What's Wrong With Daylighting?
Where It Goes Wrong and How Users Respond to Failure

Prasad Vaidya, Tom McDougall, Jason Steinbock, Jim Douglas, and David Eijadi,
The Weidt Group

ABSTRACT

Daylighting, hailed as a cornerstone of sustainable design of buildings, has the potential to reduce lighting energy which can be 40% or more of the energy cost of a commercial building. We find that daylighting control systems often do not provide the expected energy savings. In the construction industry which is very risk averse, even limited failures can dramatically slow the advance of valid technologies. There are numerous reasons for failure. Natural light sources are complex and vary through the day and year, implementation requires coordination between different building design and construction trades, the documentation and specification of the controls equipment is often inadequate, and calibration after installation is rarely done well and can be confusing and time consuming.

In this paper, we provide eight case studies as representative examples where daylighting systems did not meet expectations and describe how users reacted to different types of failure and how they cope with what appears to be a failed daylighting system. We further propose a method for failure analysis, identify four modes of failure, and provide a template for each mode for easier problem resolution in future. We discuss how decisions are made and documented in the development of daylighting systems in typical commercial buildings. We describe the state of expertise of the trades involved in delivering daylighting systems in commercial buildings.

Introduction

Daylighting contributes to high performance or sustainable design in two directions. On the one hand it improves the interior environment, and on the other, it can significantly reduce the lighting energy in a commercial building. Energy savings can be accomplished in two ways; a lighting designer may choose to count daylight as a legitimate source and reduce the number of lighting fixtures installed in a space or, a design team may choose manual or automatic switching systems to turn down lights when daylight is available. Counting daylight as a source may imply that the building is used differently during the day and night. In commercial building lighting design this is often not considered an acceptable approach, so most teams design artificial lighting systems to provide all the light required in a space, day and night, and usually to the same lighting levels. This leads to a reliance on automatic control systems which are expected to provide more reliable energy savings than manual controls (Heschong Mahone Group, 1998).

Design analysis often shows daylighting control to be one of the most promising energy conservation strategies for commercial buildings; consequently, daylighting controls are more frequently installed. Because energy codes may eventually mandate the use of daylighting controls, it seems prudent to look for object lessons for success and failure from the set of early adopters.

In our energy design assistance work we have suggested daylighting as an energy conservation strategy in over 400 buildings, about a quarter of which commit to implement it through automatic daylighting controls. We generally provide architectural design assistance for developing the daylighting potential of a building and then analyze combinations of lighting and control options for their resultant energy savings. On most projects we review construction documents and verify the installation of the systems. Whenever possible, we help with calibration of the control system and gather feedback from the occupants. This has given us the opportunity to observe variables in design and implementation processes including the performance of both design teams and technologies.

Automatic switching or dimming control systems do not provide the expected energy savings as often as we would like. In industries as risk averse as design and construction, even limited failures can dramatically slow the advance of valid technologies. The possible reasons for an unsuccessful implementation of daylighting controls are numerous. Often, too little information about performance characteristics of a control system is made available to the designers. 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 often 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 issues have led to badly implemented control strategies.

If energy efficiency through daylighting controls is to proliferate as a strategy its success rate needs to be improved. [1] Though there are successes, our intention here is to throw light on the weak areas so that future research and development on improving the process can be more focused.

This paper describes eight case studies where daylighting did not meet the initial energy savings expectations. We filter the case studies through a method of failure analysis to identify the failure modes. For each failure mode we create an abstract template that may lead to quicker and more methodical problem resolution in future. We discuss how decisions are made and documented in the development of daylighting systems in typical commercial building projects through design and we identify the weak links in the flow of information.

Case Studies

The following eight 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 examples where daylighting is implemented as a successful strategy and energy savings are being realized as expected. In our experience however, the successful cases are the exception, not the rule.

[1] For example, in the Skylighting Guidelines, Heschong et al describe a case of a newly constructed building with automatic daylighting controls, where the controls had been disabled by the occupants with tape over the sensor when they were not even wired to the lights. Since the controls were not functioning, they could not have been causing a problem. So did the occupants simply not trust an automatic lighting control system?

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. Out of a number of different light sources the non dimmable ones were connected to the dimming control system. Lighting control zones wired to the system were not necessarily zones with daylight. The photosensor signal was not calibrated during construction. Thus, wiring errors were not discovered. The users in the space, who occupied it for no more than two hours at a stretch and were oblivious of the daylighting controls, 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 calibration 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.

