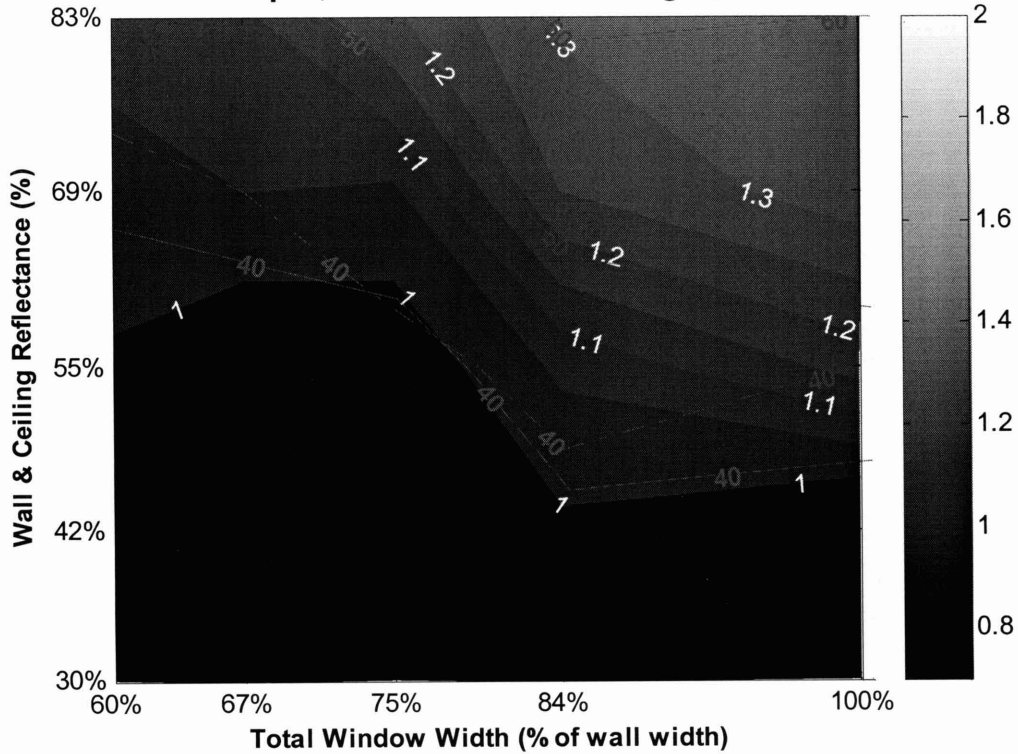




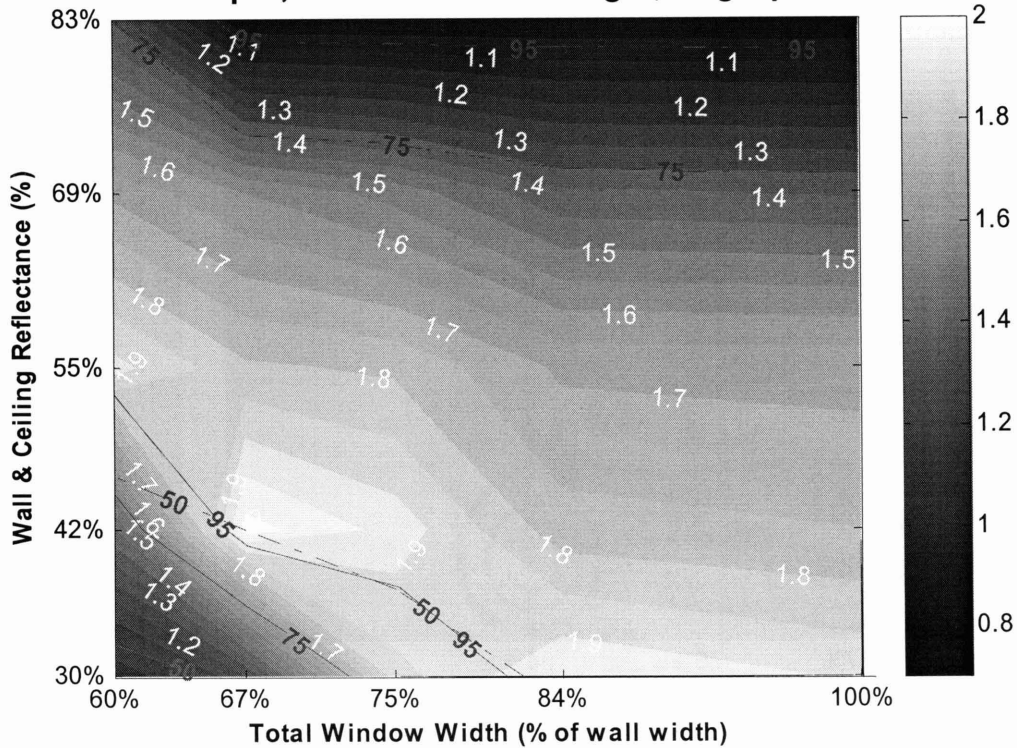
**Ani 30 Expected Improvement:  
40 ft depth, 10ft window head height, low-e**



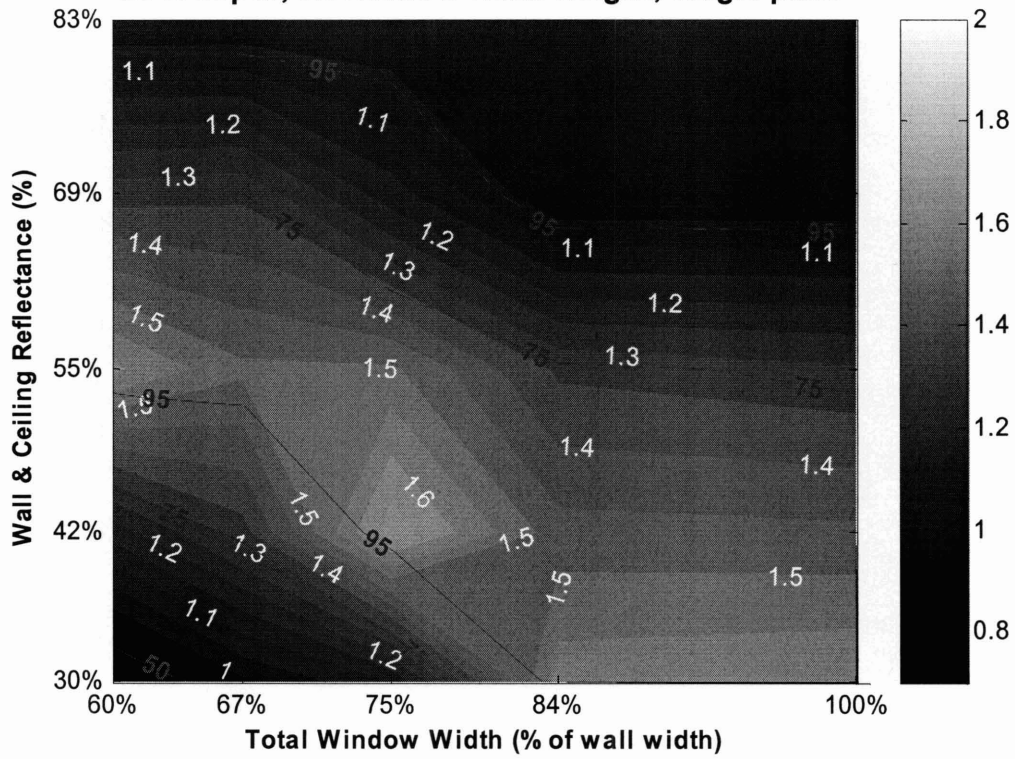
**Ani 30 Expected Improvement:  
40 ft depth, 11ft window head height, low-e**



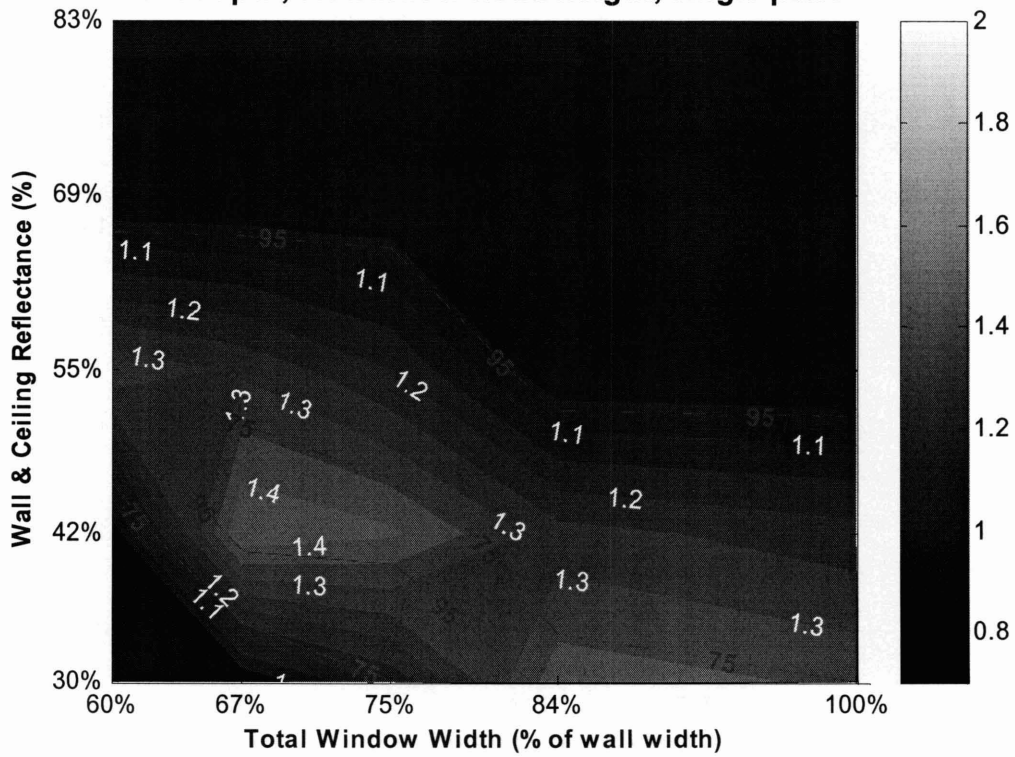
**Ani 25 Expected Improvement:  
20 ft depth, 7ft window head height, single pane**



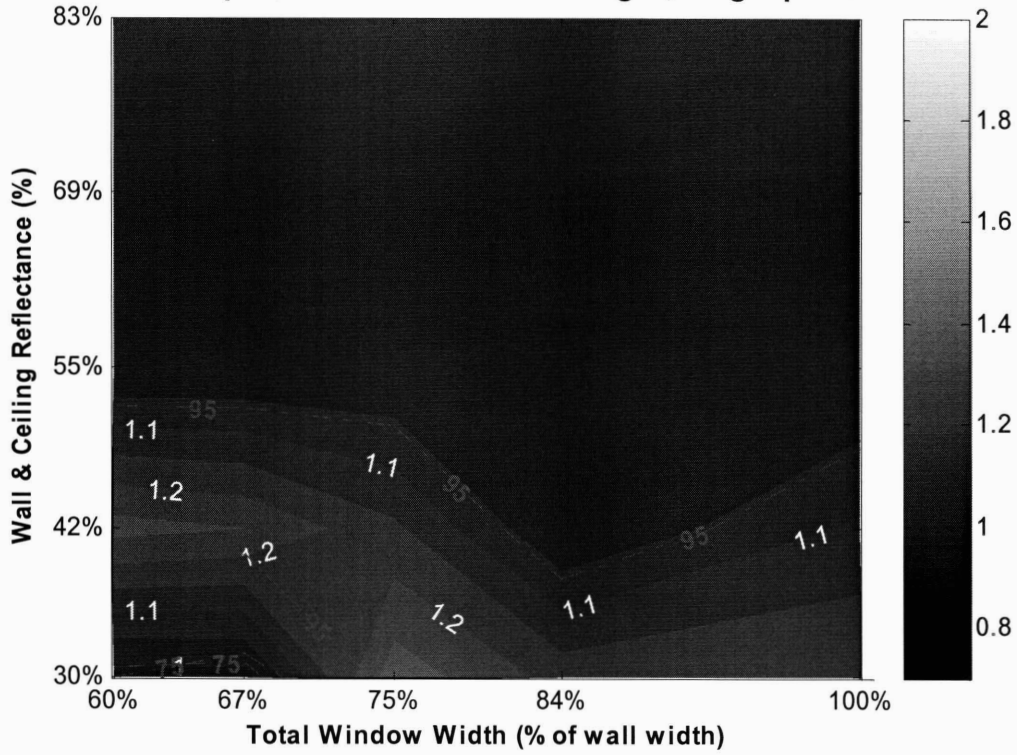
**Ani 25 Expected Improvement:  
20 ft depth, 8ft window head height, single pane**



