High-Intensity Discharge Industrial Lighting Design Strategies for the Minimization of Energy Usage and Life-Cycle Cost

Isaac Lynnwood Flory IV

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University in partial
fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Electrical Engineering

Dr. Saifur Rahman, Chair
Dr. Krishnan Ramu
Dr. Douglas Lindner
Dr. Lamine Mili
Dr. John Rossi

August 26, 2008
Arlington, Virginia

Keywords: Lighting, Industrial, Life-Cycle Cost, Energy Usage, Lighting Application, Optimization, Maintenance, Model

High-Intensity Discharge Industrial Lighting Design Strategies for the Minimization of Energy Usage and Life-Cycle Cost

Isaac Lynnwood Flory IV

(Abstract)

Worldwide, the electrical energy consumed by artificial lighting is second only to the amount consumed by electric machinery. Of the energy usage attributed to lighting in North America, approximately fifteen percent is consumed by those lighting products that are classified as High-Intensity Discharge (HID). These lighting products, which are dominated by Metal-Halide and High-Pressure Sodium technologies, range in power levels from 35 to 2000 watts and are used in both indoor and outdoor lighting applications, one category of which is the illumination of industrial facilities. This dissertation reviews HID industrial lighting design techniques and presents two luminaire layout algorithms which were developed to provide acceptable lighting performance based upon the minimum number of required luminaires as determined by the lumen method, regardless of the aspect ratio of the target area. Through the development of lighting design software tools based upon the Zonal Cavity Method and these layout algorithms, models for the quantification of energy requirements, lighting project life-cycle costs, and environmental impacts associated with conventional industrial lighting installations are presented. The software tools, which were created to perform indoor HID lighting designs for the often encountered application of illuminating general rectangular areas with non-sloped ceilings utilizing either High-Bay or Low-Bay luminaires, provide projections of minimal lighting system costs, energy consumption, and environmental impact based upon lamp selection, ballast selection, luminaire selection and lighting system maintenance practices. Based upon several industrial lighting application scenarios, lighting designs are presented using both the new software tools and a commercially available lighting design software package. For the purpose of validating this research, analyses of both designs for each scenario are presented complete with results of illuminance simulations performed using the commercially available software.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank my committee chairman, Dr. Saifur Rahman, without whose willingness to work with me over a significant distance would have prevented this research from being performed. His inputs at all stages have, to a great extent, facilitated this work and the conclusions presented herein. I would also like to offer my appreciation to the other members of my committee; Dr. Douglas Lindner, Dr. Lamine Mili, Dr. Krishnan Ramu, and Dr. John Rossi, for their inputs regarding the organization and content of the final manuscript. Over the years I have taken courses with the majority of these gentlemen, and they have had a greater impact upon me and my career than they probably realize. I would like to thank my friends and family for their support during the years of work dedicated to the completion of my graduate studies. I am grateful to Mr. Joe Nuckolls and Mr. Lewis Kenyon, who were responsible for my entry into the lighting industry as well as for a great deal of my knowledge of the subject matter. In particular I would like to thank my parents, Lynn and Nancy Flory, for their support and encouragement during my entire time as a student of Virginia Tech. The highest level of praise however belongs to my wife Lisa and our children Carole and Zack. Over the years they have been supportive and understanding beyond measure, and this accomplishment would have never been possible without them in my life. And finally I would like to remember family and friends who are no longer with us, for they have and will continue to influence me, both personally and professionally. Studies for this degree began on the main campus of Virginia Tech many years ago. A university located in a town that I will always consider my home.

Glossary

Abbreviation	Description
Δd	Layout "Ghost" Boundary Incremental Depth – Used by LAYOUTMASTER
Δw	Layout "Ghost" Boundary Incremental Width – Used by LAYOUTMASTER
Δy	Adjacent Row Spacing – Used by LAYOUTMASTER
A_b	Ceiling or Floor Area (ft^2)
ad	Floor depth (feet) - Used by IMASTERG2
admat	Additional Material Cost for Single Luminaire Installation ($)- Used by IMASTERG2 and LLCCMONTH
A_f	Floor Area (ft^2)
AT	Luminaire Ambient Temperature Loss Factor (per unit)
avolt	Actual Luminaire Supply Voltage (V_{RMS}) - Used by IMASTERG2
aw	Floor width (feet) - Used by IMASTERG2
A_w	Wall Area Used for Calculation of Cavity Ratio (ft^2)
A_{wp}	Area of Work Plane (ft^2)
BF	Ballast Factor (per unit)
blstyp	Ballast Type [CWA (1), Reactor (2), Magnetic Regulator (3)] - Used by IMASTERG2
brn	Number of Luminaires Placed in Bottom Row – Used by LAYOUTMASTER
btype	Ballast Type [CWA (1), Reactor (2), Magnetic Regulator (3)] – Used by INDUSTRIAL*XX*G2
c	Results for CU or Other Multiplication Factor – Used by COEFUTIL
ccrmax	Maximum Ceiling Cavity Ratio (CR_{CC}) – Used by INDUSTRIAL*XX*G2
ccrmin	Minimum Ceiling Cavity Ratio (CR_{CC}) – Used by INDUSTRIAL*XX*G2
cful	Lower Multiplying Factor Value Relative to *lufc* and *llfc* – Used by CUMASTER
cfuu	Upper Multiplying Factor Value Relative to *uufc* and *ulfc* – Used by CUMASTER
cleanf	Cleanliness Factor (unitless) – Used by INDUSTRIAL*XX*G2
clnfct	Cleanliness Factor (unitless) - Used by IMASTERG2
clnmatl	Cleaning Material Charge for Single Luminaire ($)- Used by IMASTERG2 and LLCCMONTH