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 -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. The photosensors located on the ceiling also read the upward component of the direct-indirect lighting system. Further, the photosensor signal was 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 calibration.

Problem resolution. During calibration it was found that the lights were in the burn-in mode and hence had not dimmed. The calibration was done to maintain the design illuminance level. Since the hallway lights were delivering 75 fc the classrooms appeared darker, requiring the hallways to be de-lamped to reduce the light levels. 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 the 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 deep perimeter open office arrangement, includes 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. The lighting power density was expected to be at 1.25 watts per sf. 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 the installed lighting was at a lower power density of 1.0 watt per sf. Dark furnishings were installed. The controls were calibrated prior to occupancy and responded well to changes in daylight levels. The furnishings combined with the lower lighting power density resulted in some cubicles with 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, so there was no buy-in from the users, only grievance. There was no problem reporting protocol for daylighting controls, and 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 probably had little experience with daylighting controls and did not catch the error. The manufacturer was probably not involved in the development of the control system and was not responsible for calibrating the system. If calibration was required of the manufacturer, they may have involved themselves in the design development and 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 was 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 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 a timeclock sensor 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 so that the lights would always stay on; 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 have the knowledge base to be able to 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 system was added with addendums after the construction documents had been issued. Baffles were added after the daylighting system had been designed which reduced the available daylight. The location of the photosensors with respect to the other disciplines was not coordinated during construction.

Summary of Case Studies

In many of the above cases, we find that calibration of the controls was not done before the occupants moved in. Calibration of the controls, also referred to as "commissioning", to be done before the building is occupied is a critical part of the process. Nevertheless, calibration is certainly not the solution to all the problems identified above. In fact, calibration would only allow us to catch some of the problems before the occupants encounter them.

In most cases, we find that the daylighting systems failed due to a lack of coordination between the design disciplines (architectural, interior and space planning, mechanical and lighting/ electrical) or a lack of clear understanding on the part of the disciplines as to how the decisions they make can affect the performance of a daylighting control system. The location of daylighting controls is as much a spatial decision as the location of windows to bring in the daylight. Not many designers realize this or create documents to reflect it.

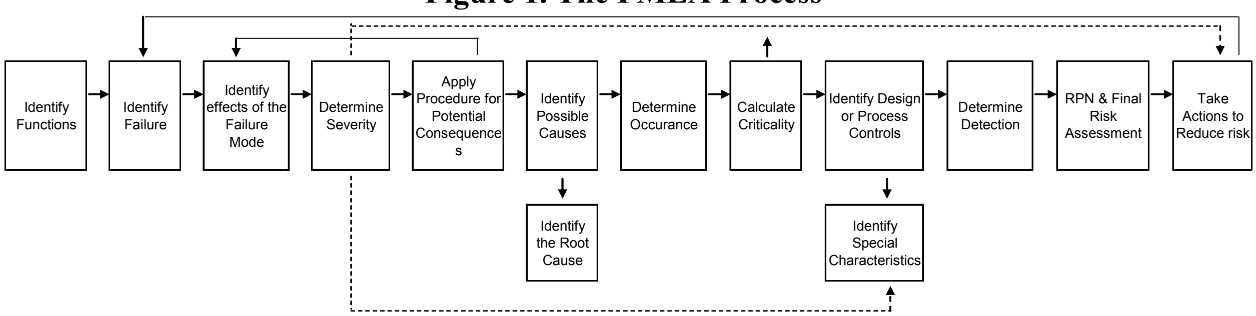
There are also examples of the right checks not being in place during the design documentation phase. Shop drawings made by the contractors that detail the daylighting system were not checked, or lighting designers simply did not know what to check for. Very often when a daylighting system performs poorly, the investigation or the compromises done later are not documented and taken back to the designer to complete the feedback loop. Given this state of things, the learning curve on daylighting is likely to be very long.

We also see in the case studies above that only some of the problems encountered can be addressed after construction is completed. While calibration can be addressed easily enough later, the problems revealed through the calibration exercise are not easily corrected. Owners or facilities operators are likely to correct and change the programmable settings in control software. At a stretch, they may reassign circuits to a daylighting controller, or even rewire it. But usually a larger scale of rewiring of the lamps to get an appropriate grouping that can then be appropriately controlled is not likely to happen after construction is completed. Window sizes, furnishings, lighting fixtures are expensive to change after the fact and also affect the aesthetics of the spaces; these will almost never be changed later. So if a daylighting system needs to perform optimally, most of its physical elements have to be done right by the time the building is certified as "completed".