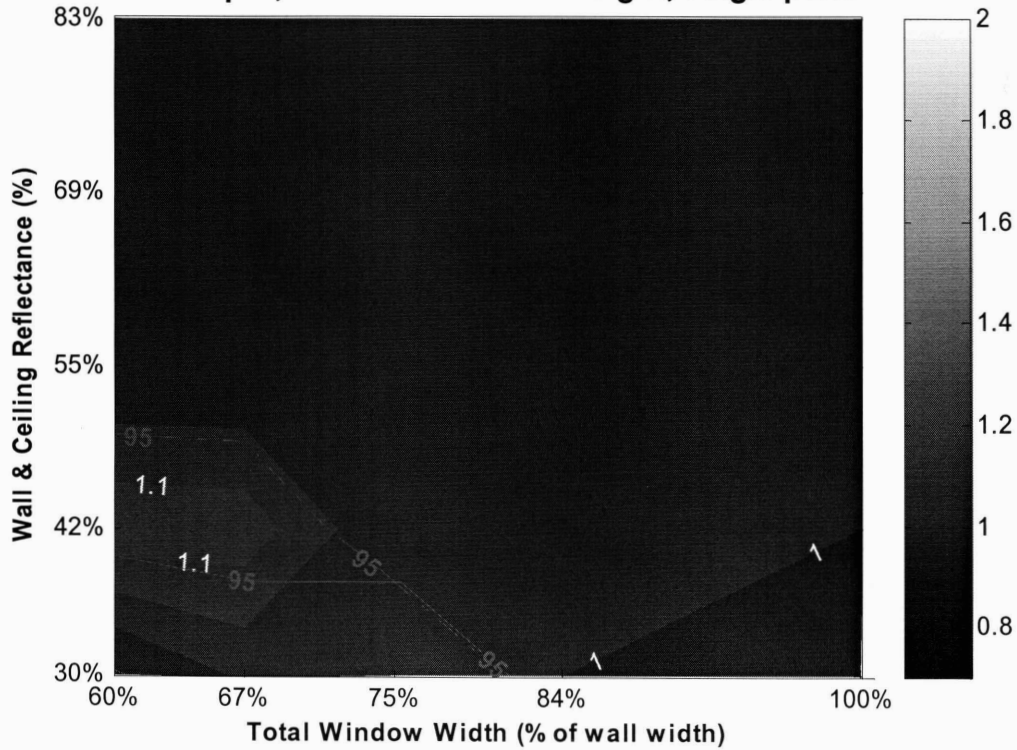
**Ani 25 Expected Improvement:  
20 ft depth, 9ft window head height, single pane**



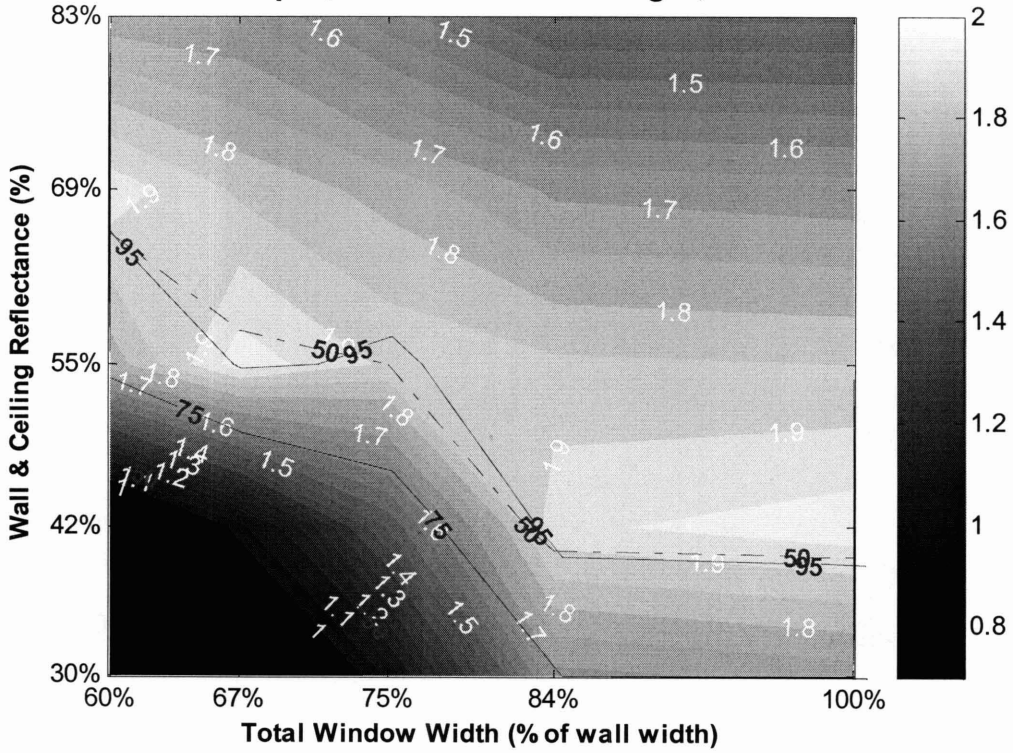
**Ani 25 Expected Improvement:  
20 ft depth, 10ft window head height, single pane**



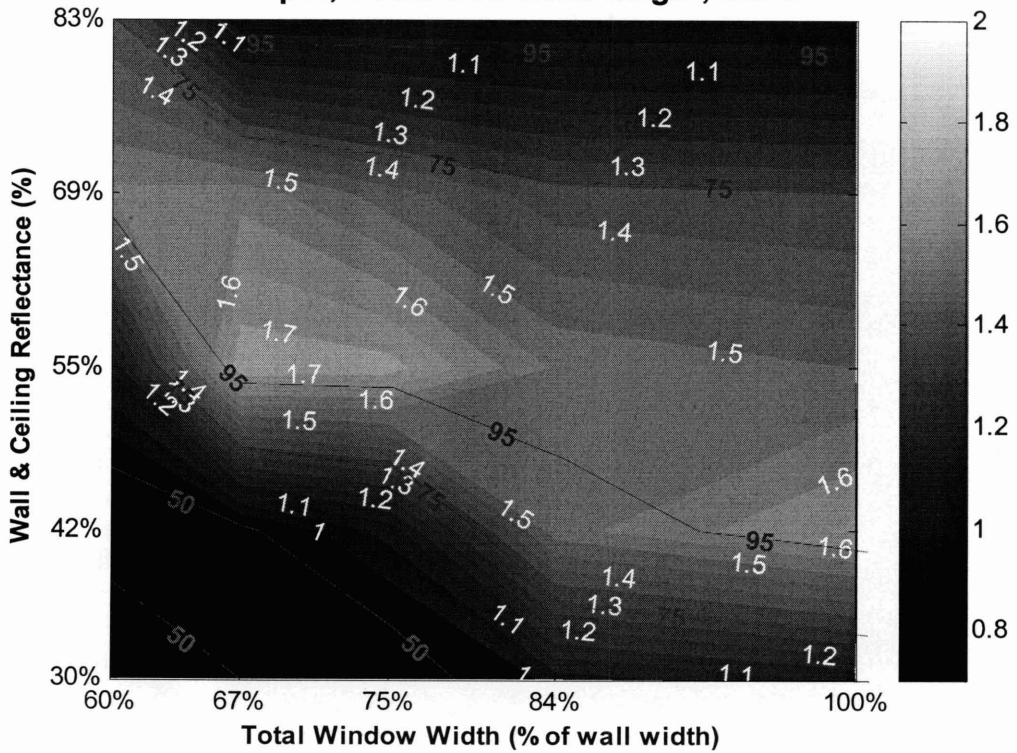
**Ani 25 Expected Improvement:  
20 ft depth, 11ft window head height, single pane**



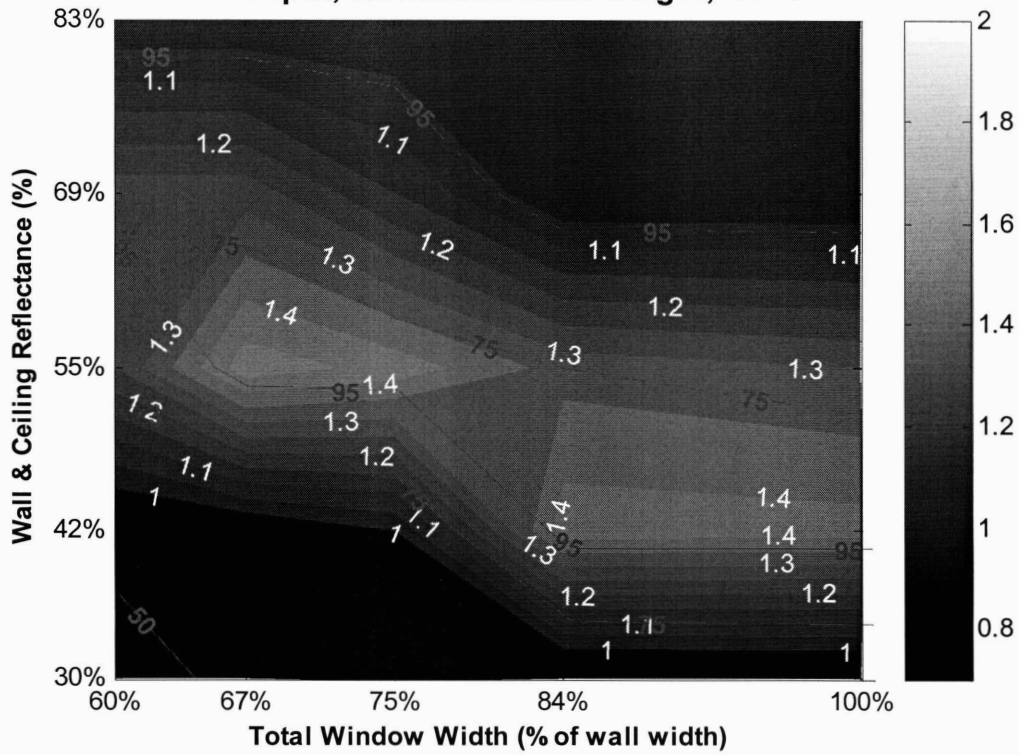
**Ani 25 Expected Improvement:  
20 ft depth, 7ft window head height, low-e**



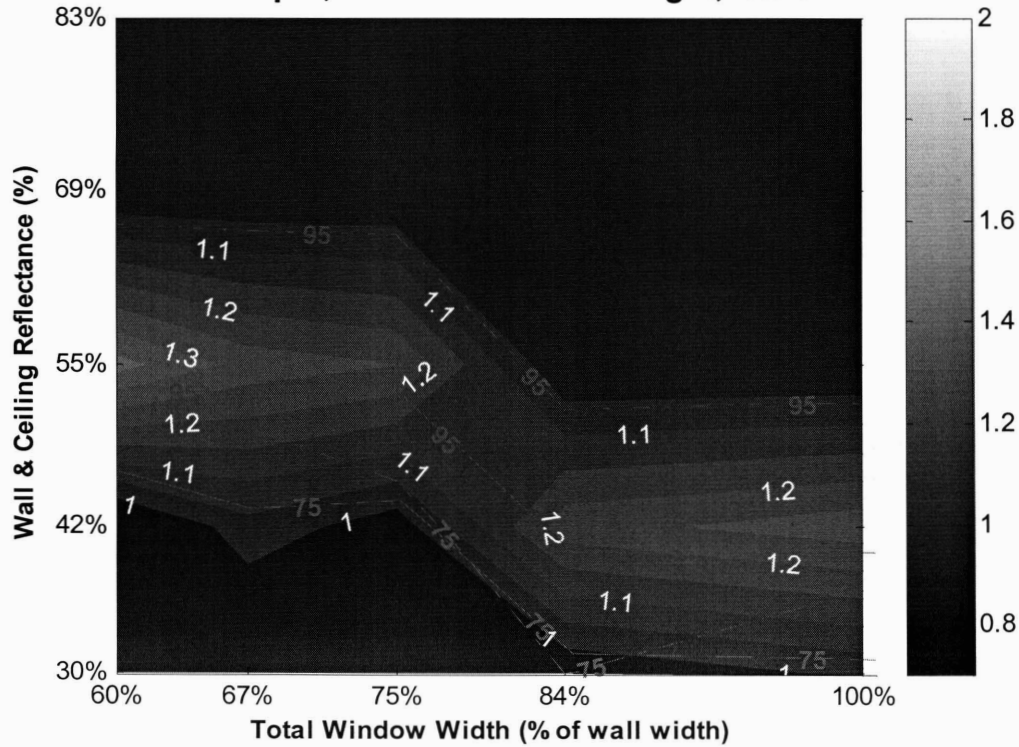
**Ani 25 Expected Improvement:  
20 ft depth, 8ft window head height, low-e**



