Making Daylighting Work: Applying Cx to Improve the Design and Implementation Process

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Synopsis

For ages daylighting has been a primary source of daytime light for human activities within buildings. During the 20th century, with the widespread use of electric lighting, daylighting assumed a more supplemental role with electric lighting levels being reduced or turned off when adequate daylight is present via the use of local or central manual controls. A large body of very effective buildings has been produced using such techniques. Some buildings are exquisite in their effectiveness and visual quality. Then in the late 20th and early 21st centuries, as a result of rapid advances in low-cost digital controls, increasingly sophisticated automatic controls are being installed instead of manual controls.

The trend toward automatic daylighting controls has been reinforced by the proliferation since the 3rd quarter of the 20th century of energy efficiency codes for buildings plus a slower but significant emergence of utility Demand Side Management (DSM) programs, particularly in the US. Neither the energy codes nor the DSM programs have recognized manual daylighting controls as viable because the uncertainty of human behavior precludes guaranteeing the energy savings. Thus, automatic controls have become the only recognized option within these programmatic contexts.

While the automatic control of daylighting systems has great potential to deliver both high visual quality and significant energy savings, this potential is not being achieved very often in recent building practice. In fact, many recent buildings with such systems are falling short of their estimated potential to save energy. A number of them also have sufficient visual quality problems such that their building operators or occupants disable them.

A stark picture emerges from data from numerous recent buildings designed and delivered with incentives from DSM programs. For buildings with daylighting from sidelighting via vertical windows in walls, the installed daylighting systems are actually operating in only about ½ of the buildings. Those daylighting systems that are actually operating, achieve only about ½ of their energy saving potential.

This paper examines case studies of 12 recent buildings that have fallen short of their potential. A number of causes are identified. The causes have distinct patterns, and strong consequences. Most problems, if not identified in time, are too difficult or expensive to fix.

Given this situation, we explore the possible use of a number of commissioning techniques, and recommend the development and publication of a number of guides and examples. The authors think that such guides could substantially raise the quality and consistency of the process of delivering automatically controlled daylighting systems. The paper contains a number of recommendations. One of the recommendations is to develop a commissioning guideline for daylighting systems and their controls in order to improve the quality of the products being delivered.

About the Authors

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Introduction

For ages daylighting has been a primary source of daytime light for human activities within buildings. During the 20th century, with the widespread use of electric lighting, daylighting assumed a more supplemental role with electric lighting levels reduced or turned off when adequate daylight is present via the use of local or central manual controls. A large body of very effective buildings has been produced using such techniques. Some buildings are exquisite in their effectiveness and visual quality. Then in the late 20th and early 21st centuries, as a result of rapid advances in low-cost digital controls, increasingly sophisticated automatic controls are being installed instead of manual controls.

The trend toward automatic daylighting controls has been reinforced by the proliferation since the 3rd quarter of the 20th century of energy efficiency codes for buildings a slower but significant emergence of utility Demand Side Management (DSM) programs particularly in the US. Neither the energy codes nor the DSM programs recognize manual controls as viable because the uncertainty of human behavior precludes guaranteeing the energy savings. Thus, automatic controls have become the only recognized option within these programmatic contexts.

While the automatic control of daylighting systems has great potential to deliver both high visual quality and significant energy savings, this potential is not being achieved very often in recent building practice. In fact, most recent buildings with such systems are falling far short of their estimated potential to save energy. A number also have sufficient visual quality problems that their building operators or occupants disable them.

Design analysis often shows daylighting to be one of the most promising energy conservation strategies for commercial buildings. Daylighting incorporates architectural elements to bring daylight in to the building and controls to interface with the electrical lighting system; the design of a complete daylighting systems spans across decisions made by multiple disciplines on a project. Architects, interior designers, lighting designers, electrical engineers, mechanical engineers, contractors, suppliers, manufacturers, building operators, and occupants can all affect the performance of daylighting in a building.

However, many daylighting systems implemented in buildings are falling short of expected energy saving potential. Vaidya (2004 and 2005) and Heschong Mahone Group (2006) have reported that automatic switching or dimming control systems do not provide the expected energy savings from daylighting as often as we would like. Greden (2006) found that daylighting systems had a low rate of successful implementation of about 40% (see figure 1). Heschong Mahone Group (2006) reported that for sidelighting systems 48% of the installed daylighting systems are functioning and that these 48% are on average saving only 53% of the savings that had been modeled prior to implementation.

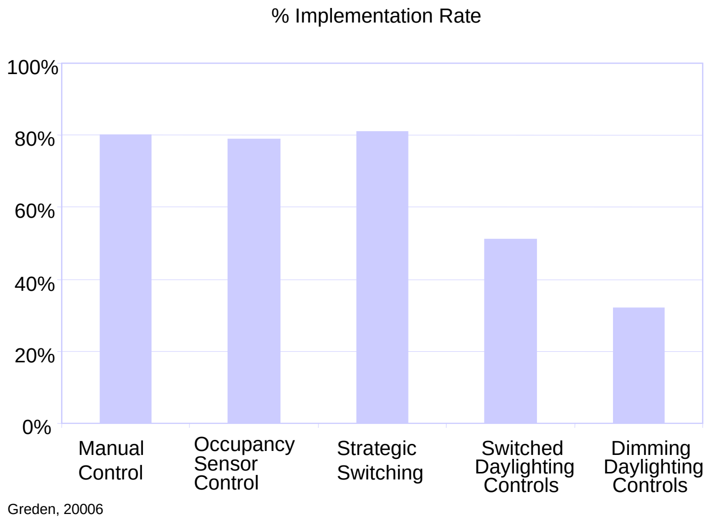

Figure 1: Implementation rates for various lighting controls. Greden, 2006.

In industries as risk-averse as design and construction, even limited failures can dramatically slow the advance of valid technologies. There are numerous possible reasons for an unsuccessful implementation of daylighting controls. Sometimes, insufficient detail in design documents leads to improper supply and installation of the systems. Often, manufacturers provide inconsistent information about performance characteristics of control system products. Even with adequate information at the top of the process, success requires better documentation of control functionality and installation requirements, coordination between design and construction trades, and explicit calibration requirements. The controls are not explained to building operators or occupants, who can then easily declare the system a failure - similar to what happened during the emerging years of occupancy sensing controls. Facility operators who are not well trained in these systems exclude them from ongoing maintenance and operation plans. These and related issues have led to badly implemented daylighting control strategies.

