LBL-21884

Presented at the IEEE/IAS 1986 Annual Meeting,
Denver, CO, September 29–October 1, 1986

THE EFFECT OF LIGHTING SYSTEM COMPONENTS ON LIGHTING QUALITY, ENERGY USE, AND LIFE-CYCLE COST

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July 1986

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Presented at the Institute of Electrical and Electronics Engineers Conference, Denver, CO October 1986

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Abstract - A computational method was developed to examine the effect of lamp, ballast, and fixture selection on the quality and quantity of illumination, energy consumption, and life-cycle cost of lighting systems. Applying this analysis to lighting layouts using different lamp/ballast/fixture combinations suggested that combinations with higher lumen outputs reduced the uniformity of the illuminance distribution at the workplane but did not reduce visibility levels. The use of higher lumen output lamp/ballast/fixture systems and higher efficiency components tended to reduce life-cycle costs as long as the premium cost of the components was not too high.

I. INTRODUCTION

The proliferation of new lighting equipment has complicated the task of specifying lighting systems for buildings but has also provided designers with the flexibility to optimize lighting layouts in a way not previously possible. To determine the number of luminaires necessary to provide the design light level, the lighting designer must consider not only luminaire efficiency, coefficient of utilization, and lamp lumen rating, but also the ballast factor for the selected lamp/ballast system. Different lamp/ballast/fixture combinations may require lighting layouts with significantly different luminaire spacings to maintain the same average illuminance. Since luminaire spacing and candlepower distribution may significantly affect the quality and uniformity of the illuminance distribution, the selection of lighting system components has a considerable impact on the quality of the luminous environment as well as lighting power density and system cost.

The paper describes a method of examining how the selection of the lamp, ballast, and fixture affects the lighting quality, the energy consumption and the life-cycle cost of the lighting system.

II. METHODS

We identified computational methods as being most appropriate for quantifying how the selection of lighting system components affects lighting quality and system costs. Few commercially available computer programs permit the computation of metrics of lighting quality as well as providing the necessary economic analysis. We selected the LUMEN-3 computer program, available from MacDonnall Douglass Computer Sharing Services, (MDCSS), for calculating lighting quality and uniformity, but for the economic analysis used a microcomputer spreadsheet program. Ideally, these functions would be merged into one program that would also calculate discomfort glare.

Point-by-point illuminance, equivalent-sphere illuminance (ESI footcandles), power densities, and system costs were computed for an open-office space with ceiling-mounted direct luminaires with a design level of 70 footcandles maintained. Eighteen lamp/ballast/fixture combinations were selected to illustrate the method. Since each combination provided somewhat different luminaire lumen outputs, a lighting layout was designed for each combination by adjusting the luminaire spacing so that the maintained illuminance was held constant at 70 footcandles.

A. Modelling an Open-Office Space

An open-office area in a typical high-rise office building was selected as the space for the analysis. The dimensions of the modelled building floor are given in Figure 1. Excluding the 5,525-ft^2 building core, there is 21,700-ft^2 of open space for the floor plan shown. To simplify the computation and input preparation, we limited the actual area where we computed lighting levels to a 900-ft^2 area. This eliminated the necessity of considering the effect of any luminaires or walls in the north or east sections of the floor since walls and luminaires further than 5 mounting heights away from the measurement grid contribute only negligibly to the lighting levels. (One mounting height equals the distance between the ceiling plane and the workplane.) As shown in Figure 1, this reduces the space for analysis to a 110 by 40-ft area with a 9-ft ceiling. Reflectances of 20% and 70% were assigned to the floors and ceilings, respectively. The east and south walls were assigned a reflectance of 40% to approximate the reflectance of typical window-walls with strip windows and window treatments. The northern side of the modelled building space was treated specially by assigning 50% reflectance to the eastern portion (to simulate the inner core wall) and 99% reflectance to the western portion (Figure 1) to simulate the effect of the luminaires in the western section of the floor.