colidx	Column Index Array – Used by LAYOUTMASTER
coordact	Matrix containing Uncorrected Luminaire Coordinates– Used by LAYOUTMASTER
coordshift	Matrix containing Shifted (corrected) Luminaire Coordinates – Used by LAYOUTMASTER
coordsort	Sorted Version of *coordshift* – Used by LAYOUTMASTER
CR_{cc}	Cavity Ratio of Ceiling Cavity (unitless)
CR_{fc}	Cavity Ratio of Floor Cavity (unitless)
CR_{rc}	Cavity Ratio of Room Cavity (unitless)
CU	Coefficient of Utilization
cu20	Intermediate CU Value Relative to *u* and *l* Based Upon a ρ_{fce} of 20% – Used by CUMASTER
cuh	Upper Bound of CU – Used by COEFUTIL
cul	Lower Bound of CU – Used by COEFUTIL
CUMASTER	Coefficient of Utilization Program
CUTxx	Coefficient of Utilization Table Array – Used by INDUSTRIAL*XX*G2
CWA	Constant Wattage Autotransformer Ballast
d	Depth of Area to be Illuminated (feet)
DDCnst	Dirt Depreciation Constants – Used by LLFACTG2
DDTABLE	Array Containing Dirt Depreciation Constants – Used by LLFACTG2
dfact	Mean Lumen Factor (MH = 0.4, HPS = 0.5)
dl	Luminaires to be Added or Removed – Used by LAYOUTMASTER
dnew	Temporary Layout Depth – Used by LAYOUTMASTER
dreq	Depth Required Based upon Revised Spacing – Used by LAYOUTMASTER
dspcost	Unit lamp disposal cost ($) – Used by LLCCMONTH
dy	Spacing Increment between Short and Long Rows – Used by LAYOUTMASTER
efc	Desired work plane illuminance (footcandles) – Used by INDUSTRIAL*XX*G2
ete	End-to-End Spacing – Used by LAYOUTMASTER
E_{wp}	Work Plane Illumination Level (footcandles)
FCFT00	Table of Multiplying Factors for ρ_{fce} of 0% – Used by CUMASTER
FCFT10	Table of Multiplying Factors for ρ_{fce} of 10% – Used by CUMASTER

FCFT20	Dummy Table of Multiplying Factors for ρ_{fce} of 30% (all values 1.0) – Used by CUMASTER
FCFT30	Table of Multiplying Factors for ρ_{fce} of 30% – Used by CUMASTER
fcr	Floor Cavity Ratio (CR_{FC}) – Used by INDUSTRIAL*XX*G2
fd	Floor depth (feet) – Used by INDUSTRIAL*XX*G2
ff	Floor Factor as Given in Equation 3.1 (feet $^{-1}$)
fw	Floor width (feet) – Used by INDUSTRIAL*XX*G2
g	Annual Rate of Inflation (%)
hc	Ceiling Height (feet) – Used by INDUSTRIAL*XX*G2 and CUMASTER
hfc	Height of work plane (feet) – Used by INDUSTRIAL*XX*G2
hfc	Work Plane Height (feet) – Used by CUMASTER
HID	High-Intensity Discharge
hmaxm	Maximum allowable mounting height (feet) – Used by INDUSTRIAL*XX*G2
hminm	Minimum allowable mounting height (feet) – Used by INDUSTRIAL*XX*G2
HPS	High-Pressure Sodium
hpsblstlarge	High-Pressure Sodium Luminaire Input Power Table (.txt file) – Used by INDUSTRIAL*XX*G2
HPSCHOICES	High-Pressure Sodium Design Results Array – Used by INDUSTRIAL*XX*G2
hpslumfile200	Array Containing Luminaire Data File – 200W HPS
hpslumfile250	Array Containing Luminaire Data File – 250W HPS
hpslumfile310	Array Containing Luminaire Data File – 310W HPS
hpslumfile400	Array Containing Luminaire Data File – 400W HPS
hpslumfile600	Array Containing Luminaire Data File – 600W HPS
hrc	Room Cavity Height (feet) – Used by CUMASTER
hrsperst	Operating Hours per Start– Used by INDUSTRIAL*XX*G2
hrsprstrt	Operating Hours per Start- Used by IMASTERG2
hrspryr	Operating Hours per Year- Used by IMASTERG2
hrspstrt	Operating Hours per Start – Used by LLCCMONTH
hrspwk	Operating Hours per Week – Used by LLCCMONTH
HVAC	Heating, Ventilation and Air-Conditioning

hvacfctr	Lighting to HVAC Energy Cost Ratio - Used by IMASTERG2 and LLCCMONTH
i	Annual Rate of Return or Annual Interest Rate (%)
icval	Initial Column Quantity – Used by LAYOUTMASTER
IESNA	Illuminating Engineering Society of North America
IL	Initial Lamp Output (lumens)
IMASTERG2	Master Design Program
INDUSTRIALHPSG2	High-Pressure Sodium Industrial Lighting Design Program
INDUSTRIALMHG2	Metal-Halide Industrial Lighting Design Program
infrate	Annual Rate of Inflation (percent) - Used by IMASTERG2 and LLCCMONTH
instcost	Hourly Rate for Installation ($/hour) - Used by IMASTERG2 and LLCCMONTH
insttime	Time Required to Install Single Luminaire (hours) - Used by IMASTERG2 and LLCCMONTH
intrate	Annual Interest Rate (percent) - Used by IMASTERG2 and LLCCMONTH
irval	Initial Row Quantity – Used by LAYOUTMASTER
k	Effective Annual Interest Rate (%)
kmint	Monthly Effective Interest Rate– Used by LLCCMONTH
l	Lower Intermediate CU Value Relative to *lu* and *ll* – Used by CUMASTER
LAYOUTMASTER	Luminaire Layout Program
LBO	Lamp Burn-Out Factor (per unit)
LCC	Life-Cycle Costing (present worth)
LDATA	Array Containing Project Specifications – Generated by LIGHTDATA
LDD	Luminaire Dirt Depreciation Factor (per unit)
lfamly	Lamp Family (MH - 1, HPS - 2) – Used by LLFACTG2
LIGHTDATA	Data Input Program
ll	Lower Intermediate CU Value Relative to *rccl* and *rwl* – Used by CUMASTER
LL	Rated Lamp Life (hours)
LLCCMONTH	Life-Cycle Cost Analysis Program
lld	Lamp Lumen Depreciation (per unit) – Used by INDUSTRIAL*XX*G2
LLD	Lamp Lumen Depreciation (per unit)