It is useful to document lessons on success and failure from the set of early adopters of daylighting using automatic controls. If energy efficiency through daylighting controls is to proliferate as a strategy its success rate will need to improve. Though there are successes, our intention here is to highlight the weak areas that will help the improvement of the implementation process.

In this paper we document twelve case studies that did not meet the initial savings expectations. We found that savings from automatic daylighting control systems are often not realized fully once the users inhabit a building. Where the controls do work, we are likely to find an involved and unusually committed owner. This obviously is not the ideal method for successful building design. Energy savings cannot depend solely on an owner or user's commitment. Many of the problems concerning the controls or their use need to be addressed during the design development and construction process.

The case studies documented here identify the design decisions that typically could be made better with more attention to their effect on daylighting savings, and we infer that adequate construction documentation that is necessary for a successful implementation is typically not included. The case studies also provide greater detail and discuss the process of design decisions and construction documents.

A well-defined commissioning methodology will include the necessary goals for design, communication and coordination methods between design disciplines and review and testing process to aid in the successful design and implementation of daylighting systems. After discussing the case studies we describe a number of specific commissioning-related activities that can be used to either avoid problems with daylighting systems or to quickly identify and fix problems when they occur.

Case Studies

The following case studies are representative in nature. Some of the case studies here are of systems that simply did not work after the building was considered completed and ready for occupancy. In most cases the systems were made to work later, albeit with limited success after an owner, occupant, or building operator observed a problem and called for help.

While the case studies listed here are examples of problems encountered, there certainly are many examples where daylighting is implemented as a successful strategy and energy savings are being realized as expected. A discussion of the problems encountered provides valuable insights about improvements to the process.

Case Study 1 – College Dining Hall

What was intended. Large windows on three sides and high diffuse glazing on the south side were to provide daylighting in this building. The south windows had a deep interior light shelf to function as a shading device. Photosensors placed near the windows, were linked to local zone controllers and a central control system.

What was built. In some cases the non-dimmable light sources were connected to the dimming control system. Lighting control zones wired to the system were not necessarily zones with daylight. The photosensors were not calibrated during construction. The users in the space, who occupied it for no more than two hours at a stretch, were oblivious of the daylighting controls and did not perceive this to be a problem. However, the facilities staff that had been involved in the design process noticed the issue and called in for investigation later.

Problem resolution. The control software and hardware were sophisticated enough and allowed the controls to be reprogrammed as switching instead of dimming. Some lighting circuits in the daylighting zones were assigned appropriately to the daylight control system. Where physical rewiring was necessary, problem resolution was harder and thus not done.

Comments on the process. The circuits were not wired as they were shown in the construction drawings. Calibration was not included as a requirement for construction completion; had this been done, the wiring problems may have been discovered before the contractors left the site.

Case Study 2 – College Classroom Building

What was intended. High clerestory windows in classrooms with interior lightshelves were to provide daylight in this building. The daylighting control system consisted of 2 photosensors located near the windows, each linked to individual local zone controllers, and subsequently to a central control system. There were two dimming zones in each classroom, one zone for the perimeter row and the other zone for the two inner rows.

What was built. The windows were designed smaller than those tested in the daylight models. The first row of the pendant lighting system obstructed the daylight and the interior surfaces were relatively dark, creating a cave-like environment. See Figure 2. The photosensors located on the ceiling also read the upward component of the direct-indirect lighting system. Further, the controls were not calibrated. The lighting system was delivering around 85 footcandles (fc) as opposed to the 50 fc design illuminance level. The lights did not dim. The users in the space did not perceive this to be a problem; however the facilities staff that had been involved in the design process noticed the issue and called in for trouble-shooting.

Figure 2. College classroom with clerestory windows installed smaller in size along with dark furnishings.

Problem resolution. Further investigation revealed that the lights were in the burn-in mode and hence had not dimmed. Calibration was subsequently done to maintain a design illuminance level of 45 fc. Since the hallway lights were delivering 75 fc the classrooms appeared darker at 45 fc, requiring the hallways to be de-lamped to reduce the light levels there. Other aspects that had not been coordinated in the design and construction process could not be fixed easily after the building was completed. The students and teachers were informed that blinds needed to be opened to allow daylight in and that electrical savings of the daylighting control system would be lost if they remained closed during the day.

Comments on the process. The window sizes were reduced in the value engineering process, but the designers did not realize that the daylighting savings would be affected. The interior designer had not been a part of the daylight evaluation study and may not have been aware of the requirements to create a successfully daylit space with lighter colors. The location of the photosensors relative to the window and the light fixtures was not checked in the shop drawings submitted by the contractor. Calibration was not included as a requirement for construction completion.

Case Study 3 - Office Building

What was intended. This office building, roughly 300,000 square feet (sf) with open offices around the perimeter, has ribbon glazing to a ceiling height of 10 feet. Single T5 high output lamp direct indirect lighting fixtures oriented parallel to the windows are controlled by the daylighting system. Daylighting control was to incorporate one photosensor per floor per orientation, oriented to view out of the window, with each row of fixtures controlled separately.

What was built. The system was built as described, but dark furnishings were installed. The controls were calibrated prior to occupancy and responded well to changes in daylight levels. Some cubicles had 25 – 40 fc of light at their work surface when daylighting controls were active. The occupants had come from an “electrically” brighter building without daylight, and voiced complaints about light levels to the facilities staff.

Problem resolution. The daylighting controls were deactivated and are presently not dimming, due to numerous complaints from the occupants. The system provides savings due to lower watts installed, but daylighting control response from the building is non-existent.

Comments on the process. Furnishing colors were not selected to support daylighting conditions. The calibration before occupancy was set too aggressively for the occupants’ comfort level, and their history with more electric light was not taken into consideration. The users were not informed about the control system and its benefits. The operations staff lost confidence in the system.

Case Study 4 - Office Building

What was intended. Large windows provided daylight in the perimeter open office areas in this building. The electric lighting system consisted of indirect fixtures laid out perpendicular to the window wall. The lighting was to be controlled with photosensors mounted on the indirect fixtures looking out of the windows with one sensor per floor per orientation. This was to be a stepped or on-off system to control about a 10 feet wide zone adjacent to the windows.

