A Cost Benefit Analysis Applied to Lumen Maintenance Controls

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A fundamental premise of lighting is that light has value. This is easy to show when the choice is between no light and some light. When the choice is between some light and more light, it is much more difficult to demonstrate. Because of this difficulty, lighting recommendations have been based on consensus judgments of the value of light. There is no formal connection between these judgments and the basic premise upon which they are founded so they are not guaranteed optimal.

In this paper, we report on a successful attempt to formally analyze a practical problem: an evaluation of the relative economics of lumen maintenance controls system vs the standard "no-controls" system. We digress briefly to describe a lumen maintenance control system.

In conventional lighting systems where lumen maintenance controls are not used, light levels drop as lamps age and dirt builds up on luminaire and room surfaces. In a properly designed standard system, the installed initial light level is higher than the IESNA recommended levels for the space. Ideally, light levels just reach the recommended level when the lamps reach the end of their economic life when it is time to replace lamps and clean fixtures.

With a lumen maintenance system (LMS), a dimming ballast is used with a light sensor and a control system to maintain a fixed light level. Initially, the light level is dimmed to the expected final maintained level. As the system ages the control system increases power to maintain the light level. When the system reaches full power it is time to replace the lamps and clean the fixtures. The ideal LMS will draw the same power as the standard system, but only at the end of the cleaning and relamping cycle. At all other times it is partially dimmed, thus drawing less power and presumably saving energy.

Because the lumen maintenance control system meets the light level recommendations at all times and requires equal or less energy than a standard system at all times, the technology is considered energy efficient and its use is encouraged in commercial buildings.[1] For example, California's Title 24 Non-Residential Building Standard allows 10 percent energy credit for this technique.[2]

The fact that a control procedure saves energy is not sufficient to prove that it is actually cost-effective or desirable. Lighting provides benefits in the form of visibility, comfort, and so on. These benefits are at least partially dependent on the overall light level—this is why there are light level recommendations and energy standards. While the cost of a lighting system may run several hundred dollars per year per employee, salaries are likely to be several hundred times higher. Thus even small decreases in the productivity of the employee will more than erase any savings from the LMS. A formal analysis of cost-effectiveness requires a cost-benefit analysis that explicitly takes into account lighting benefits as well as changes in installation and energy costs.

Unfortunately, there are difficulties in doing this calculation. Changes in energy or installation costs are tangible and fairly easy to measure. Changes in visual performance are also tangible and can be measured under laboratory conditions, but in most cases they are impractical to measure under real work conditions. Extrapolation from laboratory conditions introduces large uncertainties at this time because we are still uncertain as to what elements of visual performance—scanning, reaction time, acuity, contrast edge detection, depth and area of field, and so on, contribute to a given work situation, and to what degree. Changes in comfort and satisfaction aren't even tangible—although they may contribute to productivity, which is. These difficulties are the reason that an analytical evaluation based on the fundamental lighting premise has not been performed in the past.[3]

In reality, we know a lot more about how lighting benefits change with light level than is normally realized. Equally important, determining whether lighting controls are economic requires less information about the form of the light level/benefit relationship than one might think. These points can be illustrated by posing the initial question in reverse—that is, what type of benefit function is implied by assuming that the lumen maintenance level should be equal to the recommended maintained lighting level of the standard non-dimmed system? The value of the energy savings from dimming will be greater than the added benefit of more light, regardless of the price of electricity, only if there is no added benefit once one reaches the recommended maintained light level.

There may be considerable uncertainty about the precise shape of the benefit function, but it should be evident that a step function or cusp in the benefit function located exactly at the IESNA recommended level is not realistic or credible. What this example shows is that we do have some idea as to what form the benefit function must have vs illuminance, even if we don't know its

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precise shape. Furthermore, we know that its shape is not consistent with an analysis that ignores the benefit terms entirely.

In this paper, we identify a range of reasonable shapes for the benefit function. We have computed the cost-effectiveness of lumen maintenance controls for each of these shapes and a variety of base conditions (salary, dirt level, task difficulty, and so on). The result of these calculations is a guide to those conditions and assumed benefit shapes where lumen maintenance controls are cost-effective and those where they are not.

We close this introduction with a caution. Our conclusions apply only to the economics of using dimming ballasts for lumen maintenance control. They do not apply to the use of dimming ballasts for daylight-linking, tuning, task matching, or load shedding. Indeed, some of these other control techniques may actually enhance lighting benefits through reductions in glare, but we have not examined these issues in detail and they are not the topic of this paper.

The net benefit equation

The basic tool we use to formally include the fundamental lighting premise and to evaluate cost-effectiveness is the concept of net-benefit. We assume that the benefits of lighting have some economic value, B. If we let the cost of the lighting system be C, then the net-benefit (NB) equation is:[4]

$$NB = Benefits - Costs = B - C \qquad (1)$$

where the benefits, and costs for a lighting installation are:

$$B = f(productivity,\ comfort,\ satisfaction) \qquad (1a)$$

where f is an unknown function of the indicated arguments, and

$$C = installation + maintenance + energy \qquad (1b)$$

In order to distinguish between the readily measured factors, such as electrical costs, and intangibles or difficult-to-measure factors, such as comfort, we include discomfort and dissatisfaction from glare or other aspects of bad lighting in **Equation 1a** as negative benefits (negative comfort or satisfaction). Although the factors in **Equation 1a** are not easily measured it does not mean they don't exist. It costs money to install lighting, and so it wouldn't be done if it didn't have some value.

The benefits from going from no light to enough light to avoid safety hazards and do one's work is obvious. As the light level continues to increase, the gains in productivity become smaller, and eventually productivity may even begin to decline. In general, the benefit and cost terms are functions of many variables including illumination. However, if we fix the design, so that illumination level is the only free variable, we can then treat both the benefit and cost terms as functions of illuminance alone. This leads to the extremely important result that there is a best (economically optimal) light level where the benefits from further increases in illumination are just balanced by the increased costs, that is:

$$\frac{d(NB)}{dE(optimal)} = \frac{dB}{dE} - \frac{dC}{dE} = 0 \qquad (2)$$

where $\frac{d(NB)}{dE}$ is the derivative of the net-benefit vs illuminance, E, and $\frac{dB}{dE}$ and $\frac{dC}{dE}$ are the derivatives of the benefit and cost functions vs illuminance.

There are many factors that determine the optimal level and in general we don't know the exact answer. IESNA lighting recommendations are an educated guess of the approximate level. **Equation 2** is our starting point.

The basic economic argument

In a standard system, the lamps are replaced and the system is cleaned when the light level drops to the recommended level. The LMS is installed with the same lumen delivery capacity, but uses dimming to maintain the recommended level at all times. The average light level over time is therefore lower for the LMS than it is for the standard system. For simplicity we assume that the two systems have the same efficacy. This means that the LMS saves on operating (electricity) costs by an amount that is proportional to the difference in the average light levels. If we also assume that there is no cost premium for the lumen maintenance equipment, then the total difference in cost is due to the energy savings.

To estimate the difference in lighting benefits between the two systems, *we make the critical assumption that the maintained level is nearly optimal.* If light levels are grossly non-optimal then there is no point to the analysis as the system should not have been installed in the first place. If the level is nearly optimal, then **Equation 2**, the benefit from an increase in average light levels, is approximately equal to the change in the average light level times the total cost per unit increase. The total costs per unit of light include installation and maintenance as well as operation (electricity), and therefore are always larger than electric costs alone, so the value of the lost benefits from using the LMS should be expected to be larger than the reduced electrical costs. Thus if light levels are near optimum to start with, the LMS is less economic than the standard system.