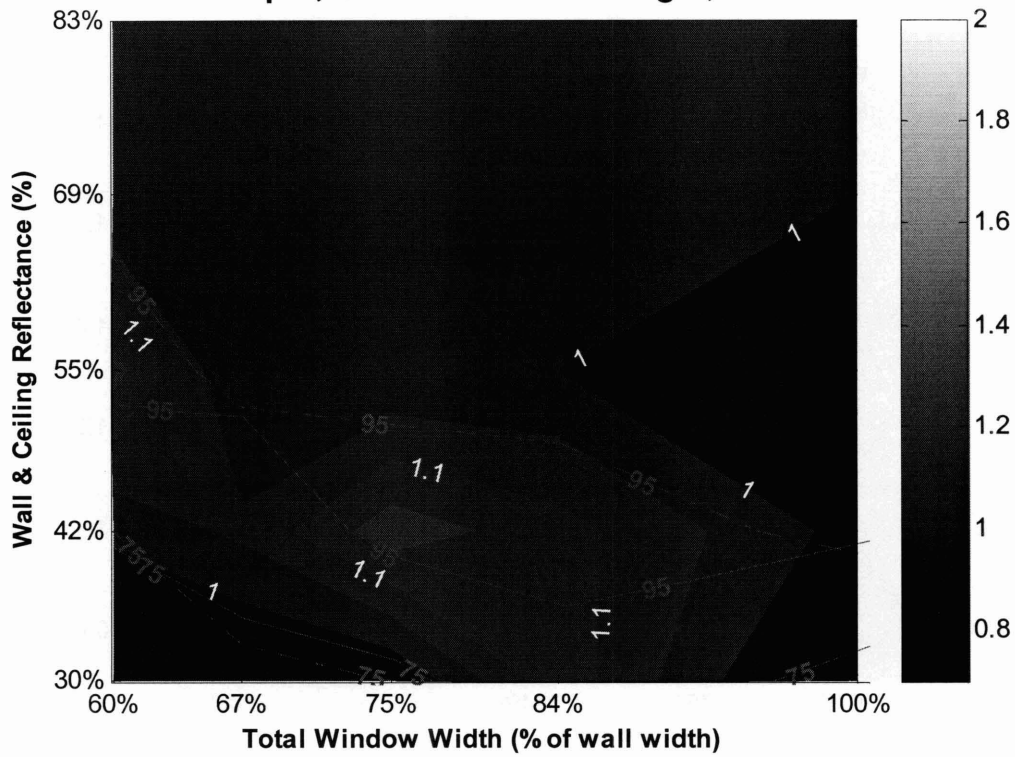
**Ani 25 Expected Improvement:  
20 ft depth, 9ft window head height, low-e**



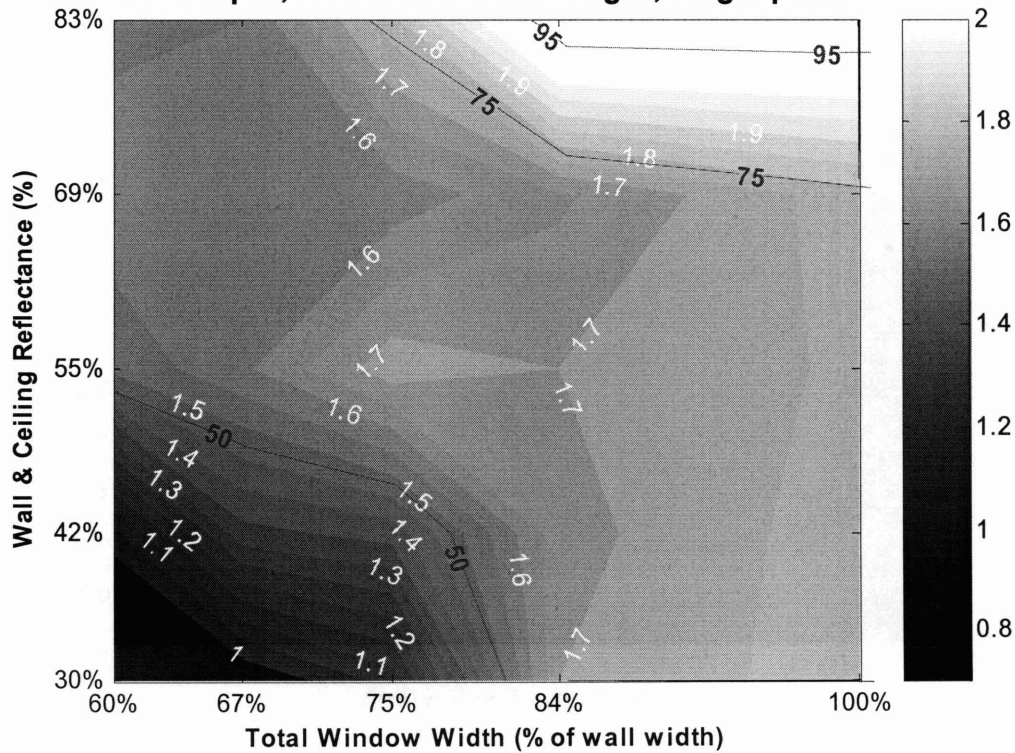
**Ani 25 Expected Improvement:  
20 ft depth, 10ft window head height, low-e**



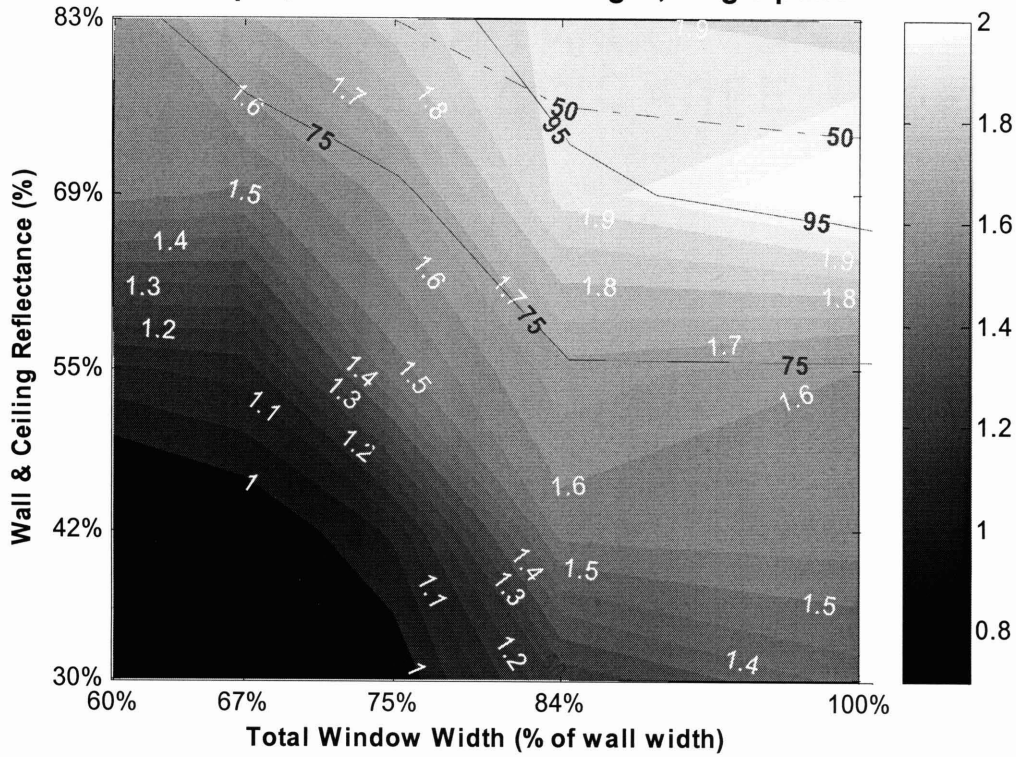
**Ani 25 Expected Improvement:  
20 ft depth, 11ft window head height, low-e**



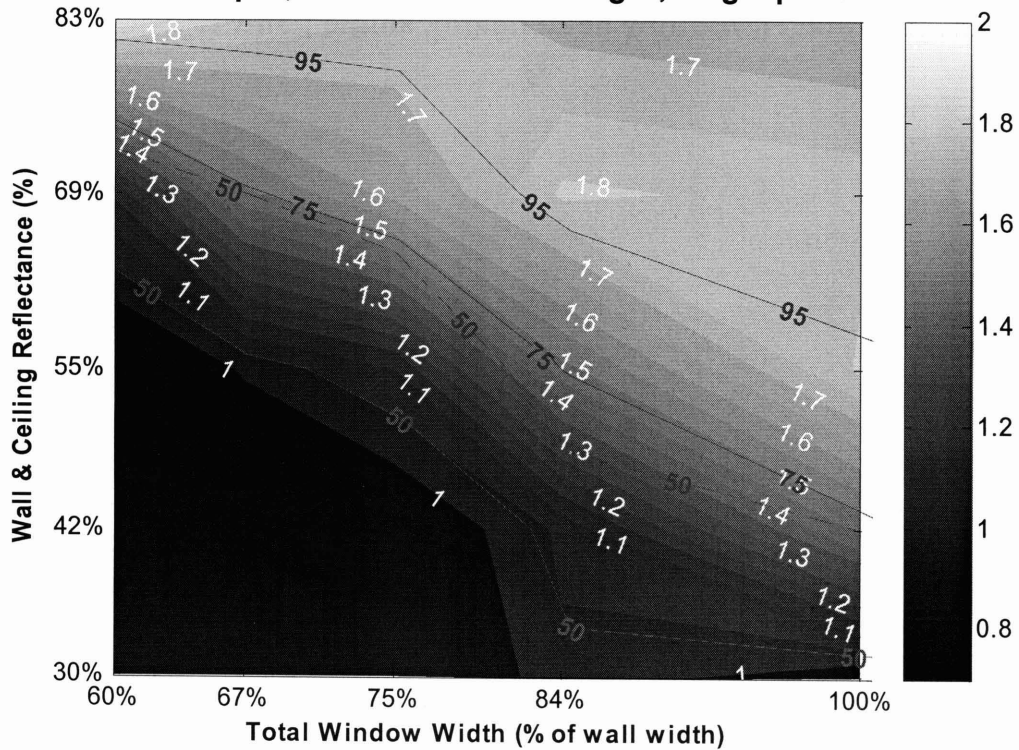
**Ani 25 Expected Improvement:  
30 ft depth, 7ft window head height, single pane**