What was built. One photosensor was installed at the end of every row of fixtures (about one sensor every 10 feet), controlling only two lamp-lengths in that row. It was impossible to calibrate the photosensors to control the lights in each row similarly. Besides, calibrating that many sensors would be huge task. Thus the photosensors were not calibrated. The lights did not turn off; the users in the space, unaware of any daylighting controls did not complain as long as they had adequate light to work in.

Problem resolution. This problem has not been fixed yet. The daylighting system is not working and the potential savings remain unrealized while the owner incurred a significant cost of buying all the unnecessary sensors.

Comments on the process. Too many photosensors were installed. The lighting designer did not catch the error. The manufacturer was probably not responsible for calibrating the system. If calibration was required of the manufacturer, they may have ensured that an appropriate number of sensors were installed.

Case Study 5 – College Classroom Building

What was intended. In this building, large windows provide daylight in the classrooms. The daylighting control system consists of one photosensor per classroom located near the windows, linked to a central control system. A constant light level maintained by the dimming system along with energy savings was expected.

What was built. The sensors were calibrated and the lights dimmed in response to the daylight. However, when the daylight level changes, say a cloud passes by, the system responds very rapidly, making the dimming very noticeable to the occupants. In addition, a lighting relay panel and the building EMS system were used to control the photosensors. One relay at the panel controls 2 to 3 classrooms by taking the average of the photosensors in all three classrooms. Thus if one classroom turns its lights off, the light level increases in the other classrooms on that relay, regardless of the exterior light level.

Problem resolution. The lighting control program at the EMS was changed to allow a slower rate of change for the photosensors, making the daylighting system response less noticeable to the occupants.

Comments on the process. The daylighting system used one manufacturer's photosensors, but tried to use a lighting relay panel and EMS rather than the same manufacturer's daylighting controllers. Since the components were not integrated as a system, the start-up commissioning was more difficult and caused some occupant discomfort.

Case Study 6 - Retail, General Merchandise

What was intended. The entire sales floor is daylit using diffuse horizontal skylights uniformly distributed, representing 2% of the floor area. Shelving heights range from 8 to 12 feet in a 17 feet high lay-in ceiling space. The daylighting control system uses one closed-loop photosensor mounted on the ceiling looking downwards. The sensor provides a continuous input signal to a central lighting controller that separately dims three different daylighting control zones of lights. The 3 zones were established based on the amount of daylight each zone receives from the skylights.

What was built. The daylight control system was calibrated by the controls manufacturer after the store had opened. Short term monitoring of lighting power and exterior light level was done and showed that the system was performing as expected, saving about 35% of the lighting energy.

However, about a year later, a new store manager felt that the system was over-dimming and making the store feel dark. The photosensor was then disabled.

Problem resolution. Further daylight monitoring was done to re-calibrate the system. A plan was established to reduce the degree of dimming in two zones. However, the store manager was convinced that the control system would potentially hurt sales, and no re-calibration was done.

Comments on the process. Most of the process went well. This case study illustrates the potential long-term persistence problems daylighting systems can have when users or operators change and the new people are unfamiliar with or unaware of the system. Accurately calibrating the system in the beginning is very important, but continued user and operator education is also essential. Unless the occupants and operators request it specifically, calibration may need to be done conservatively. This may result in a reduction of energy savings, but an aggressively calibrated system may very well be deactivated in the future.

Case Study 7 - Office Building – Existing Building Major Renovation

What was intended. This was a single storied zoo building originally constructed in the 1930s, now converted in to an office facility for a local government agency. The original skylights in the building were renovated and provide daylight to the offices. Indirect fluorescent fixtures inside the skylight wells and recessed cans with compact fluorescent provide the artificial light. The electric lighting system was to be controlled with a photosensor. Since the skylights provided plenty of usable daylight, it was expected that the artificial lights would remain off for most daylight hours.

What was built. The system was built roughly as described and a single photosensor was installed on the roof to control the indirect lights. This photosensor was a photodiode type, otherwise used to control parking lot lights; it could not be calibrated on site. The photosensor, “thinking” that it was controlling parking lot lights, turned the lights off for all daylight hours, irrespective of how dark or overcast the day was. There was no manual-on control to allow the users to turn on the lights on unusually dark and overcast days. In addition, the controlled lighting was not routed through an astronomical clock to turn the lights off automatically later at night. So the photosensor turned the indirect lights on at sunset and kept them on through the night. Manual off for these lights was only possible by switching the entire circuit off at the lighting panel. The users resolved the issue for themselves by climbing up on to the roof and applying black tape over the sensor effectively disabling it; at night, someone goes to the lighting panel and switches lights off manually.

Problem resolution. The owners have been told that the wrong type of sensor was installed in the wrong location, the contractor has been asked to correct the situation.

Comments on the process. The electrical contractor installed the wrong type of photosensor. The electrical engineer did not differentiate between a photodiode and a photoconductive sensor and the capabilities of each. This problem was not identified during the shop drawings phase. A problem reporting procedure had not been specified and the users took the matter in their own hands, intervened, and resolved the situation.

Case Study 8 - Recreation Center

What was intended. In this building in Colorado, curtainwall glazing on one end of the pool and skylights distributed on the roof of the pool space provide daylight. The daylighting control system is a stepped on-off system with 3 photosensors linked to a central control system. The space is broken into three control zones, each responding to an individual photosensor.

What was built. The lights did not step off in response to the available daylight. The control system was not calibrated as a part of the construction process. For one control zone, the sensor's field of view was obstructed by HVAC ductwork. As a result this sensor did not see any daylight. For another zone, the sensor was located appropriately in the skylight, but the sensor was faulty and never read more than 8 fc. It did not turn any lights off. The sensor for the third zone did not turn any lights off since it was not calibrated. As a part of the architectural design, baffles were installed to reduce glare on the pool surface; these baffles also reduced daylight from the skylights. The electrical engineers realized that there were problems with the system and called for calibration.

Problem resolution. The calibration effort revealed all the problems described above. The calibration itself was hard to do because the photosensor output was in a proprietary metric that did not correspond to Footcandles or Lux. The location and design of the baffles could not be changed since they were designed in response to comfort and safety concerns; so the reduced daylight quantity had to be accepted as a reality. This meant that only one daylight control zone, the one adjacent to the curtainwall glazing, received adequate amounts of daylight to justify turning off lights. The lighting for this zone was controlled through the astronomical clock of the building energy system to turn lights off one hour after sunrise and turn them on one hour before sunset. The photosensor controls for the other two zones were disabled.