Installations that are not calibrated do not perform well. The failure mode of under-dimming is typically not noticed nor reported. If on the other hand the failure is over-dimming the occupant's performance may be hindered, the occupant will complain or simply sabotage the control system. The result of this is that a daylighting system that does not save energy goes unnoticed and a daylighting system that saves energy more aggressively than it should gets disabled. Overall one is therefore likely to find daylighting systems in our building stock that save less energy than their believed potential.

Failure Analysis Method

Figure 1. The FMEA Process[2]



Our attempt here is to identify, study and organize the failures in daylighting systems. Figure 1 shows the standard Failure Mode and Effect Analysis (FMEA) method diagram that is typically used in industrial processes.

We map the case studies to the FMEA process to identify the failure modes (Figure 2). Instead of reacting to each case where daylighting fails as a unique condition, the failure analysis allows us to sort the malfunctions into patterns or modes of failure, quickly look up the possible causes, identify a root cause and determine stopgap and long-term solutions. For each failure mode we create an abstract template (Figure 3) that may lead to quicker and more methodical problem resolution in the future.

[2] www.fmeca.com/ffmethod/fmeaproc.htm

Figure 2. Mapping of case studies to FMEA

Case Study	1	2	3	4
Space type	College Dining Hall	College Classrooms	Office Building	Office Building
Failure mode	**Under-dimming**	**Under-dimming**	**Over-dimming**	**Under-dimming**
Effects of Failure	Reduced energy savings	Reduced energy savings	Reduced energy savings	Reduced energy savings
Root Cause	Not wired correctly	System not calibrated	Calibrated aggressively	System not calibrated
Additional Causes	System not calibrated	Windows smaller than expected	Occupants have history of higher lighting levels	Too many sensors installed, calibration not feasible
		Sensor sees indirect lights	Dark furnishings create dark space	
Action to correct situation	Re-wire sensors to control dimming light sources	Proper calibration	Continue to test the ability of the occupants to accept some lighting control	Remove sensors from the daylighting system, control lights with 1 sensor per orientation
	Calibrate system	Educate operator		Proper calibration of remaining sensor
	Educate operator	Educate user		Educate operator and user

Case Study	5	6	7	8
Space type	College Classrooms	Big Box Retail	Office Building	Recreation Center - Pool
Failure mode	**Cycles**	**Over-dimming**	**Lights on at night**	**Under-dimming**
Effects of Failure	User irritation	Concern for store revenue to be reduced	Reduced energy savings	Reduced energy savings
Root Cause	Faulty controller	Calibrated aggressively	Night-time over-ride not available	Sensor location does not detect enough light
Additional Causes	Photosensor and controller incompatible	3 daylight zones makes calibration a more complex task to do accurately.	Wrong sensor type installed	System not calibrated
		Daylight is not uniform in the space		
Action to correct situation	Change programming in EMS system to set delay for dimming by the photosensor	New owner needs to understand system and become convinced to try re-calibration	Change sensor type and relocate sensor	Remove poorly located and not working sensors from the system.
				Control fewer fixtures with the working sensor

Daylighting systems seem to have four common failure modes. Under-dimming, over-dimming, cycling, and cases where the lights are turned on and stay on through the night.

Under-dimming. This includes lights left burning brighter than they need to be in dimming applications as well as lights left on in stepped or switching applications when there is adequate daylight to be able to turn them down. The result of this failure mode is a reduction in energy savings. Occupants of the building do not expect lights to dim or be turned off automatically in response to available daylight, so they do not notice anything out of the ordinary in this failure mode. This failure mode, unless caught in the calibration process or unless a curious and conscientious facilities operator observes it, will typically go completely unnoticed by the occupants. For the building operators the reasoning goes - if there are no complaints, it must be working. Savings expected will be reduced or lost. See potential causes in Figure 3.

Figure 3. Daylighting Failure Mode Templates

Failure mode	Under-dimming	Cycles	Over-dimming	Lights on at night
Effects of Failure	Reduced energy savings	User irritation	User irritation	Reduced energy savings
Determine Severity	Major	Catastrophic	Critical	Major
Potential consequences	Savings loss	Disabled sensor, zero savings	Disabled sensor, zero savings	Savings loss
Reccommended Immediate Action	Call commissioning agent	Call commissioning agent and disable sensor/ controller	Call commissioning agent and disable sensor/ controller	Call commissioning agent
Potential causes	System not calibrated Sensor location does not detect enough light Not wired correctly Faulty sensor Not enough windows in room Sun-glare issues, users draw shades Dark furnishings, sensor sees dark surfaces	Delay not set Not calibrated Faulty controller	System not calibrated Sensor location sees electric light Sensor location sees excess daylight Wrong sensor type installed	No night-time over-ride set Night-time over-ride not available
Identify Root Cause				
Identify Additional Causes				
Action to correct situation				
Identify Future Process Controls	Specify calibration & short term system performance monitoring Have instructions for user/ operator and phone number to call Coordinate with other disciplines Write a controls narrative Review CDs for daylighting performance Require and check shop drawings			