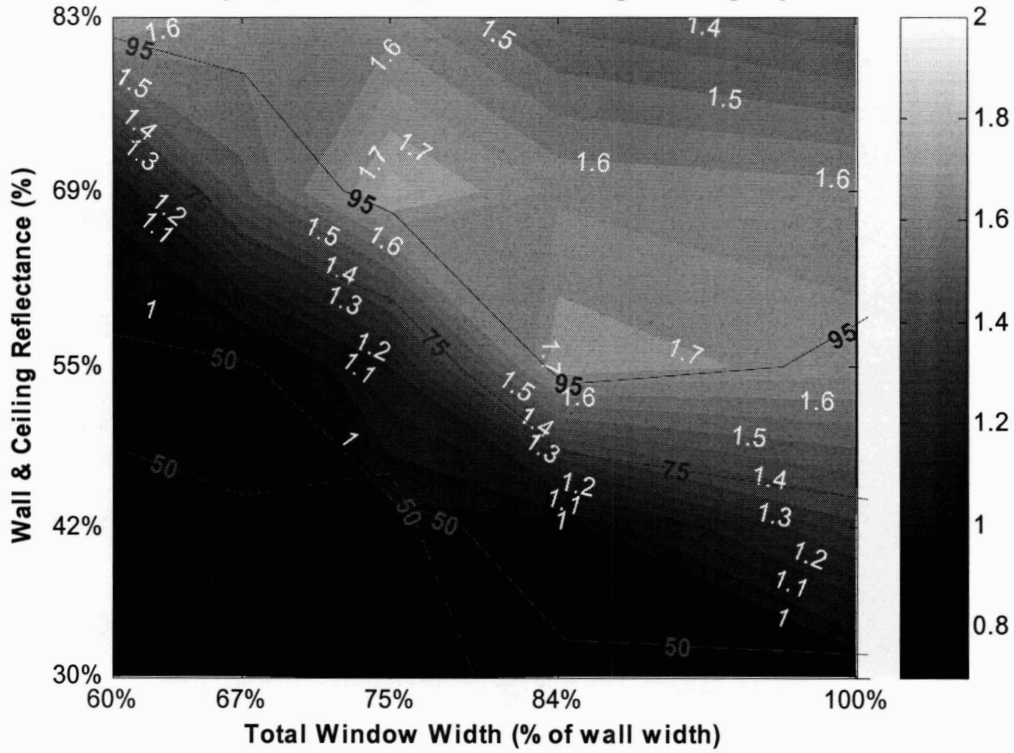
**Ani 25 Expected Improvement:  
30 ft depth, 8ft window head height, single pane**



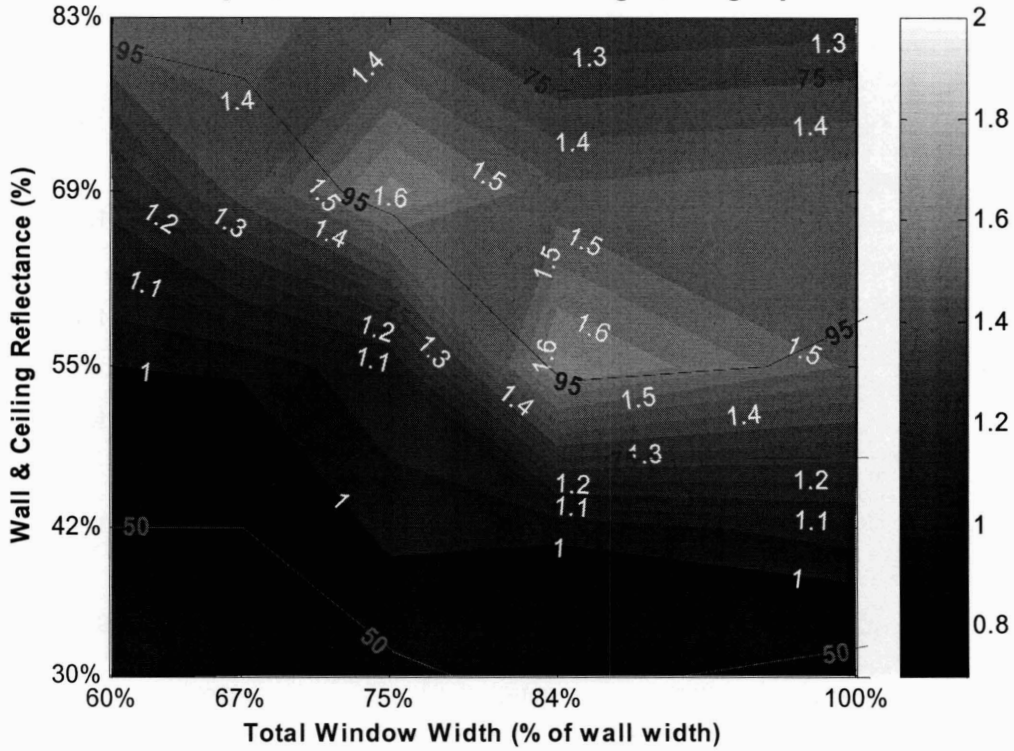
**Ani 25 Expected Improvement:  
30 ft depth, 9ft window head height, single pane**



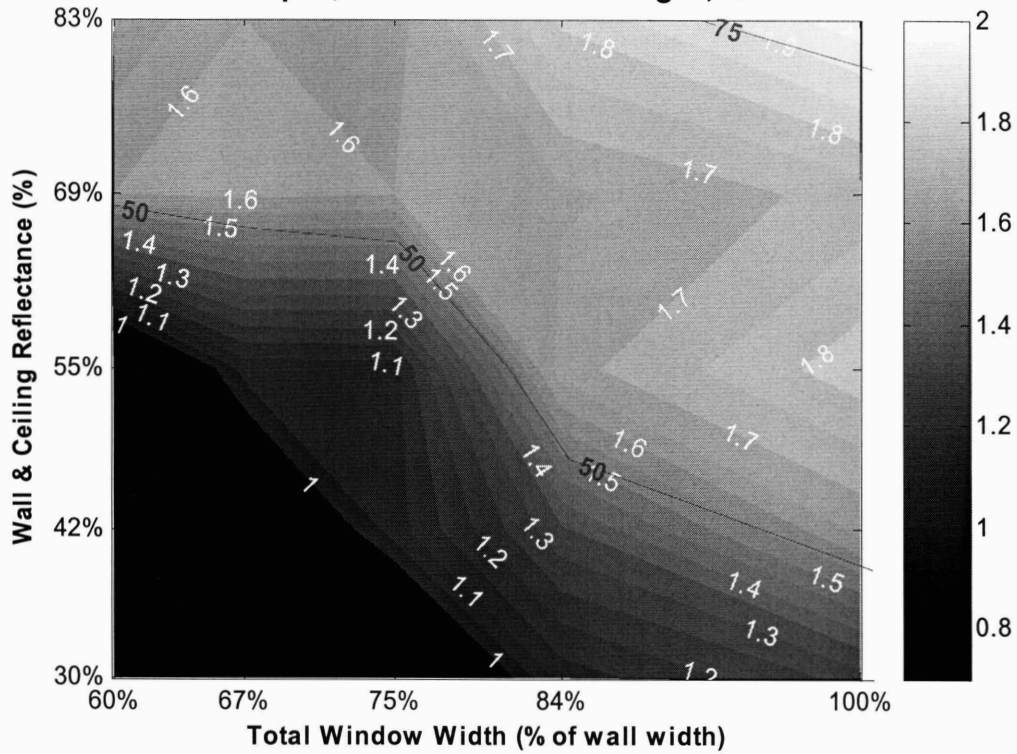
**Ani 25 Expected Improvement:  
30 ft depth, 10ft window head height, single pane**



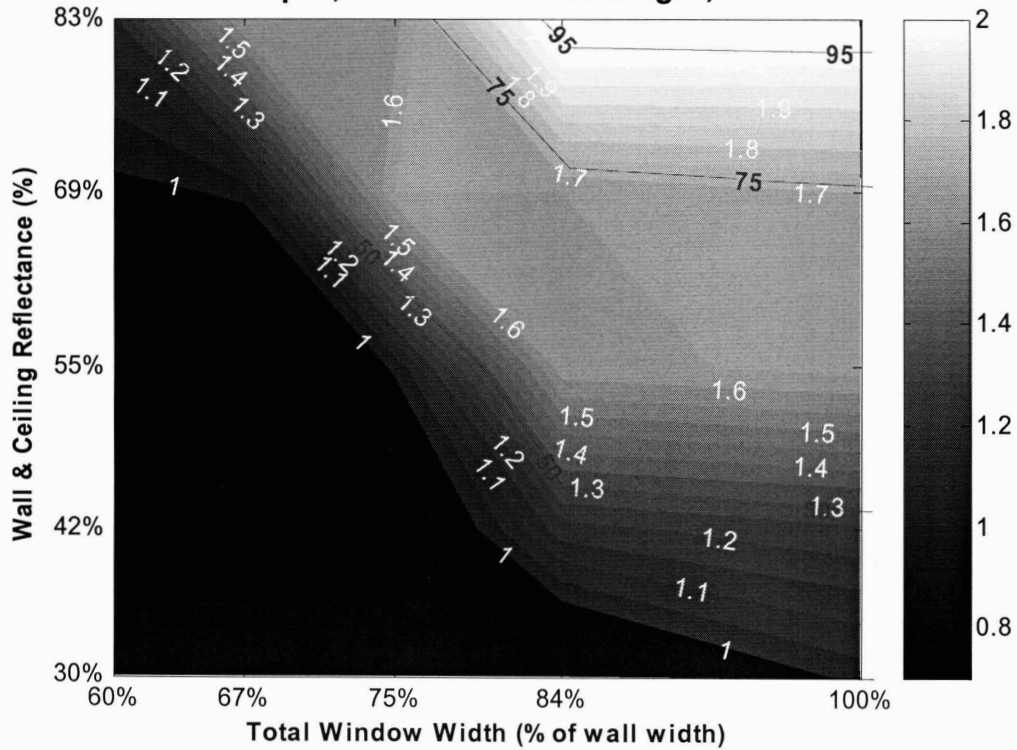
**Ani 25 Expected Improvement:  
30 ft depth, 11ft window head height, single pane**



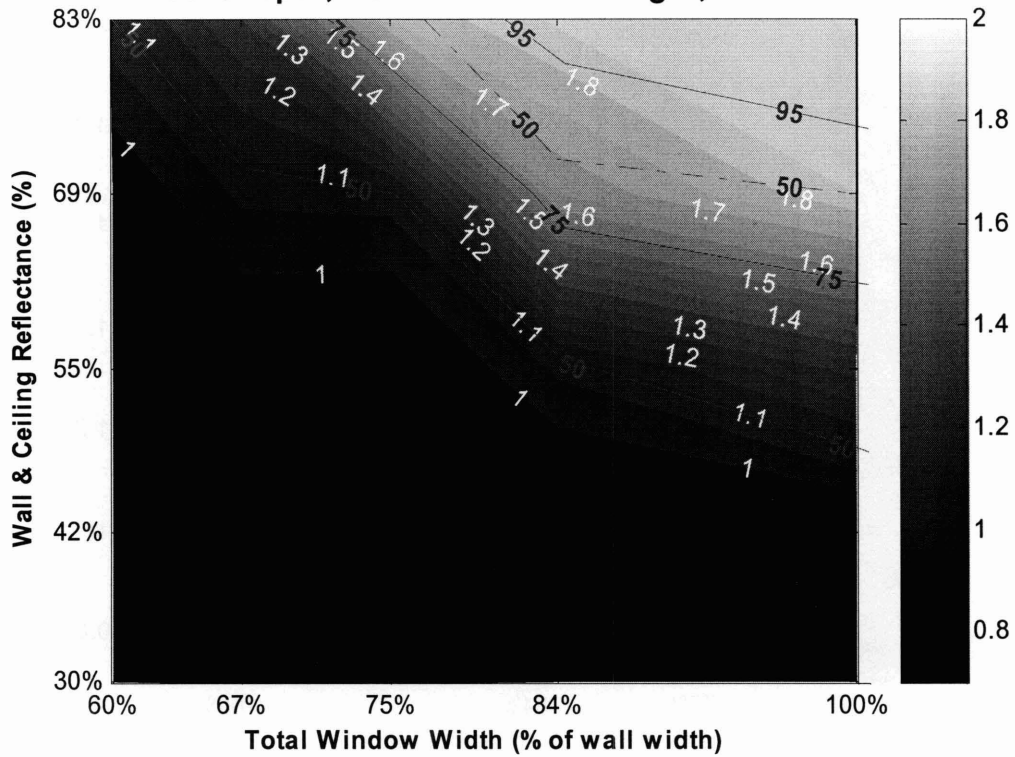
**Ani 25 Expected Improvement:  
30 ft depth, 7ft window head height, low-e**