Comments on the process. The daylighting control system was added with addendums after the construction documents had been issued. Baffles were added that reduced the available daylight. The location of the photosensors with respect to the HVAC ductwork was not coordinated.

Case Study 9- Retail, Grocery Store

What was intended: This grocery store chain, with each store typically 8,000 m^2 in size, developed its concept for daylighting using lessons learned from one store to be implemented in the next. One store was built with extensive tall windows in the check-out area and the dining alcove. This store was lit exclusively with direct fluorescent fixtures, and all fixtures have dimming ballasts to enable adaptation compensation at night, and allow daylighting control during the day. The second store was built with the same lighting and front store windows, but it also included a side clerestory window and a north facing light monitor with a deep monitor well. The owner requested measurement of both stores to determine the performance of each.

What was built: The stores were built more or less as designed. The first store did not achieve much daylighting savings. The second store gets good savings from both daytime and night-time dimming, measured at about 300,000 kWh / year, of which about 140,000 kWh / year is due to dimming during the daylight hours. The north facing light-scoop, built with a very deep well, does not contribute towards measurable daylight savings.

Problem resolution: While there are no major problems, the owner has learnt through the performance measurement that the light-scoop needs to be redesigned. The owner has become more educated about daylighting controls in terms of real savings through detailed study of the operation and is evaluating additional glazing in the form of clerestories or skylights.

Comments on the process: This is one of the rare cases where dimming controls are in place before the decision to harvest daylight has been made. The dimming controls were used store-wide, independent of daylight for night-time dimming. This owner's commitment to reducing operating costs while improving the store environment with daylighting is a great example of how high performance buildings are achieved though iterative design, closing the loop from design to operation in each subsequent project. 'Big box' retailers with chains of stores have the opportunity to successively improve their energy performance.

Case Study 10 - Technology company headquarters building

What was intended: This headquarters building was designed primarily with daylighting and views in mind. Large glazed curtain walls on the perimeter atria and skylights above the interior atria provide daylight to the thin floor plates. Under-floor air delivery with personal environment modules and indirect electric lighting were part of the design to make for a high quality interior environment. Stepped daylighting controls were to control two perimeter rows of fixtures.

What was built: In many areas, the lights were wired such that the photosensors controlled the inner rows of fixtures that were not considered to be part of the daylight zone. When these lights were turned off by the controls, there was not much daylight to compensate for it. Meanwhile adjacent areas that were part of the daylight zone had daylight as well as electric light. The contrast between the two areas was significant.

Problem resolution: The lights were rewired so that the photosensors controlled lights in the identified daylight zones.

Comments on the process: The daylighting control system was specified in the design documentation but without wiring diagrams. The controls manufacturer provided the shop drawings that were not checked by the lighting designer. Thus, although the electrical contractor wired the system according to the shop drawings, the system did not work as intended.

Case Study 11 – Energy company headquarters building

What was intended: This was an existing warehouse building that was transformed to be an open office and conference room space for the energy company. The design added a number of modular Solatube skylights to provide daylight. Dimming daylighting controls were to control the direct light fixtures in the open office area and the two large conference rooms.

What was built: In the open office areas 1 photosensor was installed to control 6 different daylighting zones via a zone controller and dimming module. The photosensor type installed was open-loop, and was located between a Solatube skylight and an electric light fixture and positioned such that it could see both the electric light and the Solatube. The dimming module has 4 different “scenes” and changes between “scenes” based on the amount of daylight detected by the sensor. Since the sensor was open loop type and owing to its installed location, there was never enough daylight to dim the electric lights.

Problem resolution: This problem has not been resolved. The solution suggested is to move the photosensor into the tube of one of the Solatube Skylights so that it could only see daylight.

Comments on the process: The project was design build. The electrical contractor specified and located the daylighting controls on the drawings. The controls manufacturer provided the shop drawings. There was no one person on the project who had complete knowledge of both how the lighting was intended to be controlled and how the control system worked.

Case Study 12 – Architectural firm headquarters building

What was intended: This was a historically significant beer brew-house that was remodelled as office space with new interior finishes and mechanical and lighting systems, reusing only the building structure and shell. The old building had large windows with high window heads that let in daylight; new glazing systems were introduced in to the window openings. The spaces are tall with over 6 m high ceilings, and stepped daylighting controls were envisioned to turn off lights in the daylight zones.

What was built: The lighting designers lit the space with compact fluorescent high bay systems with a dual level switching system. Each level provided about 70-80 Lux of electric light with the total electric illumination at about 150 Lux. No daylighting controls were included; they were added after the fact. But calibration could not be accomplished since open loop type controls were added high up on the ceiling far away from the windows. The sensors never saw enough light from their location to turn any lights off.

Problem resolution: This problem has not been resolved.

Comments on the process: The electric lighting was designed with very low lighting levels. Further lighting reduction could have been achieved but the sensors needed to be placed at the windows looking outside. The building operators and contractors who added the controls placed the sensors in the wrong location.

Summary Observations from the Case Studies

Table 1. Summary of Case Study Problems

Case Study	Space type	Failure mode	Effects of Failure	Root Cause	Additional Causes		Action to correct situation	
1	College Dining Hall	**Under-dimming**	Reduced energy savings	Not wired correctly	System not calibrated		Re-wire sensors to control dimming light sources	Calibrate system; educate operator
2	College Classrooms	**Under-dimming**	Reduced energy savings	System not calibrated	Windows smaller than expected	Sensor sees indirect lights	Proper calibration	Educate operator and user
3	Office Building	**Over-dimming**	Reduced energy savings	Calibrated aggressively	Occupants have history of higher lighting levels	Dark furnishings create dark space	Continue to test ability of occupants to accept some lighting control	
4	Office Building	**Under-dimming**	Reduced energy savings	System not calibrated	Too many sensors installed, calibration not feasible		Remove sensors from daylighting system, control lights with 1 sensor per orientation	Properly calibrate remaining sensor; Educate operator and user
5	College Classrooms	**Cycles**	User irritation	Faulty controller	Photosensor and controller incompatible		Change programming in EMS system to set dimming delay by photosensor	
6	Big Box Retail	**Over-dimming**	Concern for store revenue to be reduced	Calibrated aggressively	3 daylight zones makes accurate calibration a more complex task.	Daylight is not uniform in the space	New owner needs to understand system and become convinced to try re-calibration	
7	Office Building	**Lights on at night**	Reduced energy savings	Night-time over-ride not available	Wrong sensor type installed		Change sensor type and relocate sensor	
8	Recreation Center - Pool	**Under-dimming**	Reduced energy savings	Sensor location does not detect enough light	System not calibrated		Remove poorly located and not working sensors from system.	Control fewer fixtures with the working sensor
9	Grocery Stores	**Under-dimming**	Reduced energy savings	Not enough windows	Not calibrated initially		Continue calibration and evaluation	
10	Office Building	**Over-dimming**	User irritation	Incorrect set of lights being controlled			Rewire the lights	
11	Office Building	**Under-dimming**	Reduced energy savings	Sensor location improper for open loop control	Not calibrated initially		Relocate sensors to skylight	
12	Office Building	**Under-dimming**	Reduced energy savings	No controls installed during construction			Relocate sensors to windows- not done	

Table 1 summarizes the problems encountered in the 12 case study buildings. The table includes the failures, their causes, and the actions, if any, that were taken to remedy the problems.