Over-dimming. This is the opposite of under-dimming where a control system dims or turns off the lights more aggressively than the available daylight justifies. A system that over-dims will likely draw attention to itself and the occupants will complain about insufficient light. Some over-dimming systems that use indirect lighting fixtures may go unnoticed by the occupants because the occupants may not be able to tell if the lights are off or on! But once over-dimming is noticed, the facilities operator will be asked to correct the situation; most often the response from the facility operator is to disable the control system. Sometimes, occupants with energy and initiative, take it upon themselves to disable the system. Their most effective weapon against an over-dimming system is black tape, applied over the photosensor. Energy savings may be aggressive in the initial phases of an over dimming system, but they are usually eliminated over the long term once the system is disabled. See potential causes in Figure 3.

Cycling. Cycling occurs when the control system responds very rapidly to the changing daylight levels in the space, too rapid for occupant comfort. A system that cycles rapidly in dimming applications draws attention to the lights and lighting control system from the occupants and facilities operators. Cycling in switching applications fares even worse. It distracts the occupants, hinders task performance and is unacceptable for prolonged use of a space. A cycling system will be quickly disabled by the facilities operator and sometimes by motivated occupants themselves. In most cases a cycling system is a result of a lack of or poor calibration procedure. It requires either an increased delay setting or an increased deadband[3] adjustment to correct it. Sometimes a lighting control system may be installed without the capability for a delay or deadband adjustment, then the solution is less simple. Savings are usually eliminated unless the system is fixed instead of being disabled. See potential causes in Figure 3.

Lights on at night. There are some installations where the daylighting control system may or may not turn the lights down during the day in response to daylight, but it turns them up and burns them through the night. These are cases where the controls have not been routed through a time-clock that intelligently overrides the photosensor signal to turn the lights down after hours. Alternatively, the timeclock may simply not be programmed correctly. This failure mode does get noticed sometimes by the occupants driving by the building at night and wondering why the lights are on. See potential causes in Figure 3.

The Windows Are Open but the Savings Aren't Coming Through

Success of a daylighting system in a building depends on a series of design decisions. Figure 4 lists the types of decisions that are made on a typical daylit building. Against this list of decisions we list the primary design discipline responsible for making the decision and documenting it in the drawings or specifications. The same trade is also responsible for checking the shop drawings[4] to determine if the design intent is being followed there. We have subjectively scored the decisions for the way they get made and how they eventually affect the savings of a daylighting system[5]. In general, decisions made by the architect are made reasonably well. In any case, most buildings with windows have some amount of daylight available to them, but the corresponding savings available for lighting energy are not always realized. Even when buildings are designed to harvest daylight aggressively, the energy savings due to lighting energy reduction are not realized fully[6]. Some of the daylighting potential created by the architectural design is lost in interior design decisions made in a way that are inappropriate for daylight. But a large part of the savings is lost simply because the lighting controls do not function the way they could. In the decisions list in figure 4 we find that while bad quality decisions by the architect or interior designer may reduce the energy savings, bad quality decisions by the lighting designer may completely eliminate the savings potential. We also list the commissioning agent against a series of decisions that go beyond the simple checking of the system; we associate the commissioning agent with building operator and user education and for continued performance monitoring. These tasks are not routinely incorporated

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[3]A deadband is the range between the lower setpoint when the lights are turned on and the upper setpoint when the lights are turned off. The control system does not take any action within the deadband.

[4]In the case of complex building systems, a contractor will respond to an incomplete set of construction drawings by preparing a set of drawings called shop drawings that are sent to the designers for review. The system finally gets built to fulfill the approved set of shop drawings.

[5]This scoring is based on our experience of consulting on more than a hundred building projects where we interacted with the designers and reviewed the design documentation produced by them.

[6]Metered lighting energy savings due to daylighting controls rarely meet the modeled expectations. Investigations in the case studies in this paper also indicate that significantly more savings would have been possible in almost all cases.

into a commissioning agent's scope of work. Indeed a commissioning agent is not routinely incorporated in the work flow at all.