Discussion of the basic argument

Given the conventional wisdom, this is a surprising result. In this section we examine the simplifications and assumptions we used to see how general it is. One of our simplifications is to ignore the increase in costs that occur as system efficacy decreases as the lamps and system age. Our second simplification is that we have assumed that the costs and benefits vary linearly over the illuminance range of interest.

Appendix A provides a formal analysis of the net benefits of the lumen maintenance and standard non-dimming systems which explicitly includes the decreased efficacy and increased costs that occur over time. This analysis shows that the decrease in efficacy does not change the basic result as long as we still assume linearity.

On the other hand, major deviations from linearity could change the conclusion and make the LMS the more cost-effective of the two choices. Deviations in linearity can occur for both costs and benefits.

For costs, the assumption of linearity is that the unit cost per fixture, person-hour, or kWh is constant. This is a good assumption for a given job where one is examining cost differences due to relatively small changes in design levels. It is not true (and we are not concerned) with costs for small vs large jobs or builders. Furthermore, the analysis in **Appendix A** shows that the assumption of linearity need only be true in an average sense, since the analysis is based on integration over the light level range.

For benefits, the assumption of linearity is better than assuming that the benefit function goes flat exactly at the recommended light level, but it is still not realistic. Below the optimal light level the slope of the benefit function is larger than that of the cost function. Above the optimal light level the benefit function slope is less. This decrease in slope means that the increase in benefit with increased light levels is less than what is estimated using the linear approximation.

If the benefit function varied rapidly with illumination near the optimum it would be very easy to determine the optimum. We can infer that this is not true by the lack of explicit data or analysis identifying the optimum levels. Recommended levels have been set instead by consensus for many years, and have changed substantially over time. This indicates that the benefit function is probably nearly linear near the optimum, so our basic argument is reasonable. To determine whether our conclusion still holds, we need to examine benefit functions more closely. In the next sections we develop lumen maintenance and plausible benefit functions. We then determine net benefits by running simulations over a variety of test conditions to determine just how non-linear the benefit function has to be before the lumen-maintenance system becomes cost-effective. In addition, we examine what happens to the net-benefit when the installed and optimal illuminances are substantially different.

Benefit functions

In an earlier paper, one of the authors examined net-benefits by using relative visual performance (RVP) functions as estimators for productivity.[4] The relative visual performance functions are based on measurements of the speed with which subjects can do laboratory tasks. We assumed that the time it takes to do real work is the sum of a primarily visual component, which can be represented by an RVP function, and a non-visual component, which can be represented by an RVP function, and a non-visual component, which is not related to the lighting and can be taken as a constant. The value of the work is then given by the intrinsic value of the tasks that are being performed, multiplied by the number of tasks that can be performed in a given by the intrinsic value of the tasks that are being performed, multiplied by the number of tasks that can be performed in a given time.

The absolute value of an employee is presumably related to their salary. this varies a great deal among jobs, so it is easier to compare and graph different conditions by computing a relative net-benefit (RNB) that has a maximum value of 1. Let S be the productivity of a worker when RVP = 1. If we let F be the fraction of the productivity that depends upon the lighting under optimal conditions, then:

$$RNB = \frac{NB}{S} = \frac{1}{\left[\frac{F}{RVP} + (1-F)\right]} - \left(C_f + C_E\right)\frac{E}{S} \qquad (3)$$

Here $C_f + C_e$ are the fixed and operating (electrical) costs respectively, and E is the illuminance. The term F/RVP is that fraction of time required for a job that is related to the visibility of the task. The visual fraction F corrects for tasks such as talking on the phone that require no light. The reader should refer to the original cost-benefit paper for a more detailed derivation of this equation.[4]

At very low light levels, luminance adaptation limits visual performance, thus limiting productivity. At higher levels, adaptation is much less important and glare, comfort, and other factors may dominate. We therefore assume that the benefit function is related to the visual performance function at low light levels, but may deviate from it at higher levels.

The visual performance functions are monotonically increasing functions of luminance (illuminance) with an asymptote at high illuminances. These functions have parameters, such as age of observer or size and contrast of visual task, that affect the shape and location of the approach to the asymptote, and this, in principle, can represent a wide variety of conditions.[5–7]

Because they are flexible, they could also be used to represent non-visual benefits if those benefits are monotonic and asymptotic. In this case the independent parameters would simply be parameters in an empirical function, without a physical meaning.

The situation that is most likely to make an LMS more cost effective than a standard system is where glare or preference produces a maximum benefit at some light level, with decreasing benefits and acceptability as the illuminance increases past the optimum. To represent this situation we modified the RVP function developed by Clear by subtracting a term of the form, kE^n where k and n are constants and E is illuminance.[4] Since we do not have any firm knowledge of the actual shape of the postulated decline in lighting benefit, we performed simulation calculations for n equal 1/2, 1, and 2, so as to be sure to cover a range of possible shapes. At low illuminance levels these new composite relative benefit functions approach the visual performance function. At high illuminances they eventually bend over and decline—and thus approximate the situation where glare or preference makes high illuminances undesirable.

With the addition of these three modified benefit functions we had five benefit functions. The first was the Rea RVP function. The second was the Clear/Berman relative task performance (RTP) function. The last three were computed from the RTP function as described above.

Lumen depreciation

To determine the relative economics of a standard system and a LMS it is necessary to estimate lumen depreciation. Lumen depreciation comprises three terms: lamp lumen depreciation (LLD), luminaire dirt depreciation (LDD), and room surface dirt depreciation (RSDD). We used published data to generate procedures to compute these factors over a wide variety of conditions. **Appendix B** briefly describes the derivations and gives the formulas for these calculations.

Table 1—Maintenance conditions and results

Case	A	B
Dirt condition	Very clean	Dirty
Fixture type	Direct	Semi-direct
Maintenanceclass	IV	II
Room cavity ratio	1	1
End of cycle maintenance values		
LLD	0.913	0.913
LLD	0.827	0.704
RSDD	0.972	0.856
MF	0.733	0.553
Energy savings		
Ideal energy savings	9.8 percent	16.5 percent
Real energy savings	1.4–3.4 percent	6.5–8.6 percent

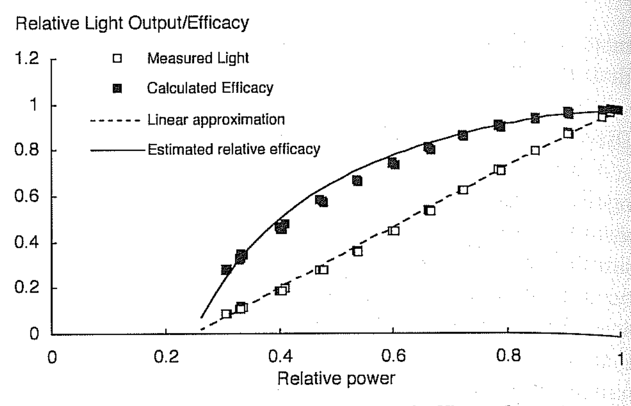

Figure 1—Measured power, light output, and efficacy for a dimming ballast.