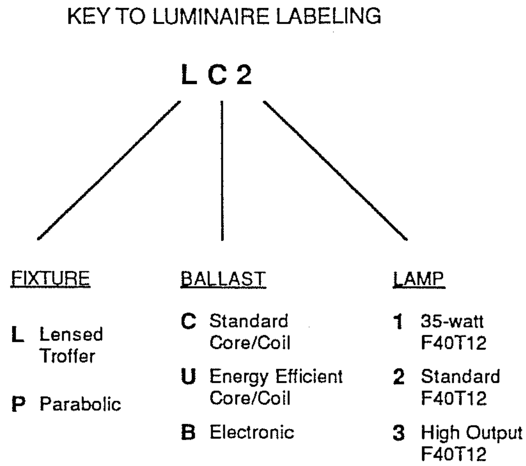
To minimize computational costs, lighting values were calculated only in a 30 by 30-ft square region as shown in Figure 1. The measurement grid consisted of a 10 by 10 array of points on 3-ft centers at a 30-in height.

B. Lamp/Ballast/Fixture Systems Examined

We examined three different lamps, three ballasts, and two fixture types for study. The lamps and ballasts represent the range of performance and efficiency encountered in typical commercial applications. The base case lamp/ballast system consisted of standard 4-foot, F40T12 lamps, rated at 3150 lumens, and standard, two-lamp Certified Ballast Manufacturers (CBM) ballasts, which have a ballast factor of .95. Table 1 lists the lamp lumen ratings, ballast factors, and fixture efficiencies for all examined components. (The ballast factor is the ratio of the lamp lumens produced by a given ballast divided by the rated lamp lumens. Fixture efficiency is the total lumens emitted by the fixture divided by the total lamp lumens). The lamp lumen ratings were obtained from manufacturers' listed ratings, while the ballast factors were obtained from the report listed as reference [1].

Two fixture types were selected to illustrate the methodology. The first, a standard four-lamp recessed troffer with prismatic lens, is commonly used in commercial buildings and has a fixture efficiency of 65.8%. The second is a four-lamp, recessed parabolic-louvered fixture with a fixture efficiency of 54.2%. Luminaire efficiences were calculated with a program developed by one of the authors (Rubinstein) using candlepower distributions from the MDCSS on-line photometric data base.

Eighteen different lamp/ballast/fixture combinations are possible, resulting in a wide range of luminaire lumen-output values. Each lamp/ballast/fixture combination is identified with a three-letter designation. The first letter, either L or P, signifies the lensed troffer or parabolic fixture, respectively. The second letter refers to the ballast: either a standard two-lamp CBM core/coil (C), energy-efficient core/coil (U), or high-frequency, electronic ballast (B). The ending number refers to the lamp: 1 is the 35-watt, F40, krypton-filled lamp (rated at 2925 lumens), 2 is the standard 40-watt, argon-filled lamp (3150 lumens) and 3, a high-output argon-filled lamp rated at 3300 lumens. Thus the designation for the base case lamp/ballast/fixture combination, for example, is LC2.



C. Luminaire Spacing

The luminaires were spaced nominally on 10.5-ft centers in the east-west direction and 8.5-ft centers in the north-south direction. With the base case luminaire, LC2 (standard lamps, CBM ballasts, and lensed troffer), this spacing results in an average maintained illuminance of 70 footcandles with 89.25 ft^2 per luminaire. For the other 17 combinations, this spacing was adjusted so that area per luminaire varied in direct proportion to the corresponding maintained luminaire lumen values given in Table 1. Thus, the area per luminaire could be as low as 69 as high as 94 square feet. The input data for each luminaire run were adjusted by keeping one luminaire position fixed as shown in Figure 1 and increasing or decreasing the spacing in the E-W and N-S directions proportionally to compensate for the different luminaire lumen-output values.

D. Computer Simulations

Point-by-point illuminance values and ESI values were computed using the LUMEN-3 computer program. The candlepower distributions for the four-lamp lensed troffer and parabolic fixtures were accessible through the photometric data base. Candlepower multiplier values were applied to each luminaire run to take into account maintenance factors, ballast factors, and differences between the lumen ratings for the tested lamps and those used in the photometric report. A maintenance factor of .7 was used for the lensed troffer while a .85 maintenance factor was applied to the parabolic fixture to take into consideration its superior maintenance characteristics.