Figure 4. Decisions and Documentation Quality

				Documentation (adequate or inadequate currently)					
		The quality of this decision		Design		Construction		Commissioning/ Calibration	Post Occupancy
Decisions that affect daylighting	**Primary Trade**	**Could be better**	**reduces/eliminates daylighting savings**	**Drawings**	**Specifications**	**Shop Drawings**	**Contractor Submittal**	**Report**	**Report**
Building Orientation	AR	Y	R	A					
Building Shape	AR	Y	R	A					
Ceiling height	AR	N	ok	A					
Window Area	AR	N	ok	A					
Window location	AR	N	ok	A					
Glazing type	AR/ ME	N	ok		A		A		
Exterior Shading	AR	N	ok	A	A		A		
Interior Shading	AR/ ID	Y	R		I		I		
Interior space planning	ID	Y	R	A					
Interior partitions	ID	Y	R	A		A	A		
Interior Colors	ID	Y	R		A		A		
Lighting Illuminance	LD	N	ok		A				
Lighting Fixture type	LD	N	ok	A	A		A		
Lighting Lamp type	LD	N	ok	A	A		A		
Lights to be controlled	LD	Y	R	I		I			
Control Sequence	LD	Y	E		I		I		
Lighting Switch/ Dim control	LD	N	ok	A					
Ballast type	LD	N	ok		I		I		
Photosensor type	LD	Y	E		I		I		
Photosensor location	LD	Y	RE	I	I	I	I		
Photosensor, number of	LD	Y	R	A		I			
Controller dials available	LD	Y	RE		I		I		
Controller location	LD	Y	RE	I		I			
Calibration	LD	Y	RE		I		I	I	
Relamping - Burning in guidelines	LD	Y	RE		I			I	
Building operator education	CA	Y	RE		I		I	I	I
User awareness education	CA	Y	E		I				I
Problem reporting protocol	CA	Y	E		I				I
Performance monitoring	CA	Y	R		I				I
Performance reporting	CA	Y	R		I				I

AR = Architect, ID= Interior Designer, ME = Mechanical Engineer, LD = Lighting Designer, CA = Commissioning Agent

R = Reduces, E = Eliminates, RE = Reduces and could eliminate, A = Adequate, I = Inadequate

As we move over in the design process from decision making to documenting the design decisions, we find a similar scenario. The architect's and interior designer's documentation related to making daylighting work is passive in nature[7] and is adequately addressed. In the lighting designer's scope of work, lighting fixture design is documented well, but lighting controls for daylighting are often documented only at a conceptual level. A commissioning agent's documentation fares even worse. All design disciplines care equally about the work they produce, the lack of adequate documentation is in no way due to a lack of intent, it is the lack of training on how to do it.

The result for daylighting control systems is pretty serious. Design documentation in the form of construction drawings and specifications is the main vehicle for getting design intentions implemented during construction. A lack of proper documentation results in ill-implemented systems.

[7]Architects have been designing and getting windows and window treatments built for centuries. If a window shape or design needs to be changed for daylighting from what is normal, they still know how to get it built. Thus window openings, glazing types and window treatments are typically well documented and implemented.

The Lighting Designers World

The success in daylighting controls appears to depend on lighting designers' experience with applications and the collective knowledge shared within a design firm. Every building project has an artificial lighting system but few buildings try to implement daylighting controls. Daylighting control is that exotic strategy that an individual designer does not try time and again (Reese 2004).

Lighting designers, like other professions, tend to rely on a repository of design experiences and published guidelines. The Illumination Engineering Society of North America (IESNA) is a professional organization that takes the lead on developing guidelines and standards for design. IESNA publishes Recommended Practices and Design Guides to be used as references. For lighting fixture layouts and fixture selection, lighting designers also use computer programs[8]. Some of these can model the effect of daylight in a space. Lighting design in terms of the source photometric data, availability of resultant light and its distribution is well documented and supported in the guidelines and software tools. On the controls side however, neither the IES publications nor the software tools seem to do justice to the topic. Lighting designers claim that since control products vary across manufacturers, their best option is to seek the documentation provided by the manufacturer (Hunt 2004). They design and prepare documentation based on the guidelines provided by the manufacturers (Hunt 2004; Nielson 2004; Reese 2004).