For the simulations we wanted conditions that spanned the range that were likely to be found in practice. **Table 1** lists the parameter input and end of cycle maintenance values for the very clean and dirty conditions that we used in the simulations. **Table 1** also gives the average energy savings over the maintenance cycle both for a real system, and for an ideal system, the latter of which has no efficacy losses vs a non-dimming ballast.

The energy savings for a real system were estimated from catalog values and a limited set of measurements. The catalog values indicate that dimming ballasts at full output are from 4 to 6 percent less efficient than non-dimming ballasts. Measurements of energy use during dimming were taken in a simulated office space auxiliary to another project.[8] **Figure 1** shows that the measured light output varied approximately linearly with power, but with a non-zero intercept. The plotted curve is based on an intercept at 25 percent power, which was the value we found from catalog data. This is slightly lower than the best-fitting intercept for our measured data (28 percent) in **Figure 5**, but still fits reasonably well.

Figure 1 also plots the efficacy as a function of power. Because light output drops faster than power, efficacy drops during dimming. This effect has to be combined with the efficiency loss of the dimming ballast at full power as compared to a non-dimming ballast. For the calculations in this paper, the relative power (RP) vs the non-dimming system was given by the equation RP = 1.043 x (0.75 x RLO + 0.25), where RLO is the relative light output of the dimming system. **Table 1** shows that the combination of initial lower efficacy and a declining efficacy with power substantially reduces the available energy savings.

Table 2—Fixed values for first simulation runs

Parameter	Value	Notes
Values used in installation cost calculation:		
Coefficient of utilization	0.7	Typical
Maintenance factor	0.73	Clean environment
Installed cost/lamp ($)	70	Includes labor - 2 lamp fixture
Initial lumens	5250	2TL80 lamps x 0.875 ballast factor
Annualized cost factor	0.075	Converts initial to annual cost
Installation costs:		
in $/lm/year	0.004	From above (rounded)
Values used in maintenance cost calculation:		
Lighting hours	3500	Typical
Maintenance cycle (yr)	4	Group relamp
Lamp cost ($)	4	Includes labor
Cleaning cost/lamp ($)	2.4	
Ballast cost ($)	30	
Ballast replacement interval (yr)	12	42,000 hr ballast life
Maintenance costs:		
in $/lm/year	0.002	From above (rounded)
Total fixed costs (sum installation & maintenance costs):		
C_f ($/lm/year)	0.006	
Value used in calculating operating costs:		
Watts	61	Typ. 2-lamp electronic ballast

Simulations

Several thousand simulations were run exploring the effects of differences in benefit functions, optimal and installed light levels, ratios of fixed to operating costs, and maintenance conditions. The simulations compared both ideal dimming systems (no cost premium or efficiency losses compared to non-dimming systems) and realistic systems, against the standard non-dimming system. In this paper we describe the calculations, summarize the inputs, the range of conditions studied, and the results. A more complete description of the simulations can be found elsewhere.[9]

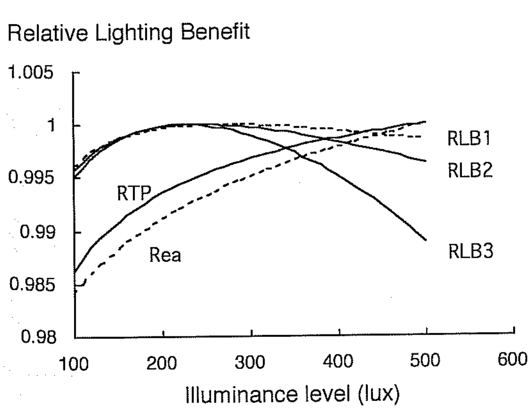

Figure 2—Relative lighting benefit (maximum in plot range normalized to unity). The five different lighting benefit curves are for a task with an optimal net-benefit light level of 200 lx.

Input values

The economic parameters enter primarily as ratios in the net-benefit calculation. We need to know the ratio C'_E/C' (electrical to total costs), and the ratio C'/FS (total cost per lumen year to the fraction of productivity attributable to the lighting m²/year). Our initial estimate of fixed costs (≈ $0.006/lm/year) was derived from the values in **Table 2**. Simulations were run both for an LMS which had no premium, and for one with an $18 premium/lamp for the dimming ballast, sensor, and automatic control system ($0.001/lumen-year). Operating costs based on an electricity rate of 8¢/kWh were calculated to be $0.0064/lm/year. This leads to a base C'_E/C' ratio of approximately 1:2 for both the standard and lumen maintenance systems. We performed simulations over the range of 1:7 to 8:9, with most of them being above 1:2, as this is the range that is most favorable to lumen maintenance systems. The maximum possible range for this ratio is from 0 to 1.

To estimate C'/FS we assumed salaries ranging from $10,000 to $100,000/year, a work area of 10 m²/employee, and a visual work fraction ranging from 5 to 20 percent. The productivity of an employee has to be higher than the employee's salary, or the company cannot make money. We therefore performed simulations over the range $100 < FS < 3000$ $/m²/year. Ratios of C'/FS ranged from about 1:400,000 to 1:5000/lx. Although we examined this ratio over a wide range we found that it primarily affects the optimal light level and has only a minor effect on the relative cost-effectiveness of lumen maintenance versus standard lighting systems.

Two types of simulations were performed. In the first type, the parameters of the benefit functions were adjusted to give a static (fixed efficacy) maintained optimum at 200, 500, or 1000 lx, and then the dynamic benefits were calculated for the optimal installed level. In the second type of simulation, the maintained installed level was fixed at 500 lx, and the benefit function was varied to give static maintained optima ranging from 50 to several thousand lx.

Figure 2 illustrates the behavior of the five benefit functions we used as a function of illuminance. The curves labeled Rea and RTP are visual performance functions, while the three curves labeled RLB1 through RLB3 represent the RTP visual performance function minus kE^n to account for glare or discomfort, with n being 1:2, 1, and 2, respectively. The slopes of the relative

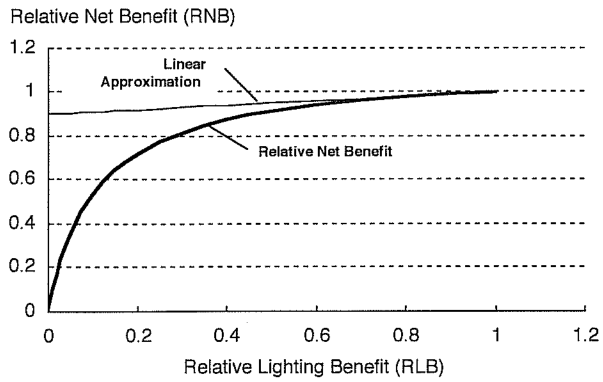

Figure 3—Relative gross benefit (RGB) versus relative lighting benefit (RLB). The "lighting fraction" is 10 percent.