III. ANALYSIS

A. Lighting Quality

The LUMEN-3 computer program can calculate a number of quantities related to the quantity and quality of illumination, including ESI footcandles. However, prior studies have suggested that visibility level (VL) or the log of VL is better correlated to visual performance than equivalent sphere illuminance[2]. Therefore, we transformed the ESI tables produced by LUMEN-3 into equivalent tables of VL values after the derivation given by Clear and Berman [2]:

$$VL = C_{eq} * a * \{[(b/(\rho * ESI)]^{.4} + 1 \}^{-2.5} \qquad (1)$$

In the above, C_{eq} is the equivalent contrast (i.e. the contrast of a reference target of equal visibilty to the target of interest), a and b are parameters that vary as a function of age, and ρ is the reflectivity of the task. We assumed the standard pencil target (C_{eq}=0.682, ρ=0.846) for the standard 20-year-old reference observer (a=16.847, b=0.4784).

FIGURE 1. Floor plan of high-rise open-office area modelled in study. Exploded view of modelled area gives reflectances of surfaces and shows luminaire spacing for base case luminaire combination. For other combinations, luminaire spacing was adjusted to keep design level at 70 maintained footcandles. Computations were made at indicated measurement grid.

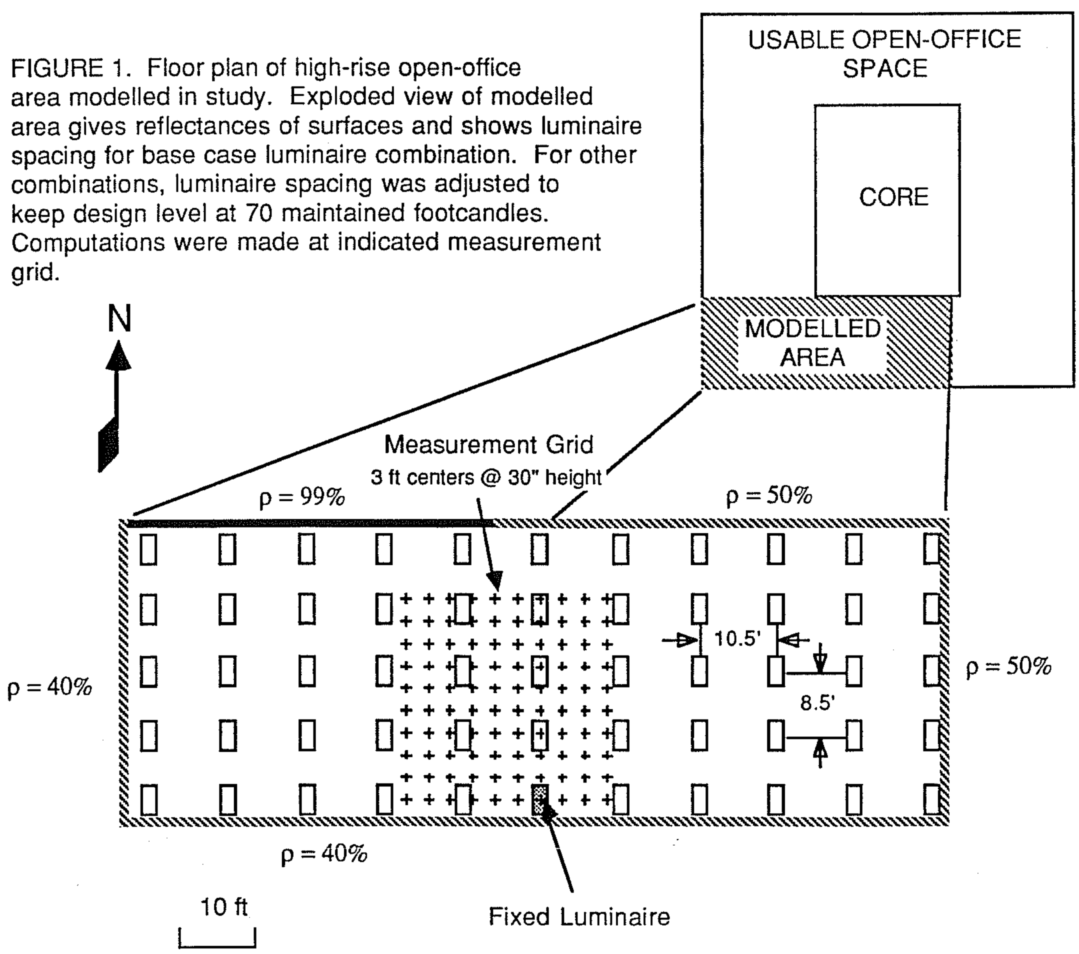


TABLE 1

EFFECT OF LUMEN OUTPUT ON LUMINAIRE SPACING AND LIGHTING POWER DENSITY

Combination	Rated Lamp Output (lumens)	Ballast Factor	Fixture Efficiency	Initial[a] Luminaire Output (lumens)	Maint.[b] Luminaire Output (lumens)	Area† Per Luminaire (ft^2)	Power[c] Per Luminaire (watts)	Maint.[d] Luminaire Efficacy (lm/watt)	Power† Density (w/ft^2)
LC1	2925	0.88	0.659	6785	4750	76.77	159.4	29.80	2.08
LC2	3150	0.95	0.659	7888	5522	89.25	186.2	29.66	2.09
LC3	3300	0.95	0.659	8264	5785	93.50	195	29.67	2.09
LU1	2925	0.863	0.659	6654	4658	75.28	141.6	32.89	1.88
LU2	3150	0.922	0.659	7656	5359	86.62	166.2	32.24	1.92
LU3	3300	0.922	0.659	8020	5614	90.74	174.2	32.23	1.92
LB1	2925	0.793	0.659	6114	4280	69.18	113.6	37.68	1.64
LB2	3150	0.856	0.659	7108	4975	80.42	134	37.13	1.67
LB3	3300	0.856	0.659	7446	5212	84.24	140.4	37.12	1.67