To assess the quality of information available to the lighting designers, we reviewed the product information, design and installation guidelines provided by 3 leading manufacturers (see table 2). We found that none of the products available can be used off-the-shelf. They all require careful consideration by the designer, and require calibration after installation. While some technical data for the sensors is available, typically in the form of the cone of the sensor's view, other data such as spectral sensitivity, ideal locations for installation, do's and don'ts are not always available. The controllers are documented but their compatibility with other manufacturer's products, the calibration adjustments (dials) available, the control algorithm used are not always explicitly stated. One manufacturer sells products by applicability for particular space type[9]. In this case it is relatively easy for a lighting designer to look up the space type where controls are to be installed and use the recommended mix of control products. But the same manufacturer does not provide any guideline or checklist on what a designer needs to decide and document in terms of drawings, specifications and narratives, to convey the design intent to the contractor or manufacturer. Another manufacturer provides a fair amount of detail on documentation and specification, but does not sell products by application types. Across the manufacturers there is no consistency on how the controls are achieved, the component mix to achieve the same controls, the documentation of their products, or a set of guidelines that a lighting designer can use. All of these are likely to improve. One manufacturer is in the process of creating a checklist of specifications for the lighting designer so that they can respond to the bid documents more appropriately. But consistency is unlikely until an external entity such as

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[8]Some of these are distributed by the manufacturers (e.g. Visual by Lithonia), while others are made available by non-affiliated software makers (e.g. Lumen Micro, AGI32).

[9]Like open office applications, classroom application etc. Other manufacturers give short examples of how the products have been applied (successes) in the past.

the IESNA develops the guidelines for designers to specify requirements and for the manufacturers to publish their data in a standard format[10].

Table 2. Controls Manufacturer Survey

CONTROLS MANUFACTURER	1	2	3
Products Available (Catalog/ Website)			
Photosensor	Yes	Yes	Yes
Controller	Yes	Yes	Yes
Calibration equipment	No	No	Yes
Performance monitoring equipment	No	No	No
Easily Available Information (Catalog/ Website)			
Technical information	Yes	Yes	Yes
Compatibility info with their own products	Yes	Yes	Yes
Compatibility with other manufacturers' products	Yes	No	No
Application guidelines (by space)	ND	ND	Yes
Sample wiring diagrams	Yes	Yes	Yes
Other drawing samples	ND	ND	Yes
Sample control sequence narrative	No	No	No
Specification guidelines or samples	No	Yes	Yes
Installation guidelines	No	Yes	Yes
Calibration guidelines or requirements	ND	Yes	ND

ND = Not detailed enough

To some extent this gap in the collective knowledge for realizing daylighting savings is slowly being filled by high-performance or sustainable design guidelines. Skylighting Guidelines, the California High Performance Schools guidelines, EPRI Guidelines for Lighting Controls and Daylighting Design and the Advanced Lighting Guidelines, are some examples. These guidelines explain the concepts of daylighting and controls in detail. They also list design considerations, albeit with a disclaimer that the guidelines are generic in nature and for specific applications the best source may be the manufacturer of the controls. The detail and knowledge has improved with each successive guideline. Currently the guidelines are aimed at explaining the conceptual application of daylighting controls and providing a list of design considerations for the designers. What is needed is a list of the documentation that needs to be completed by the designer and a diagram of a process that incorporates checks and feedbacks.

Conclusion

Savings from automatic daylighting control systems are often not realized fully when a building is turned over to the users. Where the controls do work, we are likely to find an involved and unusually committed owner. If controls are to be automatic, savings cannot depend solely on an owner or user's commitment.

Calibration of daylighting control systems is not the definitive solution to the problems we see today. Many of these problems need to be solved during the design development and construction process.

[10]Until a few years ago, window glazing was in a similar nebulous climate till the National Fenestration Rating Council paved the way for a standardized reporting of performance data.

Lighting designers can play the biggest role in ensuring energy savings through automatic daylighting controls. But many lack sufficient familiarity with the controls and do not have a clear process for proper implementation. They depend on manufacturers' information which is often in adequately presented and inconsistent within the industry. Thus, most failures can be traced back to inadequate specification of the controls systems, component parameters and sequence of operations.

Solutions could include generic guidelines on selecting the equipment and creating the required design documentation. A stronger advocacy role by lighting designers experienced with regards to the daylighting controls can reduce the occurrences of failure and provide a way of diffusing their knowledge through the profession and building industry. Validation of the documentation has to become as much a part of the process as calibration. Additionally, the process needs to include building operators' education and occupant feedback to the designers about the workings of the control system.

Daylighting control has not matured enough to become an off-the-shelf technology yet - and making it a code requirement may need to be delayed for some time.

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