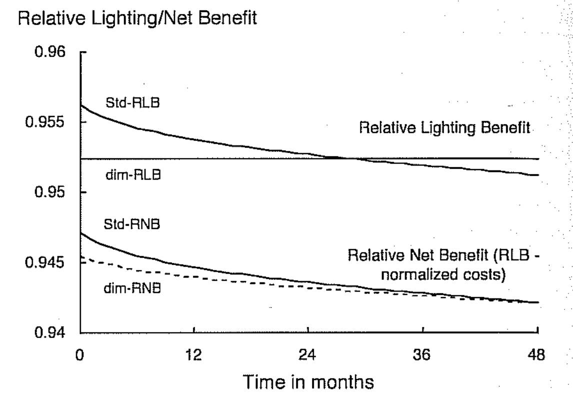

Figure 5—Relative gross or net benefit (RGB or RNB) vs time for the LMS and standard systems using the Rea benefit function.

curves near the optimal net-benefit level (200 lx in this case) are not the same, because these slopes equal C′/S, and the maximum productivity levels (S) for the five curves were not the same. **Figure 2** represents a case with a relatively easy visual task, and a low optimal light level. The curves have a similar shape, but a much larger vertical range (e.g., a 20 percent variation vs the 1.5 percent variation shown in **Figure 2**) for simulations where the task is more difficult.

Figure 2 shows only the relative visual portion of the net benefit. It does not include the diluting effect caused by non-visual work that would convert it to a relative gross benefit (RGB), nor does it include the costs, which convert RGB to a relative net benefit (RNB). The reason the two pure relative visual performance curves (Rea or RTP) show no maximum is that these functions do not consider operating costs.

For the cases we are interested in, the transformation from relative lighting benefit (RLB) to relative gross benefit (RGB) simply dilutes the lighting benefit. The first order Taylor's expansion of RGB in **Equation 3** (the first factor on the right hand side) gives RGB = (1-F) + F x RLB. **Figure 3** shows that this simple dilution formula is quite accurate for RLB $\geq$ 0.8 or so.

The RGB axis in **Figure 3** is directly proportional to the economic value of the lighting. For example, for an employee worth $100,000 per year, a drop in RGB of 0.001 costs $100 per year. If the visual fraction is 10 percent this corresponds to a drop in RLB of 1 percent. In **Figure 2**, if we assume an employee occupies 10 m^2, then a 1 percent change is worth $44 (10 x 2200 x 0.2 x 0.01) for the Rea curve, $49 for the RTP curve, and approximately $195 for the three RLB curves. This disparity in the absolute values is why we have plotted the relative values instead.

All benefits and costs were computed monthly and converted to a present value with a 10 percent discount rate. For the LMS the light level was fixed at the end of cycle value, while the power and costs changed monthly. For the standard system the costs were fixed and the benefits changed monthly.

Illustration of the basic calculation

Figures 4–6 illustrate the basic calculation. **Figure 4** shows an example of normalized costs versus time for both the LMS and the standard non-dimming system for a dirty environment. Two benefit functions spanning the range of results are shown for each system.

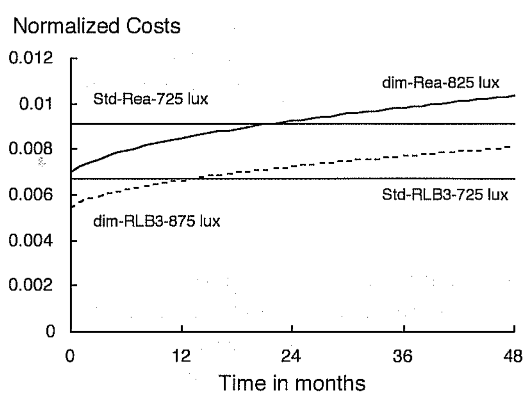

Figure 4—Normalized costs vs time for lumen maintenance dimming system and standard non-dimming system. Costs are calculated at the light levels shown.

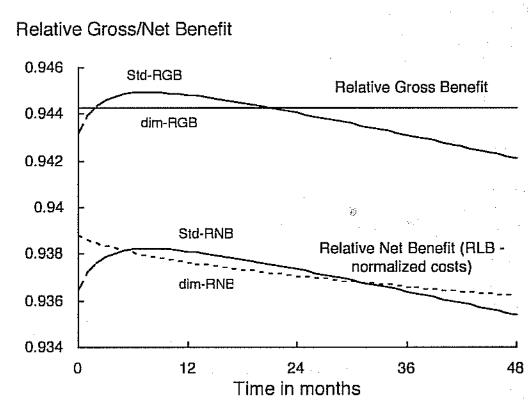

Figure 6—Relative gross or net benefit (RGB or RNB) vs time, for the LMS and standard systems using the square modified benefit function (RLB3).

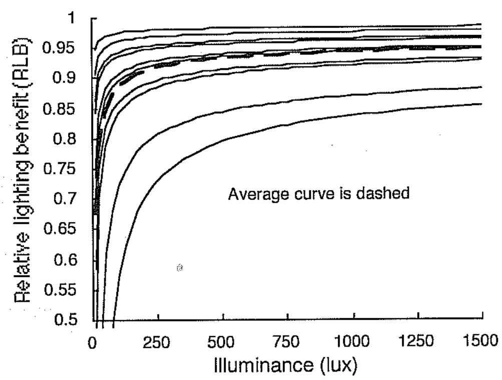

Figure 7—Relative lighting benefit curves (undiluted) for the RTP function vs illuminance. The heavy dashed line is the average over all curves, and is shown for reference only.

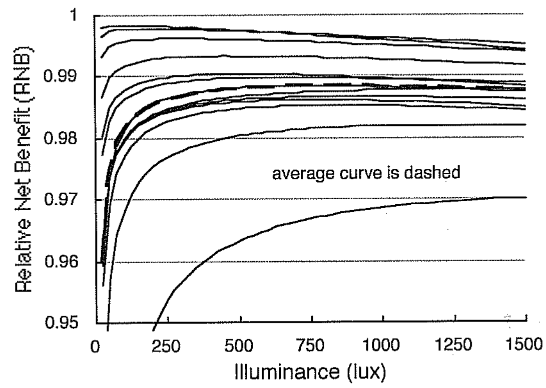

Figure 9—Sample RTP RNB curves vs illuminance. The heavy dashed line is the average over all curves, and is shown for reference only.

Normalization is by 1/S, which differs for the various benefit functions. The annualized costs for the non-dimming system are constant, while the costs for the dimming system increase with time as the system strives to maintain a fixed illuminance. For all the conditions we have examined, the optimal illuminance for the LMS was slightly higher than that of the standard system. This is the reason that the costs for the LMS in **Figure 4** are higher than those of the standard system at the end of the maintenance cycle when the LMS is no longer dimming.

Figure 5 shows the relative gross benefit, RGB, and relative net-benefit, RNB, for the Rea benefit function for the same conditions as in **Figure 4**. The two top curves show the RGB, while the two bottom curves give the RNB, which is just RGB minus the costs from **Figure 4**. The standard system starts out with a higher initial light level, and thus a higher RGB. As the standard system ages, its light level drops below that of the LMS' level, and so its RGB is lower too. However, the figure shows that the inclusion of costs makes the RNB of the standard system higher than that of the LMS system. This was true for all the simulations with the Rea and RTP visual performance functions. Both these benefit functions increase with light level at all levels of interest.

Figure 6 is the same as **Figure 5** except that it shows RGB and RNB for the RLB3 benefit function. The RLB3 benefit function declines at high light levels, so the lumen maintenance dimming system will give higher RGB and RNB for at least some of the time. In the case shown the discounted average over time is actually slightly in favor of the dimming system.