LLF	Light Loss Factor
LLFACTG2	Light Loss Factor Program
llfc	Lower Multiplying Factor Value Relative to *rccl* and *rwl* – Used by CUMASTER
llfmin	Minimum Value of LLF – Used by LLFACTG2
llum	Initial Lamp Output Rating (lumens) – Used by LLFACTG2
lmpcost	Unit lamp cost ($) – Used by LLCCMONTH
lmplife	Rated Lamp Life (hours) = Used by LLFACTG2
longcol	Array Containing Column Numbers of Long Columns – Used by LAYOUTMASTER
lotable	Lower Multiplying Factor Table Bounding *rfce* – Used by CUMASTER
LPD	Lighting Power Density (watts / ft^2)
lrfc	Lower Value of ρ_{fce} – Used by CUMASTER
LSD	Luminaire Surface Depreciation Factor (per unit)
lu	Lower Intermediate CU Value Relative to *rccl* and *rwu* – Used by CUMASTER
lufc	Lower Multiplying Factor Value Relative to *rccl* and *rwu* – Used by CUMASTER
lumcln	Time Between Luminaire Cleanings (months) - Used by IMASTERG2
lumcost	Unit luminaire cost ($) – Used by LLCCMONTH
lumpwr	Unit Luminaire Input Power (watts) – Used by LLCCMONTH
LV	Luminaire Voltage Factor (per unit)
lvls	Mounting Heights to Evaluate (positive integer) – Used by INDUSTRIAL*XX*G2
M	Coefficient of Utilization Table – Used by COEFUTIL
mbase	Base Maintenance Expense – Used by LLCCMONTH
MH	Metal-Halide
mhblstlarge	Metal-Halide Luminaire Input Power Table (.txt file)– Used by INDUSTRIAL*XX*G2
MHCHOICES	Metal-Halide Design Results Array – Used by INDUSTRIAL*XX*G2
mhdsgns	Metal-Halide Design Array - Used by IMASTERG2
mhlumfile200	Array Containing Luminaire Data File – 200W MH
mhlumfile250	Array Containing Luminaire Data File – 250W MH
mhlumfile320	Array Containing Luminaire Data File – 320W MH

mhlumfile350	Array Containing Luminaire Data File – 350W MH
mhlumfile360	Array Containing Luminaire Data File – 360W MH
mhlumfile400	Array Containing Luminaire Data File – 400W MH
mhlumfile450	Array Containing Luminaire Data File – 450W MH
mhlumfile750	Array Containing Luminaire Data File – 750W MH
mhm	Minimum allowable mounting height (feet) - Used by IMASTERG2
mhx	Maximum allowable mounting height (feet) - Used by IMASTERG2
mill	Desired work plane illuminance (footcandles) - Used by IMASTERG2
minfrate	Monthly Equivalent Inflation Rate – Used by LLCCMONTH
mintrate	Monthly Equivalent Interest Rate – Used by LLCCMONTH
ML	Mean Lamp Output (lumens)
mntcost	Hourly Rate for Maintenance ($/hour) - Used by IMASTERG2 and LLCCMONTH
mntlvls	Mounting Heights to Evaluate (positive integer) - Used by IMASTERG2
mnttime	Time Required to Re-lamp/Clean Single Luminaire (hours) - Used by IMASTERG2 and LLCCMONTH
MR	Magnetically Regulating Ballast
mrcrl	Lower Bound *rcr* – Used by COEFUTIL
mrcru	Upper Bound *rcr* – Used by COEFUTIL
N	Number of Luminaires
nci	Initial Number of Columns
nl	Required Number of Luminaires – Used by LAYOUTMASTER
nli	Initial Luminaire Quantity – Used by LAYOUTMASTER
nol	Number of Luminaires Installed – Used by LLCCMONTH
nrgcost	Cost of Electrical Energy ($/kw-Hr) - Used by IMASTERG2 and LLCCMONTH
nri	Initial Number of Rows
PDD	Percentage of Dirt Depreciation – Used by LLFACTG2
pddl	Lower Bound of Dirt Depreciation Percentage– Used by LLFACTG2
pddu	Upper Bound of Dirt Depreciation Percentage– Used by LLFACTG2
plife	Planned Life of Project (years) - Used by LLFACTG2

prjlife	Planned Life of Project (years) - Used by IMASTERG2 and LLCCMONTH
PWAI	Present Worth of Acquisition & Installation Expenses ($) – Used by LLCCMONTH
PWDISP	Present Worth of Disposal Expenses ($) – Used by LLCCMONTH
PWMAIN	Present Worth of Maintenance Expenses ($) – Used by LLCCMONTH
PWOPER	Present Worth of Operating Expenses ($) – Used by LLCCMONTH
q	Maintenance Based Effective Interest Rate (%)
qeff	Monthly Maintenance Based Effective Interest Rate – Used by LLCCMONTH
r	Maintenance Interval in Months – Used by LLCCMONTH
rc	Ceiling Reflectance (%) – Used by INDUSTRIAL*XX*G2 and CUMASTER
rcce	Effective Ceiling Cavity Reflectance ρ_{cce} (%) – Used by CUMASTER
rccf	Effective Ceiling Cavity Correction Factor – Used by CUMASTER
rccfl	Lower Table Multiplying Factor Value Relative to *cfuu* and *cful* – Used by CUMASTER
rccfu	Upper Table Multiplying Factor Value Relative to *cfuu* and *cful* – Used by CUMASTER
rccl	Lower Published Bound of ρ_{cce} – Used by CUMASTER
rccu	Upper Published Bound of ρ_{cce} – Used by CUMASTER
rclean	Time Between Work Area Cleanings (months) – Used by INDUSTRIAL*XX*G2
rcr	Room Cavity Ratio – Used by CUMASTER
RCR	Room Cavity Ratio (see CR_{rc})
rcrdel	Room Cavity Ratio Increment – Used by INDUSTRIAL*XX*G2
rcrl	Lower Bound of *rcr*– Used by LLFACTG2
rcrmax	Maximum Room Cavity Ratio (CR_{RC}) – Used by INDUSTRIAL*XX*G2
rcrmin	Minimum Room Cavity Ratio (CR_{RC}) – Used by INDUSTRIAL*XX*G2
rcru	Upper Bound of *rcr*– Used by LLFACTG2
redux	Spacing Reduction Factor – Used by LAYOUTMASTER
reflc	Ceiling Reflectance (percent) - Used by IMASTERG2
reflf	Floor Reflectance (percent) - Used by IMASTERG2
reflw	Wall Reflectance (percent) - Used by IMASTERG2
relamp	Time Between Group Relamping (months) - Used by IMASTERG2