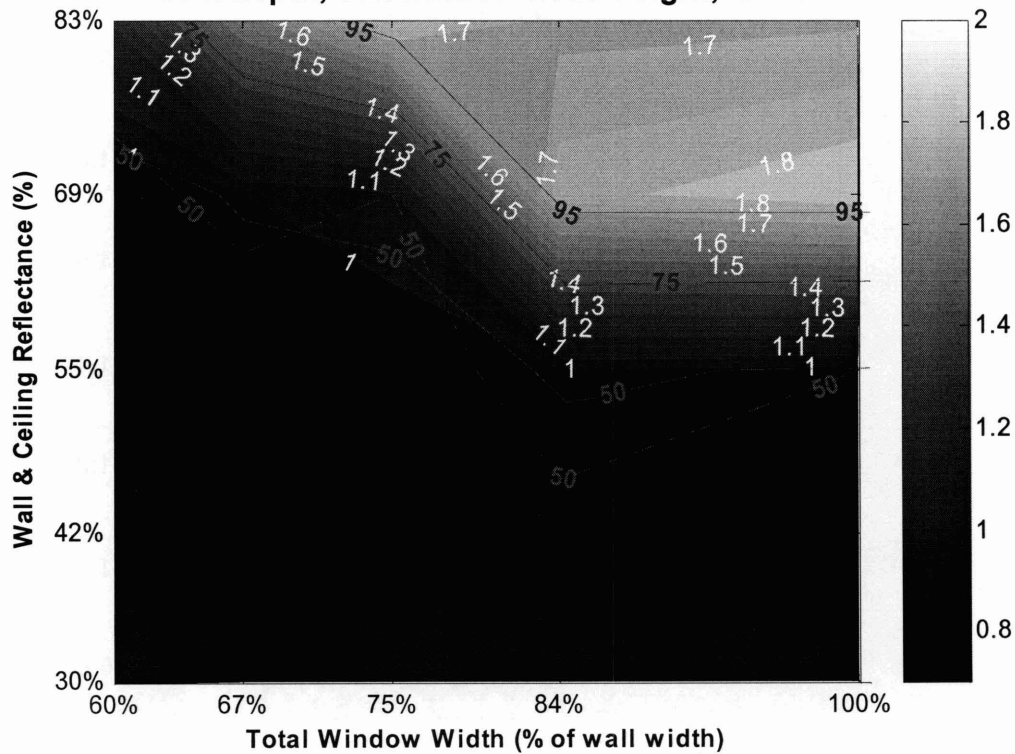
**Ani 25 Expected Improvement:  
30 ft depth, 8ft window head height, low-e**



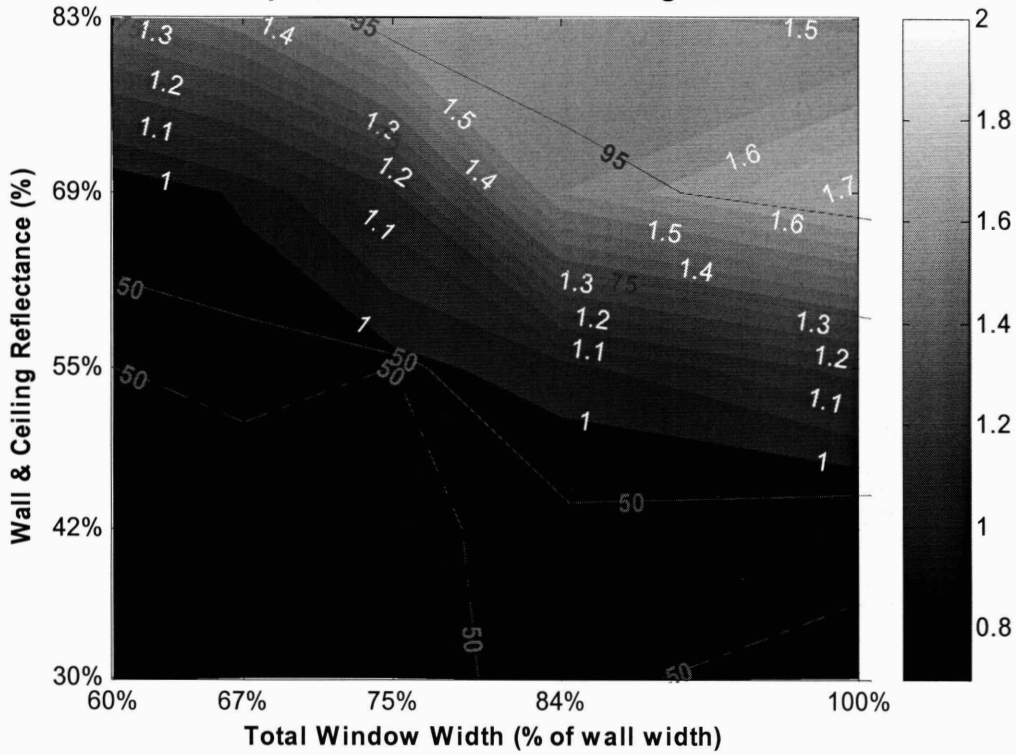
**Ani 25 Expected Improvement:  
30 ft depth, 9ft window head height, low-e**



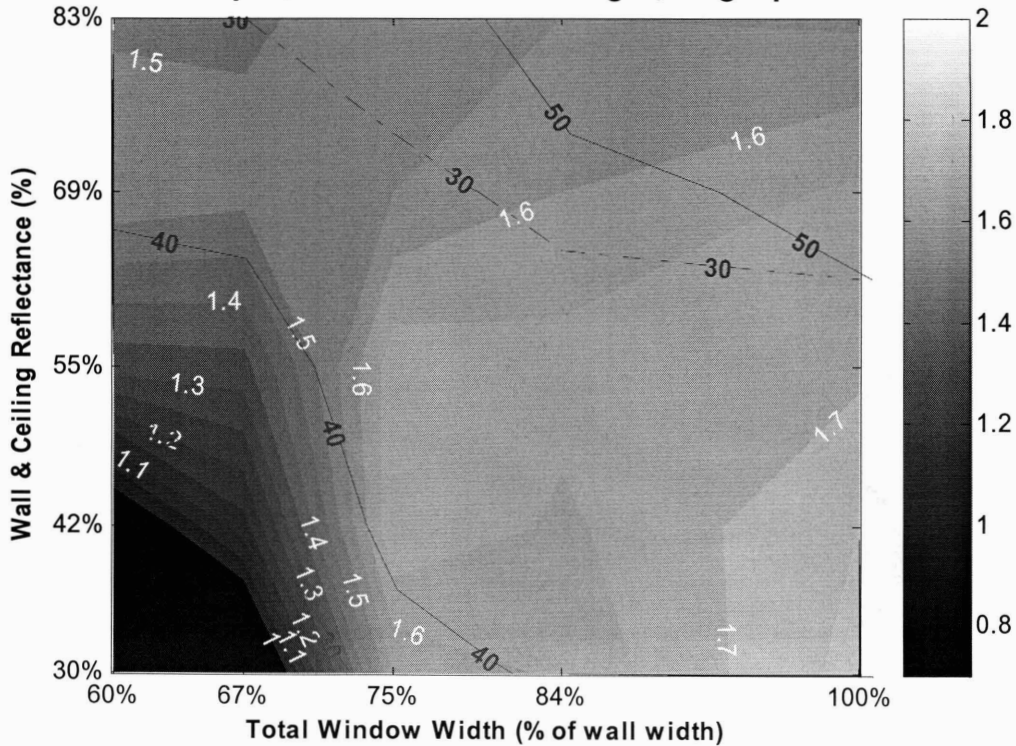
**Ani 25 Expected Improvement:  
30 ft depth, 10ft window head height, low-e**



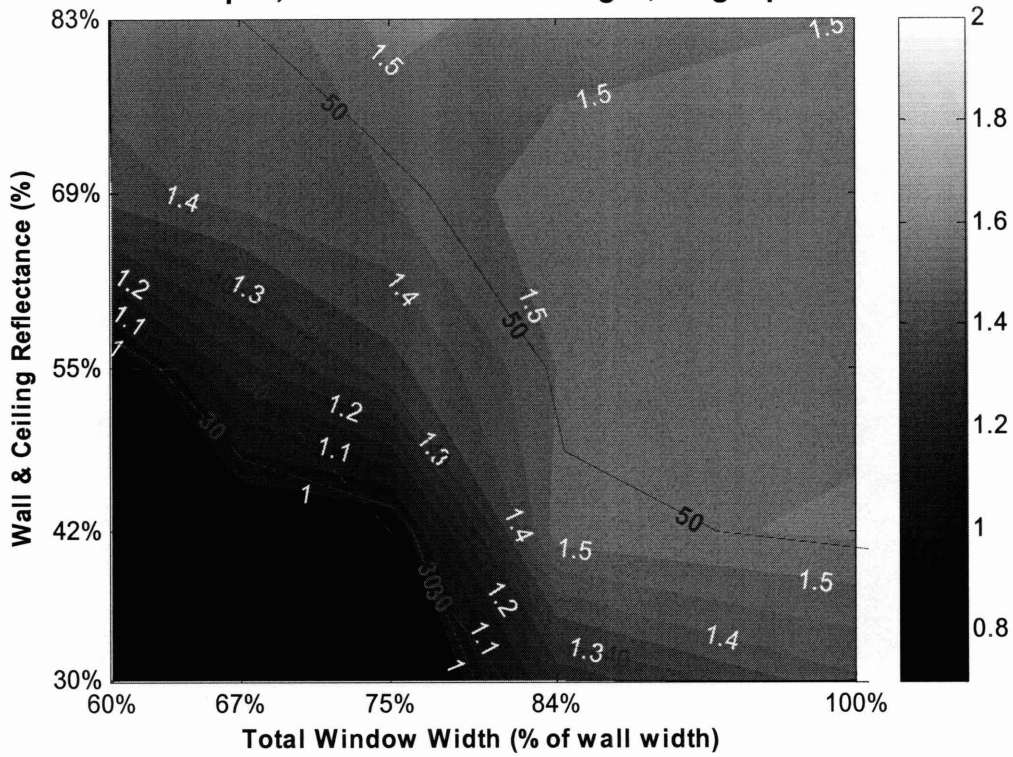
**Ani 25 Expected Improvement:  
30 ft depth, 11ft window head height, low-e**



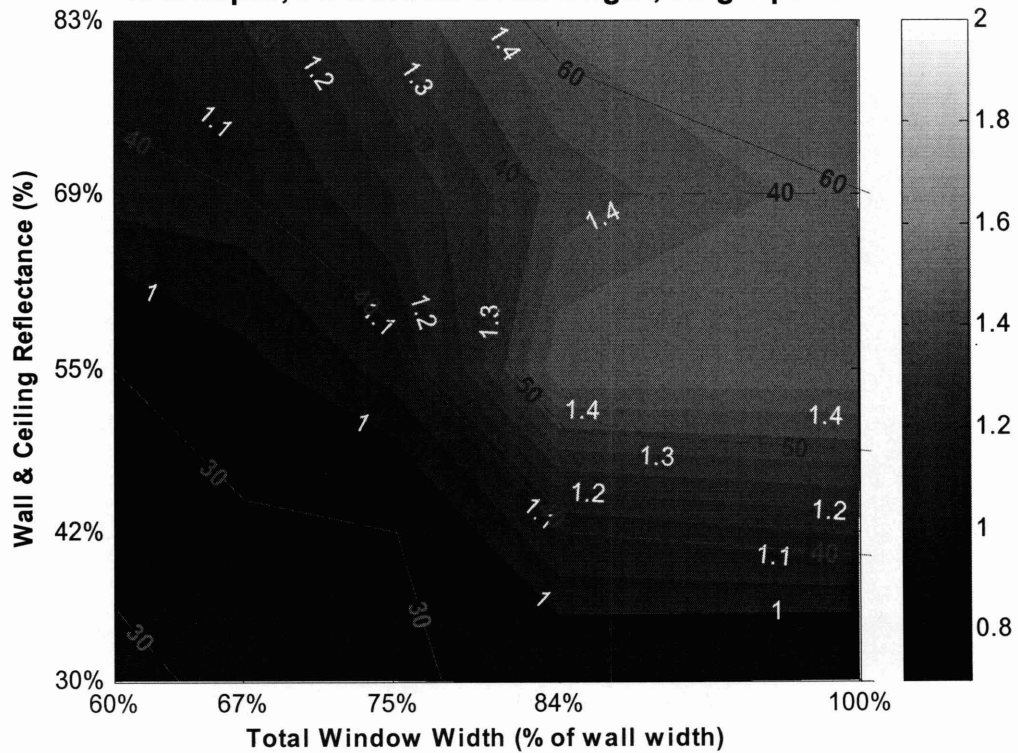
**Ani 25 Expected Improvement:  
40 ft depth, 7ft window head height, single pane**