Results of simulations

The most illustrative simulations were those comparing the LMS and standard systems at a fixed installed lighting level for different optimal light levels. **Figures 7** and **8** show the RLB versus illuminance (E) for two benefit functions that nearly span the range of conditions examined in this set of simulations. Relative lighting benefit is prior to dilution by the non-visual or lighting fraction of work, and prior to inclusion of any costs. **Figure 7** shows the curves for the RTP function, which is monotonically increasing. **Figure 8** shows the curves for the RLB3 function, which was computed from the RTP function by subtracting a term equal to $k * E^2$. There are more curves in **Figure 8** than in **Figure 7** because several of the curves have the same input parameters for the

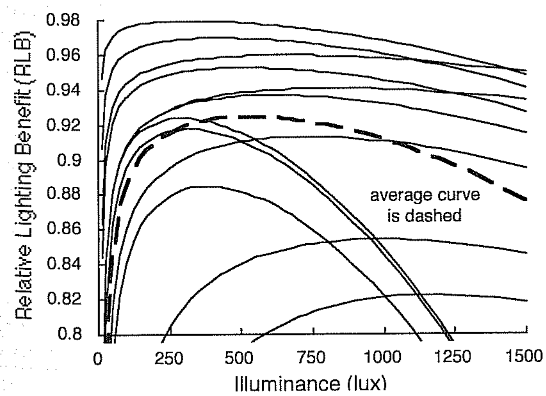

Figure 8—Sample RTP3 Relative lighting benefit curves (undiluted) vs illuminance. The heavy dashed line is the average over all curves, and is shown for reference only.

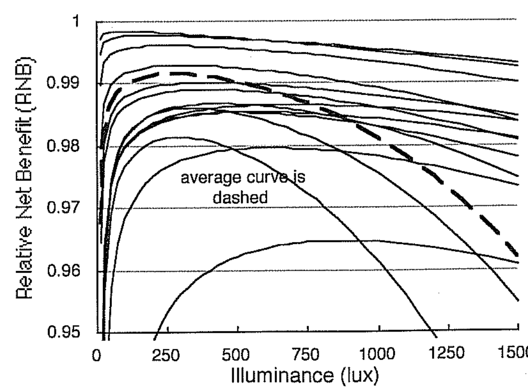

Figure 10—Sample RTP RNB3 curves vs illuminance. The heavy dashed line is the average over all curves, and is shown for reference only.

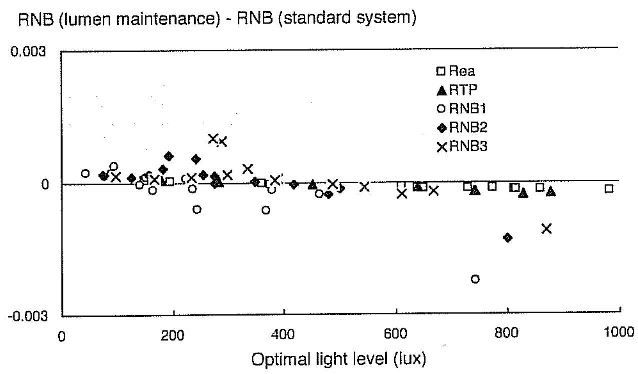

Figure 11—Relative net benefit as a function of optimal illuminance and benefit function: Clean environment—500 lx maintained—ideal (no cost etc.) dimming systems.

RTP portion of the function, but different values of k. Several of the RLB3 (and the RLB1 and RLB2) curves show very distinct maxima at illuminances that are considerably less than the design illuminance.

Figures 9 and **10** are the net-benefit analogs of **Figures 7** and **8**. For simplicity the net-benefit calculations for these curves were based on the initial installed efficiencies. They are not averaged over time and serve merely to show that we have considered a range of conditions that give nominal optimum to either side of the test value light level (500 lx maintained). **Figures 11** and **12** give the actual results of the simulation in terms of a comparison of the cost-effectiveness of the two types of systems. The y-axis shows the difference between the RNB for the lumen maintenance dimming system and the standard non-dimming system. Points above the zero line indicate cases where the LMS is cost-effective, while points below indicate the opposite. The axis has been normalized by 1/S. This means that for a \$100,000 employee the axis ranges from ± \$300, while for a \$20,000 employee it ranges only from ± \$60. The x-axis is the nominal optimal light level (based on the maintained efficacy) for the conditions considered. **Figure 11** shows the results for

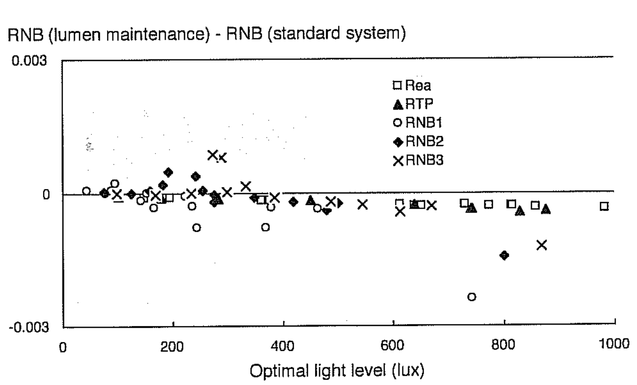

Figure 12—Relative net benefit as a function of optimal illuminance and benefit function. Clean environment—500 lx maintained—Real cost dimming systems.

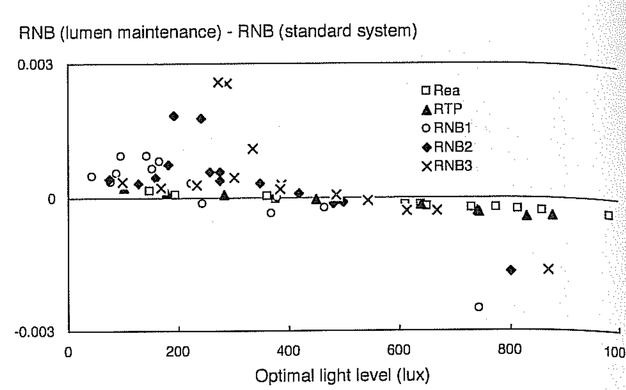

Figure 13—Relative net benefit as a function of optimal illuminance and benefit function. Dirty environment—500 lx maintained—ideal (no cost etc.) dimming systems.

the ideal case of no cost premium for the dimming system and no efficiency losses. **Figure 12** is the same as **Figure 11** with costs and efficiency losses of the LMS included. Results above 1000 lx continue the trends in the figures, but were not shown as their inclusion made it hard to see the other values.

The general trend in **Figure 11** is quite clear. Where the optimal light level is equal to or above the installed light level lumen-maintenance dimming is not cost-effective. Lumen maintenance is cost-effective only when the optimum is below the installed light level, and the lighting benefit functions have a clear maximum. For the Rea and RTP benefit functions there is no clear advantage for the lumen-maintenance technique, even if the lighting system is substantially overdesigned.

In **Figure 12** all the relative net-benefits shift down slightly. Lumen-maintenance dimming is not cost-effective for any of the Rea or RTP points when a real cost estimate is included. Of the remaining benefit functions only the linear and quadratic (RLB2 and RLB3) show really significant benefits for dimming, and again this is only for situations which have been overlit.