relmp	Time Between Group Relamping (months) – Used by INDUSTRIAL*XX*G2
rf	Floor Reflectance (percent) – Used by INDUSTRIAL*XX*G2 and CUMASTER
rfce	Effective Floor Cavity Reflectance ρ_{fce} (%) – Used by CUMASTER
rh	Height of ceiling (feet) - Used by IMASTERG2
RL	Re-lamp Point (hours)
rlmpint	Operating Hours between Group Re-lamping – Used by LLCCMONTH
rmcln	Time Between Work Area Cleanings (months) - Used by IMASTERG2
RSDD	Room Surface Dirt Depreciation Factor (per unit)
rvolt	Rated Luminaire Supply Voltage (V_{RMS}) - Used by IMASTERG2
rw	Wall Reflectance (percent) – Used by INDUSTRIAL*XX*G2 and CUMASTER
rwl	Lower Published Bound of ρ_w – Used by CUMASTER
rwu	Upper Published Bound of ρ_w – Used by CUMASTER
RX	Reactor Ballast
ry	Maintenance Cycle Period (years)
S	Luminaire Spacing (feet)
S_1	Horizontal Luminaire Spacing
S_2	Vertical Luminaire Spacing
S_{approx}	Approximate Spacing Based Upon Room Dimensions (feet)
scrptime	Time Required to Scrap Single Luminaire (hours) - Used by IMASTERG2 and LLCCMONTH
shortcol	Array Containing Column Numbers to be Shortened – Used by LAYOUTMASTER
si	Initial Luminaire Spacing (feet) – Used by LAYOUTMASTER
sn	New (reduced) Spacing in layoutA1– Used by LAYOUTMASTER
snew	New (increased) Spacing in layoutB1 – Used by LAYOUTMASTER
spcxx	Spacing Criteria Variable – Used by INDUSTRIAL*XX*G2
spsum	Summation of Spacings – Used by LAYOUTMASTER
SPW	Single Present Worth Factor
S_w	Wall to Luminaire Spacing (feet)
swc	Spacing from Outer Columns to Walls – Used by LAYOUTMASTER

swr	Spacing from Outer Rows to Walls – Used by LAYOUTMASTER
tclean	Time Between Luminaire Cleanings (months) – Used by INDUSTRIAL*XX*G2
u	Upper Intermediate CU Value Relative to *uu* and *ul* – Used by CUMASTER
ul	Upper Intermediate CU Value Relative to *rccu* and *rwl* – Used by CUMASTER
ulfc	Upper Multiplying Factor Value Relative to *rccu* and *rwl* – Used by CUMASTER
uptable	Upper Multiplying Factor Table Bounding *rfce* – Used by CUMASTER
UPW or upw	Uniform Present Worth Factor using Effective Interest Rate (k) – Used by LLCCMONTH
urfc	Upper Value of ρ_{fce} – Used by CUMASTER
uu	Upper Intermediate CU Value Relative to *rccu* and *rwu* – Used by CUMASTER
uufc	Upper Multiplying Factor Value Relative to *rccu* and *rwu* – Used by CUMASTER
vact	Actual Luminaire Supply Voltage (V_{RMS}) – Used by INDUSTRIAL*XX*G2
vrated	Rated Luminaire Supply Voltage (V_{RMS}) – Used by INDUSTRIAL*XX*G2
w	Width of Area to be Illuminated (feet)
walspace	Wall Space Multiplier – Used by LAYOUTMASTER
wcratio	Wall Area in CC to Ceiling Area Ratio – Used by CUMASTER
wnew	Temporary Layout Width – Used by LAYOUTMASTER
wph	Height of work plane (feet) - Used by IMASTERG2
x	Percent of Rated Lamp Life – Used by LLFACTG2
x	Luminaire X-Coordinate
xactual	X-Coordinates after Removal of Ghost Boundary – Used by LAYOUTMASTER
xfinalC	Final X-Coordinates for LayoutA1 – Used by LAYOUTMASTER
y	Percent of Lamps Surviving – Used by LLFACTG2
y	Luminaire Y-Coordinate
yactual	Y-Coordinates after Removal of Ghost Boundary – Used by LAYOUTMASTER
yfinalC	Final Y-Coordinates for LayoutA1 – Used by LAYOUTMASTER
yrbhr	Operating Hours per Year – Used by INDUSTRIAL*XX*G2

yrhvacnrg	Annual Energy Demand of HVAC Resulting from Lighting (kW-Hrs) – Used by LLCCMONTH
yrlumnrg	Annual Energy Demand of Luminaires (kW-Hrs) – Used by LLCCMONTH
yspace	Row Spacing Reduction Factor – Used by LAYOUTMASTER
ρ_b	Base Reflectance (%)
ρ_c	Ceiling Reflectance (%)
ρ_{cce}	Effective Ceiling Cavity Reflectance (%)
ρ_f	Floor Reflectance (%)
ρ_{fce}	Effective Floor Cavity Reflectance (%)
ρ_w	Wall Reflectance (%)
Φ_L	Initial Lamp Output Rating (lumens)

1 Introduction

The electrical energy consumed by artificial lighting is significant – approximately 22% of domestic electric power generation [1]. Consequently the application and efficiency of lighting has a profound affect upon the consumption of fossil fuels and the proliferation of environmental hazards. Considering the current state of energy costs and environmental awareness, it is timely to examine what actions can be taken to reduce the energy and environmental footprints associated with artificial lighting products and systems. There are several paths that may be taken to reduce the strain that lighting places upon our planet. One path is to develop and implement more efficient lighting sources and systems – a path which has been and currently is heavily traveled. An example of an outcome associated with these efforts would be the proliferation of more efficient electronic fluorescent ballasts, replacing their less efficient line frequency counterparts. And more recently the introduction and accelerating acceptance of self-ballasted compact fluorescent lamps which offer substantial energy savings over the incandescent sources that are destined to be displaced in the majority of residential and commercial applications. Another path is to reduce our expectations of illumination levels and lighting aesthetics - to "do with less" which will reduce energy consumption and its associated environmental effects.

A third path, which is the focus of the research presented in this dissertation, is the improved utilization of existing lighting products to reduce energy consumption - specifically as it applies to high-intensity discharge (HID) industrial lighting applications. The improved utilization is realized through a reduction in the number of luminaires needed to adequately illuminate a general area industrial lighting application. The reduction in luminaire quantity is facilitated through the use of newly developed luminaire placement (layout) algorithms, and economic analyses based upon the varying of lamp selection, ballast selection, luminaire mounting height, and lighting system maintenance practices. In addition, the impact of the reduction of energy consumption upon the environment is presented including an analysis of the potential consequences of increased frequency of luminaire maintenance resulting in increased lamp disposal.