PC1	2925	0.88	0.542	5580	4743	76.67	159.4	29.76	2.08
PC2	3150	0.95	0.542	6488	5515	89.13	186.2	29.62	2.09
PC3	3300	0.95	0.542	6797	5777	93.37	195	29.63	2.09
PU1	2925	0.863	0.542	5473	4652	75.18	141.6	32.85	1.88
PU2	3150	0.922	0.542	6297	5352	86.50	166.2	32.20	1.92
PU3	3300	0.922	0.542	6596	5607	90.62	174.2	32.19	1.92
PB1	2925	0.793	0.542	5029	4274	69.09	113.6	37.63	1.64
PB2	3150	0.856	0.542	5846	4969	80.31	134	37.08	1.67
PB3	3300	0.856	0.542	6124	5206	84.14	140.4	37.08	1.67

[a] Rated lamp lumens X 4 X ballast factor X fixture efficiency

[b] Initial luminaire output X maintenance factor (MF = .7 for lensed troffer, MF = .85 for parabolic)

[c] Power per lamp/ballast system X 2

[d] Total maintained luminaire lumen output per watt input

† For 70 footcandles maintained

B. Energy and Life-Cycle Costs

The energy consumed by the various examined systems was determined assuming that the lighting was used for 3500 hours per year, which would be typical of modern commercial buildings. The cost of the different systems was calculated using the present-worth method of life-cycle costing. This method takes into account the initial costs of the lighting system and all subsequent operating costs, including energy and maintenance, over the expected life of the lighting system. With this method any future costs, of which energy is a significant proportion, are discounted back to present-day dollars at an appropriate interest rate. We used an interest rate of 10%, an energy cost of $.10/kWh, and, to simplify the maintenance cost calculations, assumed a system life of 15 years.

The initial installed-cost estimates for the different lamps, ballasts, and fixtures examined in this study are given in Table 2, which lists the total present worth per square foot of each system.

The total costs are shown broken down into three components: installation, energy, and maintenance. Maintenance costs were computed assuming that group relamping and luminaire cleaning is undertaken every three years at a labor cost of $20 per luminaire. (By using a 15-year service life for the analysis, one can ignore reballasting costs since ballasts last roughly 45,000 hours or 15 years.)