Figures 11 and **12** are calculated for "clean" dirt conditions. **Figures 13** and **14** show the ideal and real LMS cases for dirty conditions. The monotonically increasing

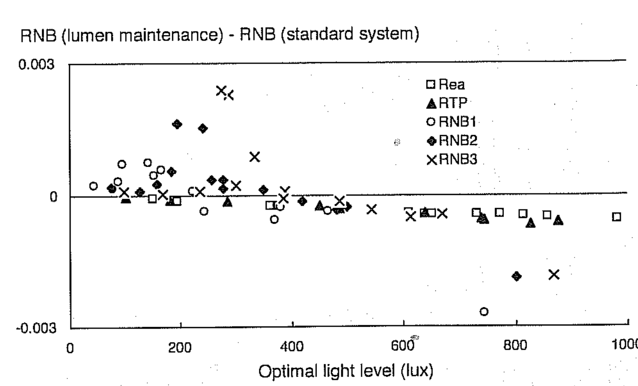

Figure 14—RNB as in Figure 13, but for real dimming systems.

benefit functions (Rea and RTP) are less sensitive to dirt conditions than the remaining functions which have a maximum RLB. The reason for this is that the base case is 500 lx maintained. For the clean condition the initial light level for the non-dimming system is 680 lx, while for the dirty environment condition the initial level is 905 lx. Clearly, if the lighting benefits begin to sharply decline above 300 lx or so, then a system which maintains 500 lx is going to be better (and more economic) than a system where the light level decays from 900 lx when new to 500 lx at the end of the maintenance cycle.

For the Rea and RTP functions the slope of a line through the points is a little steeper, but the optimal light level where lumen maintenance becomes cost-effective is about the same. The slope is still shallow enough that the addition of real costs again makes all these points not cost-effective.

Figures 11–14 showed that when the nominal optimal light levels were close to the design level of 500 lx, the standard lighting system was generally more cost-effective than the dimming system. Our other simulations examined nominal optimum levels of from 200 to 1000 lx, and optimized the design levels for the LMS and standard systems separately. The best lumen maintenance systems in these cases actually had about 10 percent higher maintained light levels than the standard systems. Despite this optimizing of the lumen maintenance systems the only cases where they were more cost-effective was for an ideal dimming system under dirty environmental conditions (**Table 1**) and assuming the sharply-peaked RNB3 benefit function. Including real costs and real dimming equipment efficacy losses were sufficient to tip the balance so that the standard non-dimming system was more cost-effective in all cases.

In the simulations above, the ratio of electrical to annualized total costs were less than about 70 percent ($C_E/C_f < 8.3$). To explore extreme conditions, we ran simulations where we assumed there were no installation costs. Fixed costs in this case consisted solely of maintenance costs, and the maximum ratio C_E/C was almost 90 percent ($C_E/Cf < 8$). The question of whether an ideal dimming system (no efficacy losses) or a real dimming system was used, was again the critical one. In the former case, the LMS was more cost-effective than the standard system in half the cases when the benefit functions had a maximum (RNB1, RNB2, and RNB3). In the latter case, the standard system was always better.

Discussion

Our analyses have covered a wide range of economic and environmental conditions to determine where lumen maintenance control might be cost-effective. Lumen maintenance systems are only cost effective when: (1) there is substantial lumen depreciation over the maintenance cycle; (2) the benefit function has a sharp maximum; and (3) the space is overlit.

Under what practical conditions might these conditions hold? From a building lease perspective, one method of appealing to the widest range of tenants has been to install as much light as possible. This will clearly lead to overlighting for some tenants. A property manager may ask whether it is worthwhile to install an LMS in such a case. Alternatively, if an LMS is already installed, a tenant may wish to know whether its dimming capabilities should be exploited or simply set to run at full light (and power) output. In the first situation, a standard fixed light level system is not really the appropriate base case for comparison. Other options which provide flexibility are switched systems, task-ambient systems, flexible plug-in systems, and tunable dimming ballast systems.

A "tuned" system is a system with a dimmable ballast that is adjusted to the appropriate level when the tenant moves in and is then left alone. Since the lumen "capacity" is already installed, the effective installation costs to the tenant are zero. This situation is similar to the situation we modeled when we examined C_E/C cost ratios of almost 90 percent. One difference is that both the LMS and tuned systems use a dimming ballast, so there should be little difference in system efficacy. By analogy with our earlier results we therefore expect that the LMS may be more cost-effective if the lighting benefit function has a maximum. In our simulations the maximum increase in relative net-benefit from using a LMS was about 0.0003 for the dirty environment and 0.00008 for the clean environment ($30 and $8 respectively per $100,000 of productivity). The corresponding losses if the benefit function was monotonic were -0.0005 and -0.00024 (-$50 and -$24). Thus the LMS does not provide a clear advantage over a tuned system if the space is not overlit. Comparisons of the LMS against the other options are likely to be less favorable to its use, as the other options do not involve losses in efficacy from dimming ballasts.

For the tenant who has an LMS the question over its use boils down to whether or not the space is overlit. If it is overlit (i.e., at a light level where the benefit function has clearly turned down), it will be economical to use the dimming capabilities of the system to save energy. If the space is not overlit, the LMS should be set at full output and allowed to operate as a standard system.

Two other points are worth mentioning. First, in retail or art display, the balance of light on a particular object might be critical. If the lighting sources have different maintenance depreciation characteristics lumen maintenance will probably be cost-effective.

The second point is that we have only examined the standard strategy of dimming to the maintained level of the system. An alternative strategy would be to dim to a level between the initial and maintained levels of the system. In this case the system would maintain a fixed level until it reached full power, and then the light level would drop over time just as if it were a standard fixed power system. Although we have not analyzed this case in detail, it seems unlikely to dramatically change our conclusion. The energy savings from this strategy will be less than from the standard strategy. In the real world, where there is a premium for installing an LMS, there are less energy savings to pay for the added costs. This strategy might be worthwhile for use in an existing system, but it seems highly unlikely to be worthwhile for a new system.

Conclusions

Our most important conclusion is that a formal analysis that includes the value of light can be useful despite our fairly crude level of knowledge of the benefit vs light level relationship. This type of analysis needs to be applied to other lighting issues to see if it can provide other useful insights.

Specifically, we have shown that lumen-maintenance controls are generally not cost-effective for most practical conditions. Lumen-maintenance controls should only be considered if higher than normal maintained light levels are an actual problem, and if operating costs are high relative to the annualized fixed costs (installation and maintenance). The critical assumptions that leads to this conclusion are: (1) that the light provided by the lighting system has real economic value and benefit; (2) that the design light levels are, at least roughly, optimal; and (3) that the optimum is relatively broad. Simply stated, if we lack accurate information as to what precise level to light a space, it does not make economic sense to deliver a precise fixed light level.

Acknowledgment

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Appendix A—The Linearized Net-Benefit Comparison

Let E_f be the recommended light level for the space. The standard base case system starts at an initial level E_i, and reaches E_f at the end of the maintenance cycle. The LMS operates at E_f throughout. Let L(t) be the fractional light lost at time t due to losses in system efficacy (1 - L(t) is the system efficacy). For a perfect (lossless) dimmer the initial operating cost of a lumen maintenance (lm) system is just $C_E' \times E_f \times [1 - L(t_f)]$, where t_f is the end of the maintenance cycle time. Note that we have defined the cost per unit illuminance, C_E', in terms of the recommended illuminance of the space, as that is the only illuminance that is shared by both the standard and lumen maintenance systems. For the dimming system the operating costs increase as system efficacy decreases, that is:

$$C_{Elm}(t) = C_E' E_f \frac{[1 - L(t_f)]}{[1 - L(t))]} \tag{A1}$$

The average operating cost is the weighted integral:

$$\langle C_{Elm} \rangle = C_E' E_f [1 - L(t_f)] \frac{\int \frac{e^{(-It)}}{[1 - L(t)]} dt}{\int e^{(-It)} dt} \tag{A2}$$

where I is the discount rate and dt is the differential over time.