1.1 Scope of Research

This research focuses upon the environmental and economic aspects of industrial high-intensity discharge lighting systems and methods for reducing the consumption of electrical energy, and coincidentally the overall life-cycle cost of industrial lighting projects. Although the methods, results and conclusions presented in this dissertation apply most directly to industrial lighting systems, they also apply in varying degrees to any general area indoor lighting application.

The methods, examples, and conclusions presented in this dissertation are the result of the development of software tools which are based upon long-standing lighting design practices as well as algorithms and analysis methods that are offered as original contributions. All of the programs supporting this research were created using the scientific computing software MATLAB® which has become one of, if not the preeminent software development suites utilized throughout the areas of science, engineering and technology.

1.2 Standard Industrial Lighting Design Practice

The standing method used in the design of general indoor lighting systems is the determination of average horizontal illumination based upon the Zonal Cavity Method. This approach to lighting design estimates the minimum number of luminaires that are required to produce a sufficient amount luminous of flux to provide a specific level of illuminance upon a horizontal surface, often referred to as the work plane. A key component in the determination of the minimum luminaire quantity is the projection of light level depreciation based upon factors such as the accumulation of dirt upon surfaces, and the natural trend of lamp output to depreciate over time. To account for this degradation in illumination levels, areas are in most cases significantly over-illuminated at the time of installation. This excess quantity of illumination represents energy that is being consumed which is greater than that needed to provide the minimum acceptable or "maintained" light level.

Once the minimum number of required luminaires is determined, standard practice is to locate or position these luminaires so that the uniformity of illumination is deemed acceptable, either by specification or convention. To this end, the number of luminaires installed is generally tied to the dimensions of the area being illuminated. For example, if a rectangular area to be illuminated is twice as wide as it is deep, the number of rows of luminaires will approximately be twice the number of columns. The goal of this practice is to maintain, with some degree of symmetry, consistent spacings between adjacent luminaires which will facilitate a high level of uniformity of illumination. As a consequence of this approach the number of luminaires installed is often greater than the quantity required, often resulting in over-illumination and wasted energy. In addition, it is typical for lighting designs to be made using a specific luminaire mounting height which places an additional constraint upon the lighting layout and in many cases does not allow for a more efficient lighting system design. If the lighting design could be optimized to minimize the number of luminaires, then both cost and energy usage could be reduced.

1.3 Lighting Design Software Development

The first step taken to complete this research involved the generation of software tools to perform general area indoor lighting designs. These tools, which require the input of all of the basic physical properties of the area to be illuminated, allows for the simultaneous usage of multiple lamp types and offers the means for minimizing the luminaire quantity based upon variable mounting heights. There are commercially available software packages that will perform similar analyses, however these products are broader in scope and generally do not offer concurrent multiple light source selection, variable mounting heights, or the provision for non-standard mounting configurations thus limiting their ability to minimize energy usage by way of reduced luminaire count. Key elements of the software developed to support this research are lighting designs based upon variable mounting heights as well as two separate luminaire layout (positioning) algorithms which provide layout options allowing the end-user the opportunity to take advantage of a reduced luminaire quantity over a rectangular target area. An additional aspect of the software is the realization of improved lumen maintenance when certain sources are operated using premium electromagnetic ballasts, specifically the magnetically regulating (MR) ballast topology. This improvement in lamp performance is supported by data recorded over the period May 1998 to May 2002 at the Rector Field House located on the campus of Virginia Tech [2].

1.4 Economics of High-Intensity Discharge Industrial Lighting Systems

A portion of this research was the development of software that would determine Life-Cycle Costs (LCC) and energy consumption profiles associated with industrial lighting installations. Generally this would be a rather straightforward set of calculations, however the program developed incorporates the flexible design capabilities previously described (section 1.3) allowing for LCC calculations to be performed over a range of lighting designs and maintenance schedules. This software provides the data necessary to determine which designs and under what maintenance scenarios will result in substantial reductions in lighting project costs, energy consumption, and environmental stress.

1.5 Contributions

The contributions to the areas of lighting design and its impacts upon energy and the environment include:

(i) A method/model for the creation of lighting design software based upon the Zonal Cavity Method for industrial (and general indoor) applications which will accommodate multiple lamp types and power levels, ballast types, and luminaire mounting heights.

(ii) Two luminaire layout algorithms that provide acceptable lighting performance for any luminaire quantity applied to a rectangular target area providing that spacing restrictions are not exceeded.

(iii) Data and conclusions as to the relative performance of Metal-Halide (MH) lamps which are operated using magnetically regulating (MR) and constant wattage autotransformer (CWA) ballasts.

(iv) A method/model for determining the minimum LCC of an industrial lighting application under variable design parameters and maintenance schedules.

(v) A method/model for projecting energy consumption and environmental impact of greenhouse gas and mercury pollution as a result of variable lighting designs and maintenance schedules.

1.6 Organization of Dissertation

The first sections of this dissertation, Chapters 1 and 2, serve as an introduction to industrial lighting design and application. Presented are the methods for determining the Coefficient of Utilization and Light Loss Factors by way of the Zonal-Cavity Method as well as conventional luminaire layout procedures. Lighting system costs are explained along with concepts used in the determination of LCC. In addition, an explanation of environmental concerns surrounding artificial lighting is presented. Chapter 3 presents the development of the software needed to determine light loss factors required for use in the lighting design process as well as two luminaire layout algorithms. These algorithms are designed to generate luminaire layouts which will provide high levels of uniformity while preventing the need for additional luminaires to effectively even out the distribution of luminous flux upon the work plane.

Chapter 4 demonstrates not only the application, but also the validity of the software by performing designs based upon three different industrial lighting scenarios. The first scenario is a relatively small rectangular area measuring 50 feet by 100 feet. Several different MH lamps are used in the analysis and the most attractive design is selected and its optical performance is simulated to establish the credibility of the developed software. The simulations are performed using the commercially available lighting design software package LitePro®, and the design is also compared directly with a design recommended by the LitePro® software which also employs the Zonal Cavity Method of average illumination calculation. A second scenario, which is directly based upon the first scenario, illustrates a key design safeguard provided by the software in the event that satisfactory luminaire layout cannot be achieved for a minimal number of luminaires. The third scenario targets a larger industrial area in which two different lamp families are used to compare the relative performance of both and illustrate the way in which the software presents the design results.