IV. RESULTS

The results of applying the methodology to the lamp/ballast/fixture combinations examined are summarized in Table 3. The average and standard deviation for the 100 illuminance values are computed for each luminaire layout to calculate uniformity, defined here as the ratio of the average illuminance to the standard deviation. Average visibility levels calculated for the four viewing directions (north, east, west, and south) are also given in Table 3.

A. Uniformity

The illuminance distributions for the systems examined become less uniform as the luminaire lumen output (and thus the area covered by each luminaire) increases. This is to be expected, since those luminaires that produce more light are spaced farther apart to achieve the same design footcandle level. Note also that for a given lamp and ballast, layouts with parabolic fixtures provide less uniform illuminance distributions than layouts with lensed troffers. This follows since the parabolic fixtures examined here have a narrower candlepower distribution than the lensed fixtures and therefore tend to exhibit more pronounced minima between luminaires as the spacing between them increases.

B. Visibility Levels

The effect of luminaire spacing on visibility levels for the selected lamp/ballast/fixture combinations is most apparent for the south and north directions. For example, the average VL increased from 7.33 (for the LB1 luminaire every 69 ft^2) to 7.65 (for the LC3 luminaire every 93.5 ft^2.) for the south direction, with a similar change in average VL for the north direction. The same two luminaire layouts, though, showed no significant difference in average VL for the east or west directions. Similar results were observed for the parabolic fixtures. It should be noted, though, that the parabolic fixtures examined in this study consistently showed lower average VLs compared to equivalent lensed troffers, regardless of direction. For example, with CBM ballasts and 35-watt lamps, the lensed troffer (LC1) had an average VL of 7.38 for all directions while the parabolic-type luminaire with the same lamps and ballasts (PC1) had an average VL of 7.28.

TABLE 2

INITIAL COMPONENT COSTS AND LIFE-CYCLE COSTS PER SQUARE FOOT
FOR 18 LAMP/BALLAST/FIXTURE COMBINATIONS

	Initial Costs							Life Cycle Costs	
Combination	Fixture[a] (S)	Ballast[b] Premium (S)	Lamps[c] (S)	Total Initial (S/ft^2)	Power Density (w/ft^2)	Annual[d] Energy (S/ft^2)	Pres. Value[e] Energy ($/ft^2)	Pres. Value[f] Maint. ($/ft^2)	Pres. Value Total (S/ft^2)
LC1	110	0	6	1.51	2.08	0.73	5.54	0.70	7.75
LC2	110	0	4	1.28	2.09	0.73	5.56	0.55	7.40
LC3	110	0	6	1.24	2.09	0.73	5.56	0.57	7.38
LU1	110	5	6	1.67	1.88	0.66	5.00	0.71	7.39
LU2	110	5	4	1.43	1.92	0.67	5.11	0.57	7.11
LU3	110	5	6	1.39	1.92	0.67	5.11	0.59	7.09
LB1	110	15	6	2.11	1.64	0.57	4.37	0.77	7.25
LB2	110	15	4	1.79	1.67	0.58	4.45	0.62	6.85
LB3	110	15	6	1.73	1.67	0.58	4.45	0.64	6.82
PC1	155	0	6	2.10	2.08	0.73	5.54	0.70	8.34
PC2	155	0	4	1.78	2.09	0.73	5.56	0.56	7.90
PC3	155	0	6	1.72	2.09	0.73	5.56	0.57	7.86
PU1	155	5	6	2.27	1.88	0.66	5.00	0.71	7.99
PU2	155	5	4	1.95	1.92	0.67	5.11	0.57	7.64
PU3	155	5	6	1.89	1.92	0.67	5.11	0.59	7.59
PB1	155	15	6	2.76	1.64	0.57	4.37	0.78	7.91
PB2	155	15	4	2.35	1.67	0.58	4.45	0.62	7.42
PB3	155	15	6	2.27	1.67	0.58	4.45	0.64	7.35