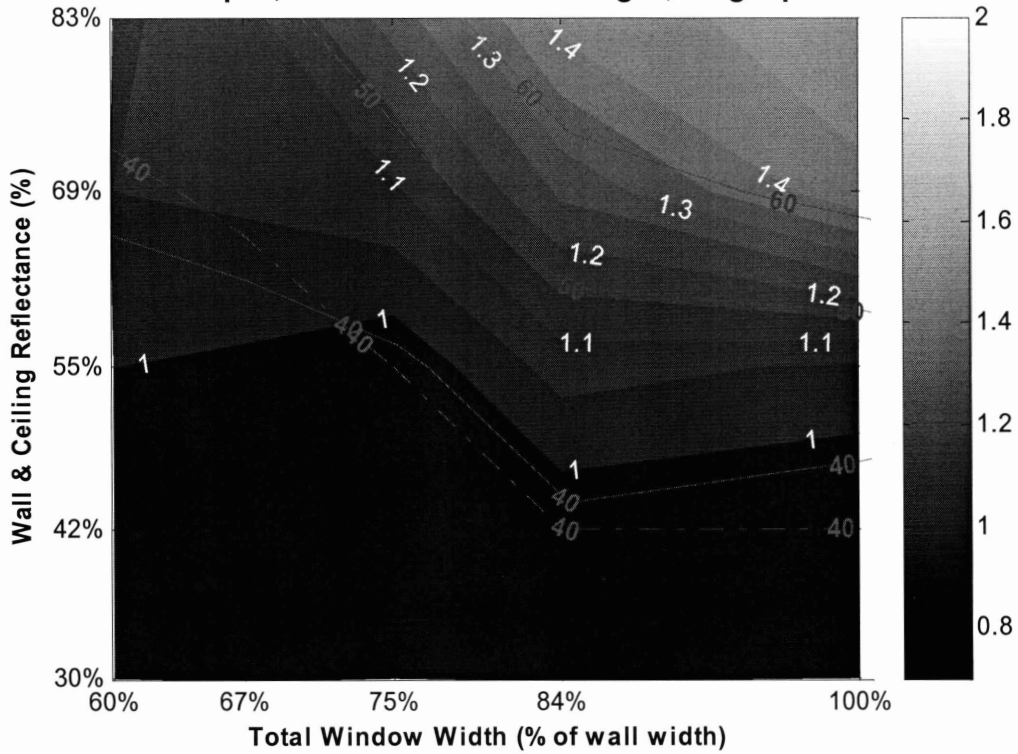
**Ani 25 Expected Improvement:  
40 ft depth, 8ft window head height, single pane**



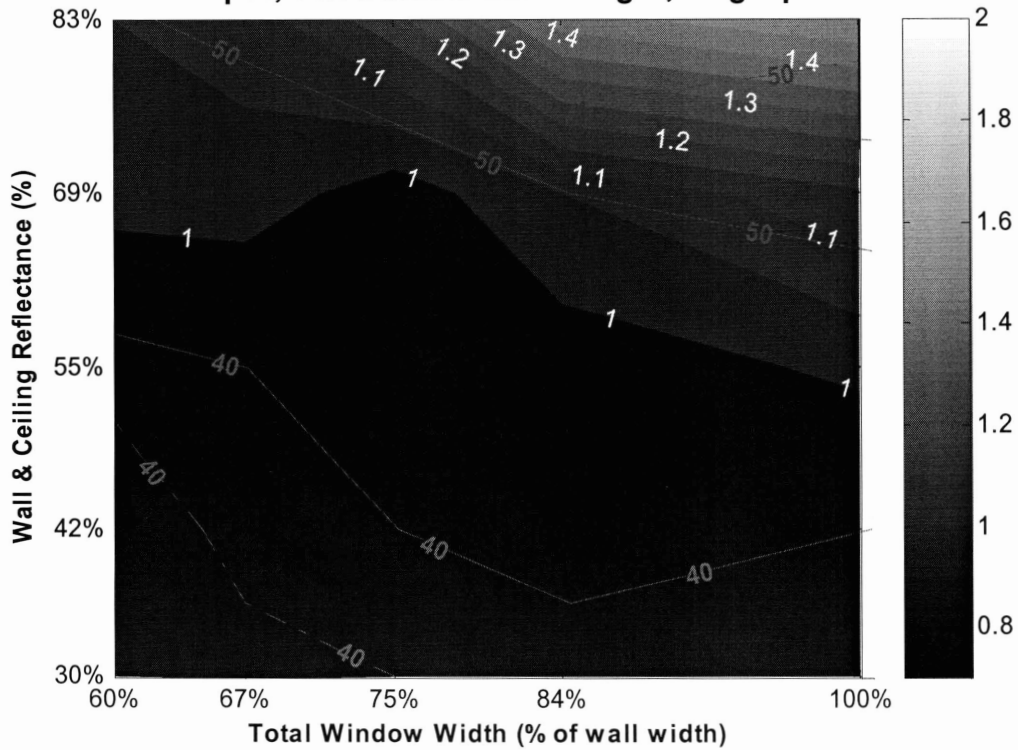
**Ani 25 Expected Improvement:  
40 ft depth, 9ft window head height, single pane**



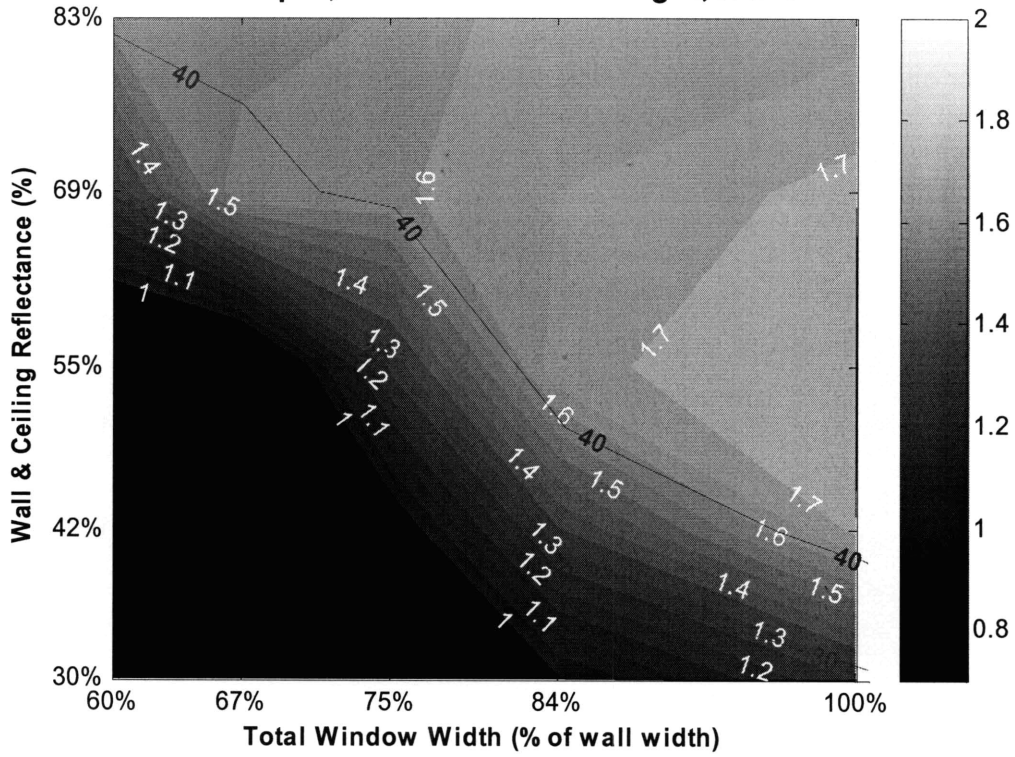
**Ani 25 Expected Improvement:  
40 ft depth, 10ft window head height, single pane**



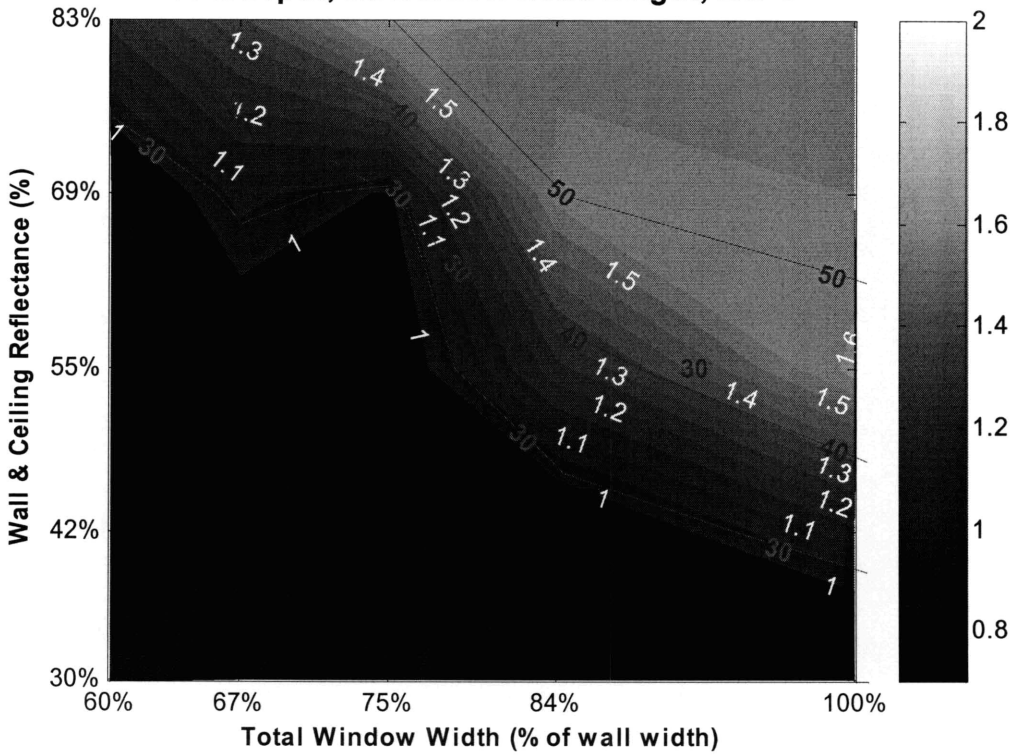
**Ani 25 Expected Improvement:  
40 ft depth, 11ft window head height, single pane**