Issue \ Fix	Add/ Change Control equipment	Disable control	Add manual override	Move sensor/ Control Location	Change sensor/ Control Location	Add/ Change fixture connections	Change fixture location	Program/ calibrate the system	Educate building operator
Not implemented (const.)	hard					very hard		easy	
Not Calibrated								easy	easy
Wrong Control Equipment	hard							easy	easy
Sensor Location				very hard	easy			easy	easy
Sensor Angle					easy			easy	easy
Not enough sensors installed	hard					very hard		easy	easy
Too many sensors installed	hard	hard				very hard		easy	easy
All fixtures not connected						very hard		easy	easy
Wrong fixtures connected						very hard		easy	easy
Window postion is different				very hard	easy		very hard	easy	easy
Lower surface reflectances				very hard			very hard	easy	easy
Higher partitions				very hard		very hard		easy	easy
Other obstructions				very hard		very hard		easy	easy
Daylight quantity is less	hard	hard		very hard	easy	very hard			easy
Users want more control			very hard						easy

Table 2. Matrix of issues against fixes showing degree of difficulty to fix problems

As Table 2 shows above, most of the problems identified in the case studies are extremely difficult to fix once they have occurred and once the construction has been completed. As a consequence, such problems are usually not fixed, and the daylighting system is never effectively used.

The overall conclusions to be drawn from the analysis of these case studies are that, if automatically controlled daylighting systems are to be effectively delivered and used, then:

- Much more understanding is needed of the control system hardware, software, and operations. Improving design products is very important (drawings, checklists, specifications, testing plans, etc).
- Problems with the daylighting systems should be avoided before they happen. This is a primary role of modern commissioning approaches.
- If problems do occur, they should be fixed as soon as possible.
    - Waiting until the end of construction is too late.
    - Thus, developing and implementing an incremental testing and calibration program for the construction period is vital.

Since many of the recommended actions are related to commissioning (Cx) techniques and procedures, we explore in the following sections of this paper how Cx can potentially help avoid some of the problems that have been identified.

Using Cx to Improve Daylighting Results

As we have said above, a key to resolving most of the problems with daylighting systems identified in the case studies is to avoid them before they occur, or to fix them quickly once they have occurred. Cx activities can help in doing just that.

Cx can be described as a quality-oriented process with an independent set of eyes that avoids problems before they occur. If the problems do occur, then Cx provides techniques to identify and fix the problems in a timely fashion. Thus we think that many of the above problems might be avoided, before they happen, or fixed when they happen, via increased attention to several key commissioning (Cx) activities throughout the process if designing and delivering daylighting systems. Specifically:

1. Cx activities during pre-design and design[1] can help improve the consistency and detail of daylighting design information that is shared among the design team and then passed on to the construction and operator/occupant teams.
2. Cx activities during bidding and construction can help the daylighting system that is supplied and installed to better reflect the design intent.
3. Cx training activities throughout the entire delivery process can help building operators and occupants to better understand the effective operation and use of the daylighting system that is produced.

We recognize that each building owner may have a different approach to balancing the costs of delivering a project with the risk of inadequate performance of daylighting or any other building system. Relative to the building's daylighting system, we recommend that the building owner:

- Use the Cx activities discussed in this paper from the outset of a project's life cycle.
- Use these Cx activities to help determine a balance among the functional, quality, risk and cost objectives for the daylighting system.
- Indicate in the Requests for Proposals to the design team, construction manager, and commissioning authority for the project that Cx activities like these be used in accomplishing the work for the project.

In applying Cx activities in this paper we follow the Total Building Commissioning documents produced from a collaboration of ASHRAE and NIBS. We will use the Cx procedures defined in ASHRAE Guideline 0-2005 and the technical requirements for the building exterior enclosure defined in NIBS Guideline 3-2006.

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[1] We include 3 sub-phases as part of the design phase: (1) schematic design, (2) design development, and (3) the development of construction documents.

Before Design Begins:
Clearly Identify Owner Project Requirements

Good daylighting design involves integrating solutions across several building systems and coordination and communications among several design and construction disciplines. Often, tradeoffs among competing objectives can also be involved. Thus, it is important for the design team to clearly identify as early as possible the owner's desires and criteria on daylighting requirements relative to other design objectives. This is important for resolving potential competing or conflicting design objectives.

The Owner's Project Requirements for Daylighting (OPR-DL) should be developed as early as possible in the design process, preferably during pre-design.[2] The OPR-DL for daylighting could include such factors as:

- Illumination criteria
- Daylight objectives
  - Percent of each space to provide task lighting predominantly from daylighting
  - Percent of each space to provide ambient lighting predominantly from daylighting
  - Variability expected diurnally and seasonally
- Glare criteria and preferred control devices
- Electric lighting system performance characteristics
- Control system criteria
  - Variability acceptable given the space use
  - Possible manual override of controls to provide operators and occupants adequate control
- Interior design objectives
  - Brightness objectives
  - Reflectance criteria for interior surfaces and furnishings
  - Partition locations, heights, and opacity criteria
- Level of visual uniformity or contrast desired in spaces

The above is just a partial list of factors, and each of the above factors can also be delineated in more detail.

Once developed, the OPR-DL can be a valuable document for evaluating options and for resolving conflicts among competing objectives. Thus, it should be used as the defining document for developing, supplying, installing, testing, calibrating and using the daylighting system (and other systems as well).

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[2] For a discussion of the OPR for the building exterior enclosure, see NIBS GL 3-2006, Section 5.2.2, and for discussion of the OPR within the overall Cx process, see ASHRAE GL 0-2005, Section 5.2.2.