[a] Installed cost per fixture including standard ballasts
[b] Premium cost per ballast for factory installing non-standard ballasts
[c] Cost of four lamps per fixture
[d] 3500 hours per year at $.10/kWh
[e] Present value at 10% interest for 15 years
[f] Assuming group re-lamping and cleaning at $20 labor per luminaire every 3 years

TABLE 3

MEAN ILLUMINANCE, UNIFORMITY AND VISIBILITY LEVELS
FOR 18 LAMP/BALLAST/FIXTURE COMBINATIONS

Combination	Area Per Luminaire (ft^2)	Mean Illum.[a] (lm/ft^2)	Std. Dev.[b] (lm/ft^2)	Uniformity[c]	Mean VL[d] North	Mean VL East	Mean VL West	Mean VL South	Mean VL All Directions
LC1	76.77	68.35	5.07	13.48	7.430	7.356	7.360	7.370	7.379
LC2	89.25	70.1	6.78	10.34	7.660	7.360	7.350	7.580	7.488
LC3	93.50	70.9	7.54	9.4	7.720	7.390	7.380	7.650	7.535
LU1	75.28	70.3	4.67	15.1	7.350	7.350	7.360	7.330	7.348
LU2	86.62	69.76	6.4	10.9	7.610	7.360	7.350	7.530	7.463
LU3	90.74	71.27	6.9	10.33	7.660	7.360	7.350	7.580	7.488
LB1	69.18	67.13	3.98	16.87	7.320	7.320	7.350	7.330	7.330
LB2	80.42	68.85	5.53	12.45	7.460	7.360	7.360	7.420	7.400
LB3	84.24	69.49	6.04	11.5	7.570	7.360	7.360	7.490	7.445
PC1	76.67	68.58	7	9.8	7.320	7.260	7.270	7.260	7.278
PC2	89.13	69.44	10.13	6.85	7.580	7.260	7.270	7.520	7.408
PC3	93.37	69.45	10.8	6.43	7.600	7.240	7.240	7.500	7.395
PU1	75.18	70.64	6.44	10.97	7.240	7.260	7.280	7.200	7.245
PU2	86.50	69.2	9.5	7.28	7.520	7.240	7.240	7.440	7.360
PU3	90.62	70.6	10.3	6.85	7.580	7.260	7.270	7.520	7.408
PB1	69.09	67.49	5.73	11.78	7.200	7.240	7.270	7.210	7.230
PB2	80.31	69.06	7.87	8.78	7.390	7.260	7.260	7.320	7.308
PB3	84.14	69.09	8.96	7.71	7.480	7.240	7.240	7.400	7.340

[a] Average of the 100 illuminance measurements
[b] Standard deviation of the 100 illuminance measurements
[c] Mean illuminance divided by standard deviation
[d] Mean VL is average of 100 visibility level measurements

C. Lighting Power Density

The effect of the different lamp/ballast/fixture combinations on installed lighting power density is seen in Table 1. The choice of ballast has the largest effect on power density while the choice of lamp type has relatively small effect. Using standard F40 lamps with electronic ballasts reduced the lighting power density 20% compared to the standard CBM ballast. When used with the standard CBM ballast, the 35-watt lamp did not reduce the lighting power required to provide the required light level compared to the standard F40 lamp.

For a given choice of lamp and ballast, the lensed troffers have the same lighting power density (i.e. the same efficacy) as the parabolic fixtures. This is because the better maintenance characteristics of the parabolic fixture is offset by the higher fixture efficiency of the lensed troffer. This result would be different for other luminaires. For example, some parabolic fixtures, especially 2- and 3-lamp fixtures with larger baffles, have higher fixture efficiencies as well as higher maintenance factors than lensed troffers.

D. Life-Cycle System Costs

The estimated total costs of the compared systems are graphed in Figure 2. Energy is the major cost of lighting while maintenance costs are relatively small. The total costs of the lamp/ballast combinations with the parabolic fixtures are consistently higher those with the lensed troffers. The higher cost of the parabolic fixture examined in this study was not offset by a lower energy cost because these parabolic fixtures have effectively the same efficiency as the lensed troffers.