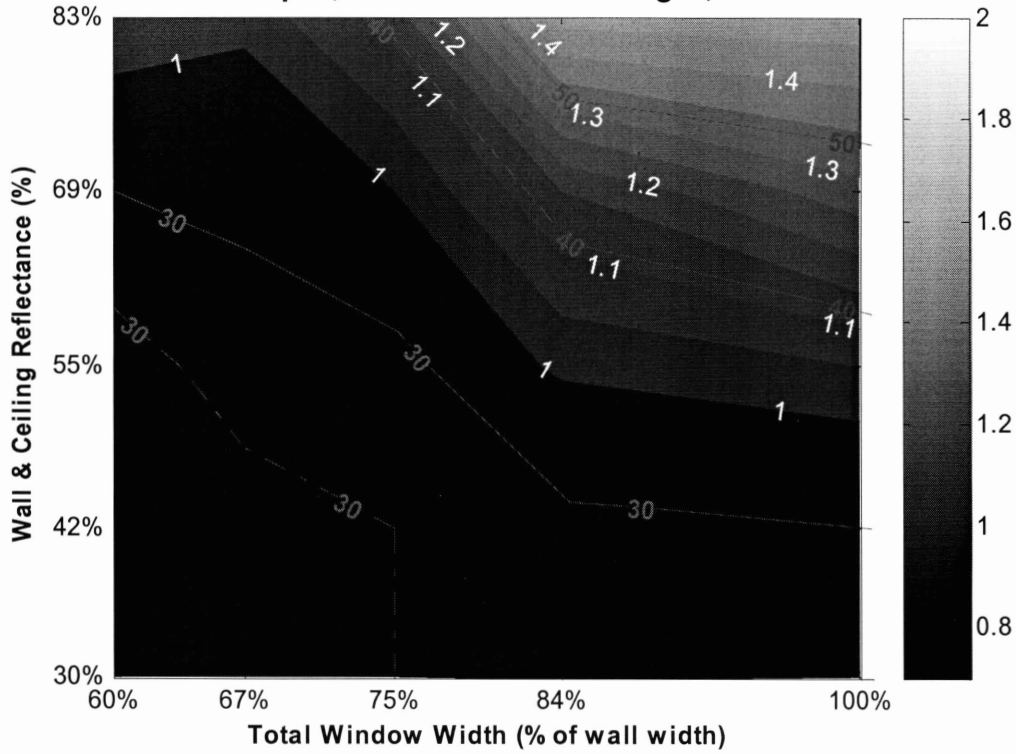
**Ani 25 Expected Improvement:  
40 ft depth, 7ft window head height, low-e**



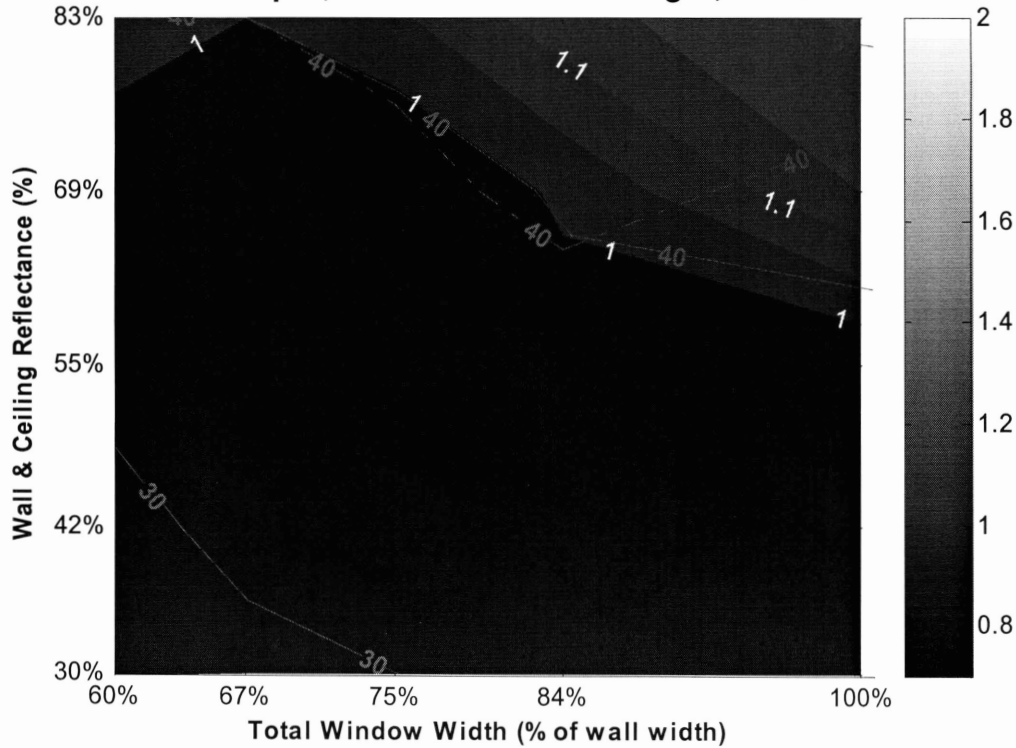
**Ani 25 Expected Improvement:  
40 ft depth, 8ft window head height, low-e**



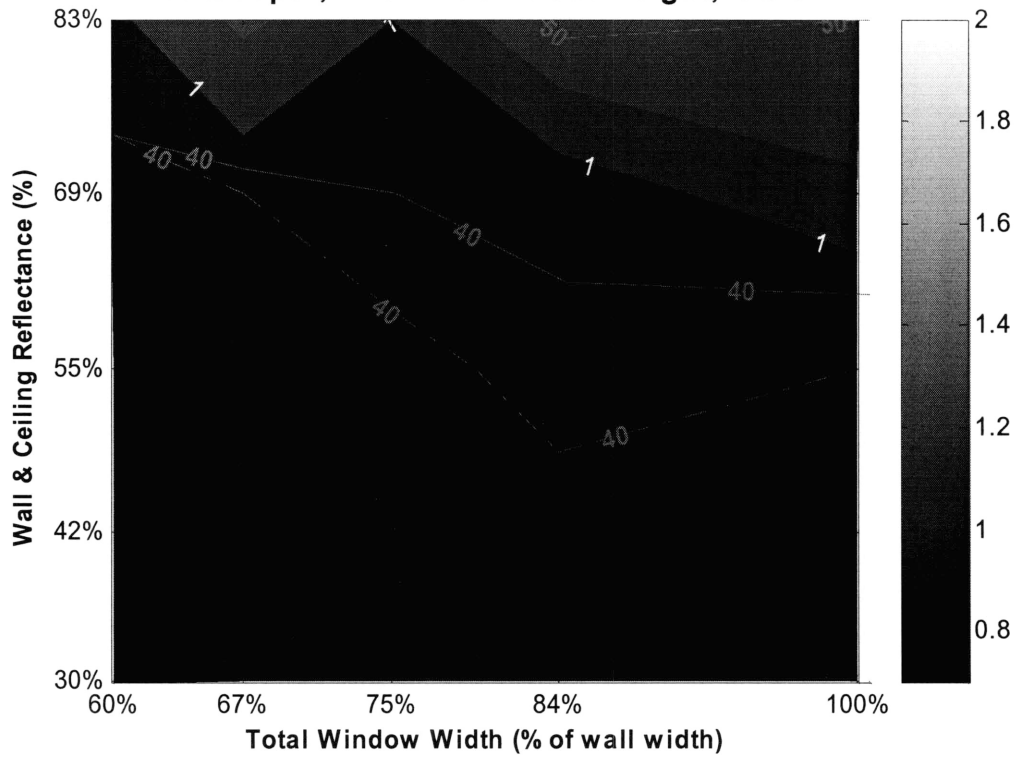
**Ani 25 Expected Improvement:  
40 ft depth, 9ft window head height, low-e**



**Ani 25 Expected Improvement:  
40 ft depth, 10ft window head height, low-e**



**Ani 25 Expected Improvement:  
40 ft depth, 11ft window head height, low-e**





## 10 APPENDIX B: RADIANCE Material Definitions and Geometry Files

```
#
# Materials file for adjustable classroom.. these are often aliased as
# "wallmat" or "ceilingmat" or "windowmat", etc, so that the
# materials in the geometry files may be easily changed.
#

#PAINTS

#greyscale white paint
void plastic whitepaint
0
0
5 .83 .83 .83 0 0
# red green blue speculariry roughness

#greyscale light grey paint
void plastic litpaint
0
0
5 .69 .69 .69 0 0

#greyscale medium grey paint
void plastic midpaint
0
0
5 .55 .55 .55 0 0

#greyscale dark grey paint
void plastic darkpaint
0
0
5 .3 .3 .3 0 0

#greyscale ground grey paint
void plastic grndpaint
0
0
5 .2 .2 .2 0 0

#greyscale black paint
void plastic blackpaint
0
0
5 .05 .05 .05 0 0

#METAL: two different ways to make anidolic reflective material

#anidolic reflective material
void metal metallic
0
0
5 .9 .9 .9 1 0
```

```

void mirror reflector
0
0
3 .9 .9 .9

#GLASS

#window glass
#clear single pane: transmittance 90%
void glass clear1
0
0
3 .98 .98 .98

#clear double pane: transmittance 81%
void glass clear2
0
0
3 .88 .88 .88

#low-e double pane: transmittance 73%
void glass lowe2
0
0
3 .80 .80 .80

#tinted: transmittance 50%
void glass tint
0
0
3 .55 .55 .55

#
# Extra materials for the detailed classrooms
#

void brightfunc chalky
4 dirt dirt.cal -s .1
0
1 .8

#white paint
void plastic white_paint
0
0
5 .923 0.808 .761 .05 .05

#yellow paint
void plastic yellow_paint
0
0
5 .682 .559 .323 .05 .05

```

```

#pink paint
void plastic pink_paint
0
0
5 .9 .56 .52 .05 .05

#orange paint
void plastic orange_paint
0
0
5 .86 .64 .46 .05 .05

#purple paint
void plastic purple_paint
0
0
5 .24 .07 .29 .05 .05

#blue paper
void plastic blue_paper
0
0
5 .12 .27 .71 0 .05

#green paper
void plastic green_paper
0
0
5 .12 .39 .2 0 .05

#yellow_paper
void plastic yellow_paper
0
0
5 .82 .78 0 0 .05

#red_paper
void plastic red_paper
0
0
5 .67 .08 .08 0 .05

#acoustic spray ceiling
void texfunc fractal
6 xfrac yfrac zfrac /usr/local/lib/ray/fractal.cal -s .05
0
1 1

# fractal.cal:
#xfrac=fnoise3(Px/A1,Py/A1,Pz/A1);
#yfrac=fnoise3(Px/A1,Py/A1,Pz/A1);
#zfrac=fnoise3(Px/A1,Py/A1,Pz/A1);

fractal plastic ceiling
0
0
5 .923 .808 .761 .05 .05

```

```

#linoleum floor blue
dust plastic blue_linoleum
0
0
5 .344 .386 .427 .25 .05

#linoleum floor white
dust plastic white_linoleum
0
0
5 .65 .65 .65 .25 .05

#linoleum floor black
dust plastic black_linoleum
0
0
5 .0838 .0838 .0838 .3 .1

#window shades
void plastic shademat
0
0
5 .923 .808 .761 0 .2

#chalkboard
void plastic greenboard
0
0
5 .308 .29 .198 .02 .05

chalky plastic greenboard_chalky
0
0
5 .308 .29 .198 .02 .05

void plastic blackboard
0
0
5 .199 .182 .153 .1 .1

chalky plastic black_chalky
0
0
5 .199 .182 .153 .05 0

#bulletin board
void texfunc cracks
6 cdx cdy cdz adobe.cal -s .01
0
1 .3

cracks colorfunc corky
6 red green blue /usr/local/lib/ray/fleck.cal -s .01
0
7 .8 .421 .323 .18 .210 .160 .09

```

```
corky plastic cork
0
0
5 1 1 1 0 .90
```

```
#silver
void metal silver
0
0
5 1 .79115 .4976 .9 0
```

```
#aluminum
void metal aluminum
0
0
5 .5 .5 .5 .1 0
```

```
#greymetal
void metal greymetal
0
0
5 .3 .3 .3 .2 .2
```

```
#bluemetal
void metal blue_metal
0
0
5 .12 .27 .71 .2 .2
```

```
#brass
void metal brass
0
0
5 .68 .27 .002 .3 0
```

```
#wood
void colorfunc wooddoor
6 zgrain zgrain zgrain woodpat.cal -s .020
0
1 .5
```

```
wooddoor plastic wood
0
0
5 .6 .35 .15 0 0
```

```

#####
#
# This is a sample adjustable classroom file (though without any
# supporting files except one sample anidolic). The orientation
# of the windows is south.
#
#
# *Dimensions are in feet*
#####

# walls and wall fixtures (door, chalkboard, etc) #

# North wall (back wall)
!genbox wallpaint northwall 31 .5 15 | xform -t -.5 40 -.5
# change this number to change depth of room--> **

# East wall (right wall)
!genbox wallpaint eastwall .5 65 14 | xform -t 30 0 0

# West wall (left wall)
!genbox wallpaint westwall -.5 65 14

# South Wall (windows)
!genbox wallpaint southwall1 31 -.5 4 | xform -t -.5 0 0
# Change height of window sill-->**
# (2.8, 4.8, 6.8) (1.4, 3.4, 5.4) (0, 2, 4)

!genbox wallpaint southwall2 3.5 -.5 14 | xform -a 2 -mx -t 31 0 0 \
-i 1 -t -.5 0 0
# ** <--- Change width of side walls

!genbox wallpaint southwall3 31 -.5 3 | xform -mz -t -.5 0 14
# Change window head height---> ** (14 - X = head height)

# 60% Window Width Posts
!genbox wallpaint southwall4 1.5 -.5 14 | xform -a 2 -mx -a 2 \
-t 9 0 0 -i 1 -t 10.5 0 0

# 67% Window Width Posts
!genbox wallpaint southwall4 1.24875 -.5 14 | xform -a 2 -mx -a 2 \
-t 9.1675 0 0 -i 1 -t 10.41625 0 0

# 75% Window Width Posts
#!genbox wallpaint southwall4 .9375 -.5 14 | xform -a 2 -mx -a 2 \
-t 9.375 0 0 -i 1 -t 10.3125 0 0

# Ceiling
!genbox ceilingmat ceiling 31 61 .5 | xform -t -.5 -.5 12
# Change ceiling height---> **

# Floor