> ***Recommendation:*** *We recommend that several examples of Owner's Project Requirements for Daylighting (OPR-DL) be made publicly available, in order to improve the quality and consistency of the Owner's Project Requirements for Daylighting (OPR-DL) being developed for buildings. Such examples should enable designers to use them as templates to quickly develop and at low cost an OPR-DL for their building. This would help improve the consistency of daylighting design.*

During Design:
Develop More Detailed Daylighting Information

In this section we identify activities that should occur during the 3 design phases[3] – schematic design, design development, and construction document preparation.

During the schematic design phase, the design team can then use the OPR-DL in order to develop the Basis of Design (BOD-DL)[4], which embodies the design intent for daylighting. The OPR-DL and BOD-DL together provide the bases for the daylighting design.

Daylighting is not yet "standard" design practice. Thus, design information should be well detailed and consistently detailed in order to protect against suppliers and contractors making incorrect assumptions or decisions because of insufficient design instructions.

The BOD-DL for daylighting could include such factors as:

- Top lighting and/or sidelighting to achieve the interior illuminance levels
- Aperture sizes, locations, and glazing characteristics
- Interior design parameters
- Surface reflectances
- Choice of colors related to brightness contrast objectives
- Control narrative explaining a typical operation of the control system including response speed

Project Objectives Meetings Begin and End each Design Phase

At the beginning of each phase, the OPR-DL should be used as the basis for defining objectives for the daylighting products for the phase. Then, at the end of the phase the daylighting products should be reviewed to see how well they have achieved the objectives for the phase.[5]

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[3] See NIBS Guideline 3-2006, Section 6, for a more detailed discussion of the 3 phases relative to general commissioning activities.

[4] For a discussion of the OPR for the building exterior enclosure, see NIBS GL 3-2006, Section 6.2.2, and for discussion of the OPR within the overall Cx process, see ASHRAE GL 0-2005, Section 6.2.2.

Issues should be documented in an issues log, to be maintained and used as input to the objectives meeting to begin the next phase. This process will help to surface and resolve issues that might otherwise only surface too late at the end of construction. Thus, maintaining an issues log throughout the course of the design and construction phases, and using the log as a basis for resolving outstanding issues, will be important to the ultimate success of the daylighting system.

Modeling of Daylighting

Ideally, physical or computer-based modeling should occur as a routine part of daylighting design in order to estimate projected energy savings from daylighting. Then, the modeling should be updated whenever significant changes occur in any feature or combination of features that would affect the daylighting performance of the design. For example, the models should be updated with significant changes in key items such as window size, glazing visible transmittance, interior surface reflectances, etc.

> ***Recommendation:*** *As for the OPR-DL and BOD-DL, we recommend that several examples of the modeling of daylighting illumination and energy impacts be made publicly available. It would be especially useful to have such modeling examples linked to the example OPR-DL and BOD-DL for the same building. It would also be useful to demonstrate when such modeling should be revised as key factors in the daylight design change during the building delivery process. This would help improve the consistency of daylighting impact assessments.*

Checklists and Specifications

During the construction document phase, the OPR-DL should be used as the defining document to prepare checklists and specifications to guide the supply and installation of each element of the daylighting system. It is especially important to prepare detailed checklists and specifications for those elements of daylighting systems that have caused past problems. From Table 2 above these should include at a minimum:

- Detailed specification of control equipment functionality
- Sensor locations
- Proper number and type of sensors to be installed
- Clear specification of which fixtures are to be connected to which daylighting circuits
- Aperture locations, sizes and visible transmittance characteristics
- Surface reflectances (minimum criteria)
- Partition heights and opacity characteristics (maximum criteria)
- Obstruction of daylighting from other objects (maximum criteria)

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[5] To review this pattern of objectives meetings during the design process relative to the building exterior enclosure, see NIBS GL 3-2006, Sections 5.2.8, 6.2.8, 6.2.9, 7.2.2, 7.2.6, and 7.2.11.

Control system Specification: The lack of in-depth understanding by designers, contractors and installers of the functions and operational requirements of daylighting control systems is perhaps one of the key obstacles to delivering successful modern daylighting systems. A significant educational effort is warranted to overcome this deficiency. One valuable resource to support improved understanding would be a publicly available performance specification for the automatic control system for the electric lighting system subject to daylighting controls.

A similar public performance specification has recently been written in California for performance monitoring systems with a focus on HVAC.[6] A similar public performance specification for daylighting controls systems would be very valuable.

> ***Recommendation:*** *Thus, we recommend that a public performance specification for daylighting controls be developed and published. It would be very useful to include with the performance specification several examples of its application to the daylighting control systems for several buildings.*

Attachment A to this paper contains an example daylighting control specification plus examples of daylight control narratives for a few typical situations. These examples have developed by The Weidt Group Inc. The material should not be used directly. If material from these examples is extracted for use on projects, the material should be modified to meet the specific requirements of each owner project delivery process.

Manual override: The control system specification should address the nature, type, and extent of any manual override capabilities for the control system. Such manual override could provide building operators and occupants with sufficient control that they would not disable or disconnect the daylighting system because they are dissatisfied with some aspects of the automatic control system or its operation.

Prepare Plan for Testing and Calibration

During the construction document phase, prior to the completion of contract documents, a testing and calibration plan should be developed that includes a listing of the tests that should be accomplished. The testing and calibration plan should, like the checklists and specifications, pay special attention to those problem areas that have caused failures or significant problems with past daylighting systems. At a minimum the testing program should verify that:

- Wiring of daylighting systems properly installed
- Installed sensors are of proper types and numbers, and that they are located and pointed in the proper directions.

[6] See References for citation. The document may be downloaded from: http://cbs.lbl.gov/performance-monitoring/specifications/

- Control hardware and software responds properly to the threshold conditions
- Control hardware and software responds properly to longer-term operating conditions. This requires datalogging and monitoring of the systems.

A calibration program should be developed to verify that all daylighting components as well as the overall system is calibrated to function as intended. The testing and calibration plan should include a schedule for when the tests and calibrations should be performed.