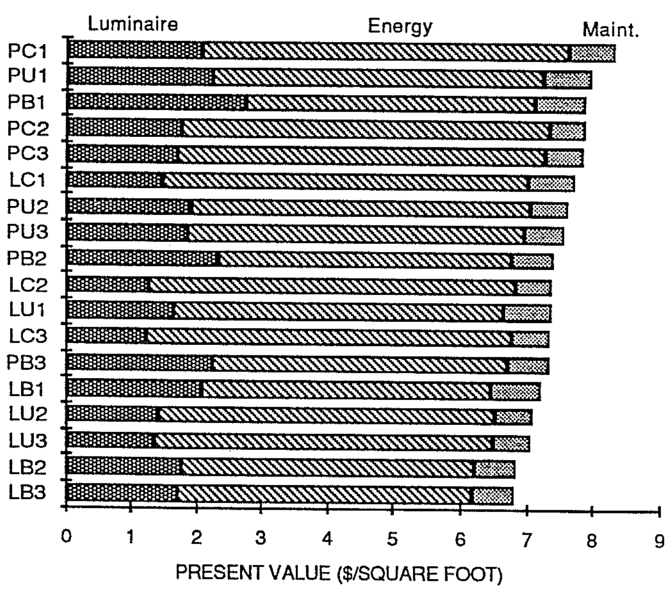


Figure 2. Present value of eighteen lamp/ballast/fixture combinations. Total costs are broken down into luminaire, energy, and maintanence costs. Luminaire costs include installation, ballasts, and first set of lamps.

V. DISCUSSION

This study has shown that the selection of lamps, ballasts and fixtures introduces several trade-offs in the design of lighting layouts. We found that the higher-output lamps and ballasts with higher ballast factors tended to reduce total system costs (as long as the system efficiencies remained the same) because fewer fixtures could be used thus reducing initial installation costs. The use of higher-efficiency lighting components, such as electronic or energy-efficient core/coil ballasts, also tended to reduce life-cycle system costs because the higher first cost was more than offset by the lower energy costs over the life of the system.

We found that visibility levels generally improved as the distance between fixtures increased even though the average maintained workplane illuminance remained approximately constant. This improvement in VL was most marked in the north-south directions (parallel to the fixtures' primary axis). Closer examination of the point-by-point VL values (not shown) revealed that this improvement occurred primarily between rows of luminaires, not directly underneath. Furthermore, perpendicular to the fixture primary axis (i.e. in the east-west direction), VL did not markedly improve as spacing between fixtures increased. This would suggest that the improvement in VL with increased luminaire spacing is due to the reduction in veiling reflections that occurs as light from luminaires on either side of the task strike the task at more grazing angles.

The generally unimpressive results obtained with the parabolic luminaires deserve further comment. The parabolic fixtures examined were not the most efficient available. Furthermore, these four-lamp parabolic fixtures did not have the distinctly bat-wing candlepower distribution typical of high-performance parabolic luminaires. Also, the VL values calculated in this study were for horizontal tasks only. The visibility of vertical tasks, such as computer screens, might be considerably improved with the parabolic fixture (compared to the lensed troffer) because the parabolics reduce the high-angle light that tends to cause veiling reflections in vertical screens. Finally, one of the major benefits of the parabolic fixture, the reduction in ceiling brightness, was not examined in this study due to software limitations. Future research will address these issues.

VI. CONCLUSION

A computational method was developed to examine the effect of lamp, ballast, and fixture selection on the quality and quantity of illumination, energy consumption, and life-cycle cost of lighting systems. Applying this analysis to lighting layouts using different lamp/ballast/fixture combinations can help elucidate the trade-offs of quality of illumination and system cost. Of the systems examined in this study, combinations with higher lumen outputs reduced the uniformity of the illuminance distribution at the workplane but did not reduce visibility levels. The use of higher lumen output lamp/ballast/fixture systems tended to reduce system costs since fewer fixtures could be installed to meet the design illuminance level. Using higher efficiency components also tended to reduce life-cycle costs as long as the premium cost of the components was not too high.

VII. ACKNOWLEDGMENTS

The authors would like to thank Robert Clear for his helpful discussions. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Equipment Division of the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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