```

```

!genbox floormat floor 31 61 -.1 | xform -t -.5 -.5 0

# Ground
#!genbox groundmat ground 11490 -550 -.1 | xform -t -5745 0 0

# Windows: GLASS (sample for 100% window width above and 60% window
# width below) windowglass#.rad is an array of
# small panes
#!xform -n wglass -s 1 -t 0 -.3 2.8 \
    /usr/local/lib/adjustable/windowglass5.rad
#!xform -n wglass -s 1 -t 0 -.3 4.8 \
    /usr/local/lib/adjustable/windowglass5.rad
#!xform -n wglass -s 1 -t 0 -.3 6.8 \
    /usr/local/lib/adjustable/windowglass5.rad

#!xform -n wglass -s 1 -t 3 -.3 0 \
    /usr/local/lib/adjustable/windowglass1.rad
#!xform -n wglass -s 1 -t 3 -.3 1 \
    /usr/local/lib/adjustable/windowglass1.rad
!xform -n wglass -s 1 -t 3 -.3 4 \
    /usr/local/lib/adjustable/windowglass1.rad

# Windows: FRAME
#!xform -n wframe -s 1 -t 0 -.3 0 \
    /usr/local/lib/adjustable/windowframe.1.rad
#!xform -n wframe -s 1 -t 0 -.3 0 \
    /usr/local/lib/adjustable/windowframe.2.rad
#!xform -n wframe -s 1 -t 0 -.3 0 \
    /usr/local/lib/adjustable/windowframe.3.rad
#!xform -n wframe -s 1 -t 0 -.3 0 \
    /usr/local/lib/adjustable/windowframe.4.rad

# ANIDOLIC SYSTEM (sample for 100% window width above and 60% window
# width below)
# 100% window width
#!xform -n anidolics -s 1 -t 0 -.25 6.85 \
    /usr/local/lib/adjustable/anim305.rad
#!xform -n anidolics -s 1 -t 0 -.25 8.85 \
    /usr/local/lib/adjustable/anim305.rad
#!xform -n anidolics -s 1 -t 0 -.25 10.85 \
    /usr/local/lib/adjustable/anim305.rad

# 60% window width
#!xform -n anidolics -s 1 -t 0 -.25 7.85 \
    /usr/local/lib/adjustable/anim301.rad
#!xform -n anidolics -s 1 -t 0 -.25 8.85 \
    /usr/local/lib/adjustable/anim301.rad
!xform -n anidolics -s 1 -t 0 -.25 10.85 \
    /usr/local/lib/adjustable/anim301a.rad

```

```

#URBAN MASKING
# Altitudinal angle masking

#grndpaint cylinder mask
#0
#0
#7
# 15 0 0
# 15 0 49
# 165

# HEIGHT of masking cylinder (above)
# 100% window width 60% window width
# deg (11whh) (9whh) (7whh) | (11whh) (9whh) (7whh)
# 15 51 49 47 | 71 69 67
# 30 102 100 9 | 148 146 144
# 45 171.8 169.8 167.8 | 254 252 250
# 60 292.6 290.6 288.6 | 437 435 433
# 75 622.6 620.6 618.6 | 937 935 933

## End of File ##

# ANIDOLIC SYSTEM SAMPLE file anim301.rad

# Exterior anidolic collector (2 ft projection)
#
# x = 'length - s*(length - 0)' where s = # segments (in this case 1)
# function a(dist from origin, where the curve stops, #segments)'
# where t = # segments (in this case 50)
# y = 'a'
# z = '(a^2)/(4 * focus)'

!gensurf anidolic outA '6 - s*(6-0)' 'a(2.5, .5, t)' \
'a(2.5, .5, t)*a(2.5, .5, t)/(4*1.19)' 1 50 \
-e 'a(x, y, t) = x - t*(x - y)' | xform -my -t 0 .25 0 \
-a 3 -t 9 0 0 -i 1 -t 3 0 -1.2

# Interior anidolic collectors
#
# x = 'length - s*(length - 0)' where s = # segments (in this case 1)
# FUNCTION: L(depth of anidolic system, characteristic angle of system)
# = depth/cos(angle) - 2*a(exit)*sin(angle) + l
# l(characteristic angle of system)
# = f - 2*a(entrance)*sin(angle)
# f(characteristic angle of system)
# = a(entrance)*(1 + sin(angle))
# y = 'L - t*(L - l)' where t = # segments (in this case 50)
# z = '+- sqrt(4 * f * y)'
# -t 0 -focus 0 -rx --(char angle) [-i 1 -t 0 0 -2*a(entrance) for top
# system]

```

```

# Top interior distributor
!gensurf anidolic top '6 - s*(6-0)' \
  'L(3.12, 30) - t * (L(3.12, 30) l(30))' \
  '0-sqrt(4 * f(30) * (L(3.12, 30) - t*(L(3.12, 30) - l(30))))' \
  1 50 -e 'f(y) = .6*(1 + sin(y*PI/180))' \
  -e 'l(y) = f(y) - 1.2*sin(y*PI/180)' \
  -e 'L(x,y) = x/cos(y*PI/180) - 2.4*sin(y*PI/180) + l(y)' \
  | xform -t 0 -.9 0 -rx 30 -mz -a 3 -t 9 0 0 -i 1 -t 3 0 -1.2

```

```

# Bottom interior distributor
!gensurf anidolic bot '6 - s*(6-0)' \
  'L(3.12, 30) - t * (L(3.12, 30) - l(30))' \
  '0-sqrt(4 * f(30) * (L(3.12, 30) - t*(L(3.12, 30) - l(30))))' \
  1 50 -e 'f(y) = .6*(1 + sin(y*PI/180))' \
  -e 'l(y) = f(y) - 1.2*sin(y*PI/180)' \
  -e 'L(x,y) = x/cos(y*PI/180) - 2.4*sin(y*PI/180) + l(y)' \
  | xform -t 0 -.9 0 -rx 30 -a 3 -t 9 0 0 -i 1 -t 3 0 0

```

```

# Bottom interior distributor cover
!gensurf gsmidgreypaint bot '6 - s*(6-0)' \
  'L(3.12, 30) - t * (L(3.12, 30) - l(30))' \
  '0-sqrt(4 * f(30) * (L(3.12, 30) - t*(L(3.12, 30) - l(30))))' \
  1 50 -e 'f(y) = .6*(1 + sin(y*PI/180))' \
  -e 'l(y) = f(y) - 1.2*sin(y*PI/180)' \
  -e 'L(x,y) = x/cos(y*PI/180) -2.4*sin(y*PI/180) + l(y)' \
  | xform -t 0 -.9 0 -rx 30 -a 3 -t 9 0 0 -i 1 -t 3 0 -.01

```

# Sides of the interior distributors

```

anidolic polygon sidel
0
0
12
  9    0    0
  9    3.12  0
  9    3.12 -1.2
  9    0    -1.2

```

```

anidolic polygon side2
0
0
12
  3    0    0
  3    0    -1.2
  3    3.12 -1.2
  3    3.12  0

```

```

anidolic polygon side3
0
0
12
  18   0    0
  18   3.12  0
  18   3.12 -1.2
  18   0    -1.2

```

anidolic polygon side4

0

0

12

12	0	0
12	0	-1.2
12	3.12	-1.2
12	3.12	0

anidolic polygon side5

0

0

12

27	0	0
27	3.12	0
27	3.12	-1.2
27	0	-1.2

anidolic polygon side6

0

0

12

21	0	0
21	0	-1.2
21	3.12	-1.2
21	3.12	0

## End of File ##

## 11 APPENDIX C: Specification for the Boston Classroom Physical Model

Below are some of the notes taken while visiting the Boston classroom. The middle column is measurement listed in metric units, and the far right is 1/15<sup>th</sup> of the original dimension.

### Classroom on 2nd floor

1 floor tile: 9 in x 9 in	22.9cm	1.52cm
Room =		
Length: 35 ft 5 in	1080cm	72cm
Depth: (from wall) 24 ft	732cm	48.8cm
Height: 10 ft 5 in	318cm	21.2cm
Front (window) wall =		
Heater		
Length: 35 ft 5 in	1080cm	72cm
Depth: 15 in	38cm	2.5cm
Height: 30 ¼ in	77cm	5.1cm
7 windows		
Depth of window ledge: 7 ½ in	19cm	1.3cm
Ht of ledge above heater: 1 ½ in	3.8cm	0.25cm
Frame wth above heater: 2 ½ in	6.4cm	0.42cm
Frame wth 'tween panes: 1 1/8in	2.9cm	0.19cm
Frame wth outside edge: 3 ½ in	8.9cm	0.59cm
Pane width: 9 in	22.9cm	1.52cm
Pane height: 13 7/8 in	35.2cm	2.35cm
# Panes: 3 across x 5 down		
Brick wall (either side of window bay)		
Width: 20 in	50.8cm	3.39cm
Overhang		
Depth from brick wall: 3 ½ in	8.9cm	0.59cm
Depth from window: 11 in	27.9cm	1.86cm
Height: 12 ½ in	31.8cm	2.12cm
Back (chalkboard) wall =		
Closet door		
Height: 7 ft	213.4cm	14.22cm
Width: 1 ft 8 in	50.8cm	3.39cm
Frame: 3 in	7.6cm	0.51cm
Main door		
Height: 7ft	213.4cm	14.22cm
Width: 3 ft	91.4cm	6.10cm
Frame 3 in	7.6cm	0.51cm
Length from left wall: 3 ft	91.4cm	6.10cm

Green Chalkboard plus bulletin board		
Height: 20 in	50.8cm	3.39cm
Length CB: 16 ft 6 in	502.9cm	33.53cm
Length BB: (approx) 3 ft 9 in	45cm	3cm
Yellow Stripe		
Height from floor: 33 ½ in	85cm	5.67cm
Left and right wall =		
Door		
Same height and width		
Dist from back wall: 2 ft	61cm	4.06cm
Yellow Stripe		
Same height		

Measured Illuminances:

Lux	1st desk	%	2nd desk	%
55 in	923	4.62%	845	4.23%
91 in	565	2.83%	459	2.30%
127 in	330	1.65%	277	1.39%
163 in	183	0.92%	128	0.64%
199 in	142	0.71%	115	0.58%
235 in	111	0.56%	91.7	0.46%
271 in	94	0.47%	72.4	0.36%
outside ~	20000 lux	heavy cloud cover		

1st desk row in front of bar between 1st and 2nd window from the left facing the back wall, 2nd desk row in front of 3rd window from the left facing the back wall

Measured Surfaces → Reflectances

Surface	Lux	cd/m2	Reflectance (lambertian)
ChalkBrd	113	9.78	27.19%
Yellow wall	145	26.39	57.18%
White wall	277	73.79	83.69%
Blue tile	410	24	18.39%
White tile	410	49	37.55%

(MODEL) Reflectance (lambertian)

ChalkBrd	29%	(glossy black card)
Yellow Wall	66%	(paper)
White Wall	85%	(white-finished wood product)
Pink Heater	32%	(paper)
Floor total	61%	(paper, quite faded)
Ceiling	74%	(white bath towel)
Door	44%	(brown package paper)
Window trans:	98%	(single piece of acrylic)
Window frame/top of heater		(spray painted silver)

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