> ***Recommendation:*** *We recommend that several public examples of daylighting testing and calibration plans be developed and published. These should be representative of such plans developed during the design phases for application during construction*

During Construction:
Review Submittals, Track Issues, Test & Calibrate

Three important construction period Cx activities for daylighting are (1) reviewing all construction submittals to verify that they comply with the OPR-DL and the design documents for the daylighting system, (2) tracking issues for the daylighting system, and (3) conducting the testing and calibration plan to verify that each aspect of the daylighting system is functioning as intended.

Reviewing Construction Submittals

During the construction phase, it is important to review all construction submittals including shop drawings and product submittals to verify that they comply with the OPR-DL, the intent of the BOD-DL, the drawings, checklists, specifications, control narrative, testing plan and other design documents for the daylighting system. Special attention should be paid to any documents that identify or involve potential changes to the daylighting system, or to any of the related building systems that would impact the performance of the daylighting system.

Equally important is to identify who should be responsible for reviewing and approving each aspect of the daylighting system, given that multiple design and construction disciplines are involved in the daylighting system. Annex F in NIBS Guideline 3-2006 provides an example table of roles and responsibilities for the building exterior enclosure. A similar table for roles and responsibilities for daylighting systems by building delivery phase would be very helpful.

> ***Recommendation:*** *We recommend that a public example of a roles and responsibilities matrix be developed and published specifically for daylighting systems. testing and calibration plans be developed and published.*

Tracking Project Issues

Earlier in this paper we recommended that an issues log be developed and maintained throughout the design process. It is now important during construction to continue to maintain and update the issues log throughout the construction process. Given recent experience with daylighting systems in a number of buildings, the issues log for daylighting systems should track two kinds of issues:

- Daylighting issues that have been identified specifically for the current project, and
- Daylighting issues derived from a list of known general problems with daylighting systems should also be maintained and regularly reviewed. This could help to avoid having the current project fall victim to problems that have plagued similar problems in the recent past.

Conducting the Testing and Calibration

From recent experience, the testing and calibration activities are by far the most important Cx activities to accomplish for producing effective daylighting systems of high quality. If possible, each daylighting component can be tested or evaluated as soon as possible so that problems can be identified before the relevant trades leave the construction site.

Also, the testing and calibration activities should continue to pay special attention to those problem areas that have caused failures or significant problems with past daylighting systems, including verifying that

- The wiring of daylighting systems is properly installed
- Installed sensors are of proper types and numbers, and that they are located and pointed in the proper directions.
- The control hardware and software functions properly.

The calibration activities should verify that the daylighting system will produce the illumination levels anticipated as well as achieve the energy savings expected.

> ***Recommendation:*** *We recommend that several public examples of daylighting testing and calibration activities during construction be developed and published.*

During Occupancy and Operation: Provide for adequate training

The building operator and occupants should understand how the daylighting system works, including its variability and limits. This should include an understanding of how each element of the daylighting system contributes to a successful solution including:

- Apertures
- Shading
- Interior surface treatment
- Partitions
- Electric lighting systems
- Lighting and daylighting control systems.

The operators and occupants should be trained about how the daylighting system is supposed to work, so that if problems occur, they can distinguish between design and operations causes.

If the daylighting system has manual override capabilities, the operators and occupants should understand how to activate such overrides. This will enable them to avoid problems without disabling or disconnecting the system.

To properly provide this understanding, training programs need to be conceived as early as the design phases and implemented throughout the daylighting delivery process. Both Guidelines 0 and 3 emphasize that the training programs should be considered and developed early in the building delivery process.[7] A similar focus should apply to training programs for daylighting.

> ***Recommendation:*** *We recommend that at least one public example of a daylighting training program for building operators and occupants be developed and published.*

Concluding Observations

Existing Cx tools and procedures can provide valuable assistance in avoiding problems in the design and implementation of daylighting systems. However, existing tools are very general. For example the examples in NIBS Guideline 3 address some aspects of daylighting systems implementation but not all. More focused guidance is needed that specifically targets daylighting systems and their issues. Such guidance could include documents from recent projects that specifically address successful daylighting system delivery activities and products such as:

- One or more example OPR documents for daylighting systems
- One or more BOD documents that respond to the OPRs.
- Example issue logs maintained over time
- Example checklists for various elements of the daylighting system
- Example specifications for each element of example daylighting systems, plus the specification for the proper *integration* of all elements of the daylighting system.
- Example testing plans and calibration plans
- Examples of testing and calibration activities that have successfully identified and resolved problems before it was too late to fix them.
- Examples of training programs and activities.

At the time this paper is being written NIBS is planning to develop a daylighting supplement to Guideline 3-2006 and has begun to assemble a project committee to accomplish this work.

[7] For discussions of training within NIBS Guideline 3-2006: during the Pre-design Phase, see Section 5.5 and also 5.2.2.(i); during the Design Phase, see Section 6.5 and also 6.2.7; during the Construction Phase, see Section 7.5, and also sections 7.2.3(d), 7.2.6(e), 7.2.7.3, and 7.2.14; and, for the Occupancy and Operations Phase, see Section 8.5 and also 8.1.3, 8.1.4, and 8.2.4.

Hopefully, providing standardized Cx procedures and example products focused specifically on daylighting systems will enable building owners and design/construction teams to consistently produce highly effective daylighting systems.

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Attachment A: Example Daylighting Control Specification and Example Control Narratives

This attachment is intended to present examples of a daylighting control specification and example control narratives for a few typical situations. These examples have developed by The Weidt Group Inc. The material should not be used directly. If material from these examples is extracted for use on projects, the material should be modified to meet the specific requirements of each owner project delivery process.

Example Daylighting Control Specification

Daylighting Control System features/ capability to be specified

1. The photosensor shall have a light level response range of100 to 10,000 FC for open loop switching systems and 5 to 500 FC for closed loop switching systems. Range shall be identified on the product.
2. The photosensor shall have a spatial (view angle) response of at least a 60-degree cone of vision.
3. The photosensor shall have a spectral radiation response range to detect less than 5% ultraviolet and infrared radiation response
4. The daylighting controls system shall have a setpoint adjustment in the form of a user adjusted setting, preferably from a remote digital device, or with a dashpot with clearly marked adjustment tick marks.
5. The daylighting controls system shall have a gain setting adjustment in the form of a user adjusted setting, preferably from a remote digital device, or with a dashpot with clearly marked adjustment tick marks. 0 to 1.0
6. The daylighting controls system shall have a fade rate adjustment for dimming systems in the form of a user adjusted setting from 30 to 90 seconds, preferably from a remote digital device, or with a dashpot with clearly marked adjustment tick marks.
7. The daylighting controls system shall have a deadband adjustment for stepped or switching systems in the form of a user adjusted setting, preferably from a digital device, or with a dashpot with clearly marked adjustment tick marks. The deadband shall be adjustable from 10% to 80% of set point adjustment.
8. The daylighting controls system shall have a time delay adjustment with a user adjustable ON delay 5 to 60 seconds and adjustable OFF delay 3 to 60 minutes for stepped or switching systems; time delay shall be user adjustable from 5 to 300 seconds for dimming systems.
9. The daylighting controls system shall have all control products be UL and CUL listed.