Chapter 5 presents analyses of the designs created using the software models. The results of these analyses are categorized so as to illustrate the impact of lamp selection, ballast selection, and lighting system maintenance upon energy consumption, LCC and the environment. The example scenarios which are presented in Chapter 4 are again used as illustrations in the presentation of the results of this research.

The customary presentation of conclusions and suggestions for future research is provided in Chapter 6, and two appendices are presented which discuss the development of the software tools in detail and the method for simulating lighting system performance using the LitePro® software package.

2 Literature Review

2.1 Introduction

Artificial lighting is one of the oldest of all electrical technologies, emerging in the 19th century in the form of the carbon arc lamp [3]. Since that time one organization, the Illuminating Engineering Society of North America (IESNA) has served as the recognized domestic technical authority concerning illumination engineering. This organization, which is now over one-hundred years old, offers a central hub for the collection and dissemination of the functional and artistic aspects of lighting. The organization is separated into a number of technical areas of interest including but not limited to daylighting, energy management, light sources, maintenance, research, and testing procedures. Areas of interest concerning the application of light are placed within categories, a partial listing of which includes industrial, office, roadway, outdoor and residential. These areas of interest, through the establishment of committees, generate a host of design guides, standards, and educational material which commonly referred to throughout the lighting industry. At the center of this network of specialized publications however lies a central document entitled the IESNA Lighting Handbook [4]. This book, first published in 1949 and now in its 9th Edition, has as a fundamental objective, the dissemination of essential information on light and lighting in a simple and condensed format. This book contains information regarding the physics and application of light and is the standard technical reference used by the North American lighting industry.

In addition to the IESNA Handbook, there are separate design guides and standards which are often referenced including the “Recommended Practice for Industrial Lighting Facilities” which is also published by the IESNA [5]. This design guide provides valuable information regarding the quality, quantity, application and economics of industrial lighting systems and is currently undergoing a revision within the corresponding IESNA subcommittee.

The Journal of the Illuminating Engineering Society of North America (JIESNA), more recently re-titled LEUKOS, is the primary domestic peer reviewed publication for lighting technology and application. Articles from this series of publications are referenced on a number of occasions throughout this manuscript.

Several independent texts have been written on the subject of lighting; some which are broad in scope, and others that are narrower of field. One such book that presents a broad range of lighting topics and which is referred to frequently in this manuscript is “Illumination Engineering: From Edison’s Lamp to the Laser”, first published in 1985 [6]. This text provides an extensive review of the physics, components, and application of both natural and artificial illumination. “Applied Illumination Engineering” is another text in the same vein, providing a comprehensive but broad treatment of the subject matter [7]. A text that places emphasis upon the economics and efficiencies of lighting systems is “Energy Management in Illuminating Systems” [8]. Another comprehensive handbook is entitled “Lamps and Lighting”, and although its origins are European, a number of the chapters translate well to North American topics including lighting design and economic analysis [9]. This text does a commendable job of addressing the variability of lighting project costs as a function of lighting system service, which is a key aspect of the research being presented in this dissertation, however the economic analysis is not based upon LCC methods. A final handbook (standard) published by the Institute of Electrical and Electronic Engineers (IEEE) entitled “Recommended Practice for Electric

Power Systems in Commercial Buildings" provides a subset of the information found in the IESNA Handbook, however it also provides a significant analysis of the effect of artificial lighting upon heating, ventilating and air-conditioning (HVAC) [10].

An excellent resource that addresses new and existing lighting technologies is a report that was prepared for the United States Department of Energy entitled "U.S. Lighting Market Characterization, Volume II: Energy Efficient Lighting Technology Options" [11]. This document, which was published in 2005, examines all different commercially available lighting technologies and outlines the areas in which these technologies may be improved. Newer technologies, such as solid-state sources, are also examined with explanation of the then current progress of research.

As stated previously, all of the software developed to support this research was done so in the MATLAB® programming environment. During research of the prior art surrounding indoor lighting design, only one MATLAB® based publication pertaining to lighting was discovered. This paper entitled "A Lighting System Model for Maximum Energy Efficiency and Cost Savings" presents a mathematical model of a lighting system which is implemented through the use of a SIMULINK® graphical interface [12]. The published model is an analysis tool rather than a design tool, allowing the user to determine the energy efficiency and system costs based upon input variables such as daylight contributions or the required level of indoor illumination. This publication does not preempt this research, however due to the subject matter it warrants mention.

2.2 Performance Factors of Lighting Systems

Source Efficacy is simply the luminous output of the light source (lamp) divided by the power consumed by the source. For a particular 400W discharge lamp with an output of 40,000 lumens, the lamp efficacy would be $40{,}000 \text{ lumens} \div 400 \text{ watts} = 100 \text{ lumens per watt}$.

The efficacy of the lighting system, or *System Efficacy*, is the luminous output of the lamp divided by the power consumed by the lamp and control gear (ballast, etc.) combination. Using the 400 watt discharge lamp again as an example it is determined that the system input power is 444.4 watts resulting in a system efficacy of 90 lumens per watt.

Source Life, or lamp life, excluding those cases where the source is operated well outside acceptable tolerances, is largely dictated by construction and materials. The same can be said for System Life, however the physical environment can also play a significant role. Source Life is specified by the lamp manufacturer and is the point in operating hours at which 50% of the lamps in a given population are expected to have failed. As will be demonstrated in this dissertation, the life of a lamp has significant financial impact upon the true cost of a lighting project.

Lumen Maintenance, also referred to as Lamp Lumen Depreciation (LLD), is the rate at which the output of a lamp decreases over its life. Some lamps, such as those in the HID family, exhibit a greater reduction in light output than certain fluorescent sources over an equivalent number of operating hours. The LLD for a given type of light source is based upon test data that is generated by the lamp manufacturers. The significance of the LLD is that it is a key factor in the determination of how many luminaires are required to perform a specific lighting task. Since the lamp output degrades over time it follows that higher light levels could be maintained if the lamps were changed more frequently thus affecting the timing of major maintenance - major maintenance being defined as the relamping, cleaning and incidental repair of all luminaires. This reasoning can be translated into a demand side requirement, i.e. if the end user requires a specific minimum light level then fewer luminaires would be required if the lamps were changed over shorter intervals.