The integral can be solved to first order in terms of the weighted average fractional loss, $\langle L \rangle = \int e^{(-It)} \times L(t)dt$, by expanding the fraction to first order:

$$\frac{1}{[1 - L(t)]} \approx 1 + L(t) \tag{A3}$$

Define K as $K = [L(t_f) - \langle L \rangle]/\langle L \rangle$. If $L(t)$ is linear, $K = 1$. For most real cases we expect it will be close to one. Upon substitution of **Equation A3** and the definition for K into **Equation A2**, we get the following expression:

$$\langle C_{Elm} \rangle \approx C_E^{'} E_f [1 - (K+1)\langle L \rangle][1 + \langle L \rangle] \approx C_E^{'} E_f [1 - K\langle L \rangle] - \ldots \quad \text{(A4)}$$

Equation A4 only includes terms only to first order. Substitution of **Equation A4** into **Equation A1** gives the first-order estimate of the net benefit for the lumen-maintenance system:

$$NB_{lm}(E_f) \approx B(E_f) - C'E_f + C_E^{'} E_f K\langle L \rangle \quad \text{(A5)}$$

In other words, the LMS saves an amount proportional to the energy costs of the system.

Note that in **Equation A5** the benefit term is based on a fixed illuminance level. In the standard non-dimmed system the illuminance level is generally higher than E_f, and it is necessary to determine the added benefit before comparing the two systems. To estimate the average benefit we begin by expanding the benefit term in a first order Taylor's series about its value $B(E_f)$:

$$B_S(E) \approx B(E_f) + \frac{dB(E_f)}{dE}(E - E_f) \quad \text{(A6)}$$

The non-dimmed system reaches the illuminance E_f at time t_f. Making the dependence of E on t explicit gives the following expression for the benefit term as a function of time:

$$B_S(t) \approx B(E_f) + \frac{dB(E_f)}{dE}[E(t) - E_f] \quad \text{(A7)}$$

From **Equation 2** we know that $dB(E_f)/dE = C'$ when E_f is optimal. From the definition of $L(t)$, $E(t)$ is given by the expression $E(t) = E_i \times (1 - L(t))$. The definition of $L(t)$ also leads to an expression for E_f: $E_f = E_i \times (1 - L(t_f))$. With the above relations we can write the average weighted benefit of the standard (s) system as:

$$\langle B_S \rangle \approx \frac{\int B(E_f) + C'E_i[L(t_f) - L(t)]e^{(-It)}dt}{\int e^{(-It)}dt} \quad \text{(A8)}$$

Equation A8 can be integrated immediately to give the following expression for $\langle B_s \rangle$:

$$\langle B_S \rangle \approx B(E_f) + C'E_i[L(t_f) - \langle L \rangle] = B(E_f) + C'E_i k\langle L \rangle \quad \text{(A9)}$$

Given **Equation A9** we can now write the first order expression for the net benefit for the standard system, and we can compare it to the net benefit for the lumen-maintenance system (**Equation A5**):

$$NB_S(E_f) \approx B(E_f) - C'E_f + C'E_i k\langle L \rangle \quad \text{(A10)}$$

and finally:

$$NB_S(E_f) - NB_{lm}(E_f) = E_i k\langle L \rangle[C' - C_E^{'}(1 - L(t_f))] \quad \text{(A11)}$$

Appendix B—Derivation of Table 1

Curves for LLD are shown in the IESNA *Lighting Handbook* for halophosphate lamps (circa 1950).[IES84] Osram shows curves for its Dulux D and L lamps, and Phillips shows curves for CW and TL80 lamps.[10,11] Values were read off the curves and fit to the following irrational fraction:

$$LLD = \left[\frac{(b^n + (at)^n)}{(b^n + t^n)}\right]^{\frac{1}{n}} \quad \text{(B1)}$$

For the seven curves available, this form gave fits that had a maximum error of 0.7 percent, and a standard deviation of 0.15 percent. The parameters of the fits were markedly different for the different lamps. The IESNA *Lighting Handbook* values are not current, while CW lamps have recently been banned in the standard office sizes, and are no longer relevant. The OSRAM lamps are current, but are not a standard type of lamp in the common office environment. We therefore have used the values for the TL80 lamps in our simulations. The parameters for this lamp are $a = 0.874$, $b = 2.265$, and $n = 1.385$. The TL80 lamp is a premium lamp, and will therefore be expected to give somewhat different results than the more common CRI = 70 lamps, however total lumen depreciation is dominated by dirt depreciation, not lamp depreciation. We looked at two moderately extreme cases of dirt depreciation, and therefore expect to get a fair picture of where lumen maintenance is cost-effective.

Table B1—RSDD constants

	Room Dirt Category				
	Very clean	Clean	Medium	Dirty	Very dirty
K0	6.227	4.147	3.081	2.528	2.150
n2	0.0766	0.0985	0.1245	0.1511	0.1830
	Fixture type				
	Direct	Semi-direct	Direct-indirect	Semi-indirect	Indirect
K1	0.0242	0.0327	0.025	0.0168	0.0282
K2	0.1617	0.36	0.575	0.675	0.975

Luminaire dirt depreciation was calculated from the equations listed in the IESNA *Lighting Handbook* as a function of the luminaire maintenance category, and the room dirt conditions.[3] For RSDD the *Handbook* provides a table that gives RSDD as a function of "Per Cent Expected Dirt Depreciation", D, the room cavity ratio, RCR, and the luminaire distribution type. The parameter D is in turn read from a chart as a function of the time in months, m, and the dirt condition. We derived the following formulas to convert this procedure to a computer algorithm:

$$d = \frac{D}{100} = 1 - \left[\frac{K_o}{(K_o + m)}\right]^{n2} \quad \text{(B2)}$$

$$RSDD = 1 - d(K_2 + K_1 RCR) \quad \text{(B3)}$$

The parameters K_0, n_2, K_1, and K_2 depend upon the room dirt category and the fixture type as appropriate, and are given in **Table 1B**.

Discussions

This paper provides valuable insight into the usefulness of lumen maintenance lighting control systems. These types of controls have been popularized over the last ten years as a way to effectively help reduce energy costs. However, real world applications have not been able to demonstrate savings from lumen maintenance strategies. The results of the work detailed in the paper will hopefully lead to improved understanding by the lighting industry regarding this control strategy. This will help designers and equipment suppliers to specify and provide cost effective systems that do not include lumen maintenance control strategies that are difficult to implement and maintain. The paper also provides justification for revising both existing and new energy codes and standards. Currently some of these codes include requirements for this control strategy that can be eliminated, which will simplify the codes.

The following are questions raised about the paper.

1. The paper is a study of lumen maintenance compensation using a photo sensor technique. Have other methods been considered and would the same resultant conclusions be expected?