10. The daylighting controls system shall have all control products include a 5-year warranty period.

Calibration requirement for Daylighting Control System

1. Factory-authorized personnel shall calibrate system.
2. The calibration shall include demonstrating and educating the Owner's representative on system capabilities, operation and maintenance.
3. Calibration shall be conducted when final room finishes, furniture and window treatments have been installed.
4. The contractor shall notify the Architect, Engineer and Owner's representative 10 days prior to the date of calibration.
5. Training of the Owner's Representative on system capabilities, operation and maintenance shall be for a minimum of four (4) hours.
6. The contractor shall maintain all calibration logs identifying all controller settings for each daylight control zone.

Submittal requirements for Daylighting Control System

1. Submit product data for photosensor and controller for the following
   (a). Algorithm (open or closed loop)
   (b). Light level response range
   (c). Spectral radiation response range
   (d). Spatial (view angle) response, drawing showing sensor cone of vision
   (e). Ballast and component compatibility
   (f). Power requirements, operating voltage, input and output current.
   (g). Maximum number of ballasts that can be controlled
   (h). Clearances and access requirements
2. Submit sensor placement drawings showing the location in plan, section and interior elevation. Drawings shall be specific to the project.
3. Submit wiring diagram in overlaid on the reflected ceiling plan showing the entire installation. Drawings shall be specific to the project.
4. Compatibility documentation – Submit evidence showing compatibility between the photosensor, controller, ballast, lamp fixture, other lighting controls, signal, control wiring, interface, input output, radio frequencies.

Project Record Documents

1. Submit drawing showing the actual installed wiring, control device identification, and schedule of control function.
2. Submit calibration logs for the control devices, including adjustment of preset controls for setpoints, fade rates, delays and overrides.
3. Submit operation and maintenance data.

EXAMPLE DAYLIGHTING CONTROL NARRATIVES

One use of narratives such as these is to edit them for insertion into project specifications.

Control Narrative and Sequence of Operation *(for dimming system in classrooms)*

4. The daylighting controls for the classrooms (and other spaces) are expected to dim the lights approximately from 2 hours after sunrise to 2 hours before sunset unless the sky is unusually overcast and dark. There will be one daylighting control zone for each classroom (or other space).
5. The expected average daylight factor for each daylight zone is above 2%, providing an average of 25 fc for a diffused sky condition of 1250 fc.
6. The design illuminance for the space is 45 fc.
7. The daylighting controls shall respond to the total illuminance in the space, reading both daylighting and electric light components to maintain the design illuminance level during daylight hours as well as during non-daylight hours.
8. The sensor-controller shall begin to dim when the total illumination levels (daylight + electric light) increase above 45 fc.
9. The sensor-controller shall not dim the electric lights below 20% of their full power output.
10. The dimming system shall adjust the light levels continuously to maintain a minimum of 45 fc total illumination.
11. During normal function, the dimming system shall respond to abrupt changes in daylight level fluctuations with a delay of not less than 20 seconds so that the occupants do not notice abrupt fluctuations in electric light illumination, and not more than 60 seconds so that energy savings are not reduced.
12. During normal operation, the dimming fade-rate shall be maintained at 60 seconds so that occupants do not notice abrupt changes in electric light illumination levels. During calibration and troubleshooting the delay and fade-rate may be disabled temporarily.
13. Manual switches, programmable controls and occupancy sensor controls in the zone shall override the daylight controls to turn lights off.

14. When manual switches, occupancy sensor controls or programmable controls are set to turn lights on, the daylighting control system will determine the light levels.

Control Narrative and Sequence of Operation (for stepped system in circulation)

1. The daylighting control for the circulation space shall be accomplished through an astronomical timeclock to switch lights off approximately from 3 hours after sunrise and turn the lights on 3 hours before sunset.
2. The expected average daylight factor for the daylight zone is above 2%, giving an average of 25 fc for a diffused sky condition of 1250 fc.
3. Programmable controls shall override the daylight controls to turn lights off during after-hours and at night.
4. Manual contact switches in daylight-controlled zones shall override the daylight controls to turn lights on for a period of 2 hours. Once 2 hours have elapsed the timeclock will turn the lights off. The building operator may adjust this 2-hour period as needed. These manual switches shall be located within in the spaces for easy occupant access.

Control Narrative and Sequence of Operation (for stepped system in circulation)

1. The daylighting controls for the circulation spaces are expected to turn off the lights approximately from 2 hours after sunrise to 2 hours before sunset unless the sky is unusually overcast and dark.
2. The expected average daylight factor for the daylight zone is above 2%, giving an average of 25 fc for a diffused sky condition of 1250 fc.
3. The design illuminance for the space is 15 fc.
4. The daylighting controls shall respond to only the exterior daylight illuminance and will not respond to the electric light illuminance in the space, to maintain the design illuminance level during daylight hours as well as during non-daylight hours.
5. The control system shall turn off when the total illumination level (daylight + electric light) increases above 40 fc.
6. The control system shall turn on the lights with the total illumination level (daylight + electric lights) decreases below 20 fc.
7. During normal operation, the daylighting control system shall respond to abrupt changes in daylight level fluctuations with a delay of not less than 10 minutes so that the occupants do not notice abrupt fluctuations in electric light illumination, and not more than 30 minutes so that energy savings are not reduced. During calibration and troubleshooting, the delay and fade-rate may be disabled temporarily.
8. Manual switches, programmable controls and occupancy sensor controls in the zone shall override the daylight controls to turn lights off.

9. Programmable controls shall override the daylight controls to turn lights off during after-hours and at night.
10. Manual contact switches in daylight-controlled zones shall override the daylight controls to turn lights on for a period of 2 hours. Once 2 hours have elapsed the timeclock will turn the lights off. The building operator may adjust this 2-hour period as needed. These manual switches shall be located within the spaces for easy occupant access.