The current metric used in the determination of the efficiency of an indoor lighting application is Lighting Power Density (LPD). This quantity is the installed input power requirement of the lighting system divided by the area which is being illuminated. Two methods for calculating these quantities are commonly used: whole building or space-by-space [13]. ASRAE Standard 90.1-2007 contains recommended LPD levels for a variety of different indoor applications including manufacturing facilities. The LPD value recommended for manufacturing environments is 1.3 watts per square foot when the whole building method of calculation is used, and between 1.3 and 1.7 watts per square foot when the space-by-space method is employed [13]. As will be seen in the presentation of the research results, these LPD levels are aggressive (low) and often difficult to attain, however from a building code perspective these levels provide a functional way to influence users to employ more efficient lighting systems.

2.3 High-Intensity Discharge Lighting Systems

High-Intensity Discharge (HID) lamps have been in use since the mid-1930's and their continued evolution has been driven by the need for improved color, greater efficacies, and more precise optical control. Lamps falling within the category of HID sources include Low-Pressure

Sodium, High-Pressure Sodium, Mercury Vapor, and Metal-Halide. Even though it provides the highest source efficacy, Low-Pressure Sodium has not found great popularity in the United States. This non-acceptance is primarily due to its deep orange color and non-standard dimensions, and as a result this source is omitted from consideration in this analysis.

High-Pressure Sodium (HPS) lighting has become a much more popular variant of Low-Pressure Sodium technology. This is largely due to improved color characteristics, smaller size, and longer lamp life. This lamp was essentially created by raising the sodium vapor pressure from between 20 and 40 times that found in Low-Pressure Sodium lamps. The result of this is a much improved color profile with a moderate reduction in lamp efficacy in contrast to Low-Pressure Sodium sources. Most HPS lamps have high efficacies that lie within the 100 to 150 lumen per watt range and a correlated color temperature in the vicinity of 2100° K, which produces an apparent yellow-orange color. Another positive aspect of these sources is that their designs have evolved such that many of the products pass the Environmental Protection Agency's TCLP (Toxic Characteristic Leaching Procedure) test, however they are still considered as falling into the category of universal waste as defined by the United States Environmental Protection Agency [14].

Mercury Vapor lighting is one of the oldest lamp families within the category of HID sources. A variant of the low-pressure mercury or fluorescent lamp, this lamp has primarily been used in outdoor lighting applications since the 1930's [6]. One of the least desirable characteristics of this lamp is that it has relatively poor efficacy, between 30 and 60 lumens per watt. However, on the positive side, this light source demonstrates a long service life (over 24,000 burn-hours) and provides better color rendering than HPS sources. The light generated by this source is blue-white in contrast to the yellow-orange color generated by HPS lamps. Certain Mercury Vapor products actually use a phosphor applied to the inside surface of the outer envelope of the lamp to improve color rendering at the expense of some efficacy. One serious drawback of this lamp is the amount of mercury that is required for its operation. Unlike other discharge lamps (HPS, fluorescent) that have had their mercury content lowered to comply with the TCLP requirements, these lamps do not appear to have any prospect of being so designated. Due to the low efficacy and poor color characteristics of this lamp type, it is not generally used in new or retrofit indoor lighting applications. For this reason mercury lighting systems were not considered in the completion of the research.

Metal-Halide (MH) lighting was developed to offer improvements over Mercury Vapor, both in terms of color and efficacy. Originating in the mid-1960's, this source is similar to Mercury Vapor in that the arc-tube is of similar design and many of the same materials are used in its construction [6]. Mercury of sufficient quantity is used in the discharge to render this lamp TCLP non-compliant. In addition to the mercury, additional rare earth metals are introduced into the arc tube in the form of their iodide salts which provide improved color over other HID sources. These sources have become the standard for the majority of indoor HID lighting applications and those outdoor applications where color performance is critical.

2.4 Lighting System Design – Zonal Cavity Method

As mentioned previously, the IESNA Lighting Handbook offers insight into the different design methodologies. The method for determining the illumination at a specific location is termed the “point method” or “point-by-point” method, and is based upon the determination of the individual contributions from individual luminaires using the inverse square law [10]. This law states that the illumination from a point source is inversely proportional to the square of the distance between the source and the target. In addition to being computationally intensive when multiple sources are involved, this method includes the shortcoming of only considering direct components of luminance, ignoring reflected components which are always present in indoor lighting applications [6].

The Lumen Method of lighting design, which is the basis for all of the designs presented herein, was originally standardized in the 1920’s and is used to determine the average amount of illumination upon a horizontal surface [6]. This method is based upon determining total amount of luminous flux emerging from the luminaires and projecting the quantity that will reach the target area (work plane) based upon the physical characteristics of the space. The “zonal cavity method” was first presented in 1964 by way of a four part series articles, and since that time this method has become the standard for all average illuminance calculations [15]. The design concept is based upon the optical efficiency of the luminaire being used and the physical and reflective characteristics of the space which is to be illuminated. Each luminaire has a luminous flux output that is less than that of the source alone due to the process of redirecting the flux into a useful and consistent pattern. Additionally, when considering a lighting application, this luminous flux is further reduced by the environment created around the luminaire and the target area to be illuminated, typically referred to as the work plane. All of these effects result in a net reduction of luminous flux and therefore illumination level. The zonal cavity method separates the room into three cavities (zones) for determining the net luminous flux available at the surface to be illuminated. There is a cavity which lies below the work plane which is referred to as the *floor cavity*, one that lies above the opening of the luminaire which is referred to as the *ceiling cavity*, and one that lies between the first two which is referred to as the *room cavity*. The concept behind this method of lighting design is that the cavity above the luminaires and the cavity below the work plane are used in conjunction with surface reflectances to create a simpler effective model of the space in question.

2.4.1 Coefficient of Utilization

The ratio of the of the luminous flux from a luminaire received on the work plane to the luminous flux generated by the lamps alone is referred to as the Coefficient of Utilization (CU) [4]. To determine the CU of a specific luminaire for a given application it is necessary to calculate a value referred to as the cavity ratio, which is the ratio of the amount of vertical surface area to the amount of horizontal surface area, for each of the three zones identified by the zonal cavity method. The equation is given in Equation 2.1, where subscript 'xx' is either the ceiling cavity (CC), the room cavity (RC), or the floor cavity (FC).

$$CR_{XX} = \frac{5h_{XX}(f_w + f_d)}{(f_w f_d)} \qquad (2.1)$$

The floor width and depth are f_w and f_d respectively, and all dimensions are based upon the English system and are therefore in feet. Once the three cavity ratios are calculated using Equation 2.1 they may be used, in conjunction with surface and cavity reflectances, to determine the CU for a given luminaire. The CU is extracted from a data table provided by the luminaire manufacturer, of which a typical example for a high-bay industrial luminaire is shown in Table 2-1.