2. The evaluations appear to include group relamping as part of the criteria for system operation. What effect would be expected if lamps were not replaced on a group relamp cycle? Are there other high maintenance elements factored into your cost analysis?

3. Although daylighting control functions are not part of the scope of this paper, what effect would daylighting and blinds /shading devices have on results, will there be an attempt to study these effects in the future?

4. In **Figure 8** the Std-RLB and Std-RNB curves start lower, what causes this effect? The results found in this paper indicate that even under ideal conditions lumen maintenance strategies work in only a few specialized situations due to improved lighting and net benefits. With the current trend towards more localized/individual and other control strategies it would seem lumen maintenance strategies may not be appropriate. Thank you again for this valuable and timely contribution.

Jim Yorgey
Lutron Electronics

In this paper the authors tackle the extremely important issue of quantifying the economic benefits of lighting. We know that some light is more valuable to us than no light, but the amount we should be willing to spend to get a little more, once we have some, is a tricky question for which there is little information to help answer.

Here the topic is approached in the context of comparing the economic value of lumen maintenance systems versus the standard practice of designing a system to provide initially too much light, knowing that light output will decline over system life until the target illuminance level is reached.

The authors make the profound observation that, if the target illuminance level is somewhere near the economic optimum, that is, near the point where marginal costs equal marginal benefits, then the energy cost savings that an LMS provides will always be less than the economic benefit of the additional light provided by the standard method. This is because the energy costs are only a portion of the total costs involved. By eliminating the "surplus" light with an LMS, one discards benefits that are necessarily worth more than the savings engendered.

When operating in a region where total marginal costs equal total marginal benefits, if all the benefits associated with a certain light level are removed, but only a fraction of the concomitant costs are saved, the net economic impact is negative, and an LM system is not economically justifiable.

The authors then spend most of the paper relaxing assumptions and examining what happens if the target illuminance level is not near the economic optimum, or if the net benefit curve is not flat in the region of the optimum. Unfortunately I was unable to follow much of the ensuing analysis, in spite of spending the better part of a day wrestling with it. Whether this was due to abstruse writing or an obtuse reader is uncertain. A main source of misunderstanding for me seems to be the authors' treatment of the simulations they performed. They never explain what these simulations entail, but make reference to an internal publication unavailable to the reader. I assume they are referring to some sort of stochastic modeling of the variables at work in a dimming system, though this is never explained.

They mention ranges of values for various parameters, but it is never clear if they are sampling from some probability distribution across those ranges or if all values are assumed equally probable. In each of **Figures 7–10**, a variety of results of the simulations are shown, superimposed with an average curve. By giving an average, I assume the authors feel that each of the averaged curves represents an equally likely outcome.

I suspect the authors omitted a discussion of the simulations in the interest of brevity, but for this reader at least, its inclusion seems necessary for comprehension. If this could be clarified, I suspect there are very valuable lessons to be learned from this work.

Clay Belcher
University of Kansas

The authors appear to have tackled the lighting equivalent of the world hunger problem in this paper and then modestly applied it to the almost-trivial question of lighting maintenance (LM) controls. Among lighting practitioners, there has been something of a "conventional wisdom" that LM controls are seldom, if ever, economical because the energy savings which are used to pay for the controls are small compared to the costs of the controls.

As indicated in the paper the author's analyses agree. New lamps, such as the second-generation T8 designs now on the market which have improved lumen maintenance characteristics, and recent developments in luminaire and high-reflectance ceiling materials suggest that if there were some economic reasons for once considering LM controls, those reasons have now become less important. Lighting systems in new, well-designed office spaces lighted with T8 fluorescent lamps and high-frequency electronic ballasts simply do not depreciate very much over time anymore. Rather, the importance of this paper, in my view, is the extension of the idea that "light has value" to the nitty-gritty issue of how much.

The authors have developed a straightforward method, via their simulation approach, for determining that value. The ranges of the variables are defined and included so the functions can be better understood. Those are powerful widely applicable tools. I hope that they will do more work on this aspect since it goes to the heart of the cost/benefit of lighting. In particular, it would be good to have a complete simulation model based upon their approach.

Some questions:

1. You say, "The total costs per unit of light include installation and maintenance and are always larger than electric costs...." Amortized installation and annual maintenance costs can be smaller than annual electricity costs. Would you clarify that please.

2. Near the end of **Appendix A**, the references to **Equations 10** and **11** appear to be wrong. Don't they refer to **A8** and **A9**?

Terry K. McGowan, FIES
GE Lighting - Nela Park

Authors' response

To Jim Yorgey

1. The type of feedback used to maintain luminance, be it a photocell, as is standard, or some other type of control, such as a running time algorithm, does not affect the results.

2. Lumen maintenance will be more economic for spot relamping than for group relamping, because lumen depreciation is larger for the former case. Based on the simulations we have run it will still generally be uneconomic compared to a standard system in a clean environment. It is possible that it would be economic in a dirty environment, but we have not examined this case. However, if the environment is dirty enough to make lumen maintenance cost effective, then spot relamping is probably not cost effective relative to group relamping. We have not confirmed this by calculation.

3. We have done some work on this question, but daylighting makes the problem more complex. The practice of maintaining the recommended level is similar to the standard lumen maintenance procedure, and is unlikely to be optimal, but we do not yet have a definitive answer as to what the best practice is. Work on this problem is currently in abeyance due to a lack of funding.

4. The **Figure 8** referred by the discusser is **Figure 6** of the final version of the paper. The reason the Std (standard) curves start lower is that the RLB3 benefit function has a maximum (see **Figure 2**). The standard system is initially too bright, with the result that the benefits first rise, and then drop. The light level for the optimal dimmed system is at or below the maximum of the benefit function.

To Clay Belcher

A number of different types of simulations were run to answer questions that arose during the course of our research. Organizing such disparate ideas is difficult, and we apologize to Dr. Belcher for the abstruseness of the writing.

The "internal" publication referred to is available from the lighting group at LBNL on request. It is much less readable, but more complete than the present publication. The average curves shown in **Figures 7–10** were primarily included as a visual summary of the conditions studied. We did not intend to imply that we had done a stochastic analysis. Such an analysis would be useful in determining the shape of the benefit function for an employee who performs many tasks, but all we need to know is that the function is similar to those we examined. The intent of the simulations was to examine a range of curve shapes and optimum levels to determine their effects on the relative cost-effectiveness of the standard and lumen maintenance systems. The simulations show that the benefit function curve shape, the extent of lumen depreciation, and the nominal optimal light level (which is determined by a combination of visual factors, costs, and productivity) are fairly good predictors of the relative cost effectiveness (**Figures 11–14**). Most importantly, the simulations showed that lumen maintenance systems were not cost-effective unless the optimum light level was less than the installed level, regardless of the curve shape or degree of lumen depreciation. We apologize again for the confusion.

To Terry McGowan

Mr. McGowan is correct in noting that the results would have been more favorable to lumen maintenance systems in the past, when lumen depreciation was much larger.

1. The total costs include the electricity costs as well as annualized installation and maintenance costs, and therefore are necessarily bigger than the electricity costs alone. We agree that electricity costs can be bigger than the annualized installation and maintenance costs, and our simulations included such cases.

2. The equation references in the appendix were wrong, and have been corrected in this final version.