Table 2-1: CU Table for TH-350M-A17 [16]

	Effective Floor cavity Reflectance = 20%																	
ρcce .	80				70				50			30			10			0
ρw ...	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
RCR																		
0	0.97	0.97	0.97	0.97	0.94	0.94	0.94	0.94	0.89	0.89	0.89	0.84	0.84	0.84	0.8	0.8	0.8	0.78
1	0.91	0.88	0.85	0.83	0.88	0.86	0.84	0.81	0.82	0.8	0.78	0.78	0.76	0.75	0.74	0.73	0.72	0.7
2	0.85	0.79	0.75	0.72	0.82	0.78	0.74	0.7	0.74	0.71	0.68	0.71	0.69	0.66	0.68	0.66	0.64	0.62
3	0.79	0.72	0.66	0.62	0.76	0.7	0.65	0.61	0.67	0.63	0.6	0.65	0.61	0.58	0.62	0.59	0.57	0.55
4	0.73	0.65	0.59	0.54	0.71	0.64	0.58	0.54	0.61	0.56	0.53	0.59	0.55	0.52	0.57	0.53	0.51	0.49
5	0.68	0.59	0.53	0.48	0.66	0.58	0.52	0.48	0.56	0.51	0.47	0.54	0.49	0.46	0.52	0.48	0.45	0.43
6	0.63	0.53	0.47	0.43	0.61	0.52	0.47	0.42	0.51	0.45	0.42	0.49	0.44	0.41	0.47	0.43	0.4	0.39
7	0.58	0.49	0.42	0.38	0.57	0.48	0.42	0.38	0.46	0.41	0.37	0.45	0.4	0.37	0.43	0.39	0.36	0.35
8	0.54	0.44	0.38	0.34	0.53	0.44	0.38	0.34	0.42	0.37	0.33	0.41	0.36	0.33	0.4	0.36	0.33	0.31
9	0.51	0.41	0.35	0.31	0.5	0.4	0.34	0.3	0.39	0.34	0.3	0.38	0.33	0.3	0.37	0.33	0.29	0.28
10	0.48	0.38	0.32	0.28	0.46	0.37	0.31	0.28	0.36	0.31	0.27	0.35	0.3	0.27	0.34	0.3	0.27	0.25

To determine the CU from Table 2-1 the values that are needed are the effective ceiling cavity reflectance (ρ_{cce}), the wall reflectance (ρ_w), and the room cavity ratio (RCR) which is equivalent to CR_{RC} as determined using Equation 2.1. The floor and ceiling cavity ratios (CR_{FC} and CR_{CC}) are only used in the determination of CU correction factors that are needed to compensate for variations in the floor or ceiling cavity reflectances. For the purpose of automating the design process the effective cavity reflectances may be calculated using Equation 2.2, where ‘xx’ represents the floor cavity (fc) or the ceiling cavity (cc) [6].

$$\rho_{xxe} = \left(\frac{\left[1 + \left(A_w / A_b\right)\right]^2}{\rho_b + \rho_w \left(A_w / A_b\right)} - \frac{A_w}{A_b} \right)^{-1} \qquad (2.2)$$

In Equation 2.2, if the effective floor cavity reflectance is being calculated the variable A_b is equal to the floor area (A_f), and ρ_b is equal to floor reflectance (ρ_f). Likewise, if the effective ceiling cavity reflectance is being determined the variable A_b is equal to the ceiling area (A_c), and ρ_b is equal to ceiling reflectance (ρ_c). The ratio of the wall area lying within the ceiling cavity to the ceiling area is given in Equation 2.3.

$$\frac{A_w}{A_c} = \frac{2h_{cc}\left(f_w + f_d\right)}{f_w f_d} \tag{2.3}$$

Substituting this ratio into Equation 2.2, ρ_{cce} may be determined, and since the A_c is equal to A_f in all cases, ρ_{fce} may be determined as well. As indicated in the first row of Table 2-1, the floor cavity is assumed to have an effective reflectance of 20% and the effective ceiling cavity reflectances presented are 80%, 70%, 50%, 30%, 10% and 0%, which is the global convention for CU tables. Since the table presents coefficients for a single value of floor cavity reflectance, an additional multiplication factor is introduced in the calculation of the correct CU for a given application. The specific correction factor is determined using $\rho_{cce,}$ ρ_{fce}, and $\rho_{w,}$ and is based upon the data presented in Tables 2-2, 2-3, and 2-4, which present floor cavity correction factors corresponding to values of ρ_{fce} of 30%, 10% and 0%.

Through the use of Tables 2-2, 2-3, and 2-4 along with the table containing the CU values for the particular luminaire of interest (of the form presented in Table 2-1), the appropriate CU may be determined for a given application using the following procedure:

Table 2-2: Multiplying Factors for 30% Floor Cavity Reflectance [4]

For 30% Effective Floor Cavity Reflectance																	
ρcce	80	80	80	80	70	70	70	70	50	50	50	30	30	30	10	10	10
ρw	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
RCR																	
1	1.092	1.082	1.075	1.068	1.077	1.07	1.064	1.059	1.049	1.044	1.04	1.028	1.026	1.023	1.012	1.01	1.008
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.026	1.021	1.017	1.013	1.01	1.006
3	1.07	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.02	1.024	1.017	1.012	1.014	1.009	1.005
4	1.062	1.045	1.033	1.024	1.055	1.04	1.029	1.021	1.03	1.022	1.015	1.022	1.015	1.01	1.014	1.009	1.004
5	1.056	1.038	1.026	1.018	1.05	1.034	1.024	1.015	1.027	1.018	1.012	1.02	1.013	1.008	1.014	1.009	1.004
6	1.052	1.033	1.021	1.014	1.047	1.03	1.02	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.01	1.005	1.014	1.008	1.003
8	1.044	1.026	1.015	1.009	1.04	1.024	1.015	1.007	1.02	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003
9	1.04	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.002
10	1.037	1.022	1.012	1.006	1.034	1.02	1.012	1.005	1.017	1.01	1.004	1.015	1.009	1.003	1.013	1.007	1.002

Table 2-3: Multiplying Factors for 10% Floor Cavity Reflectance [4]

For 10% Effective Floor Cavity Reflectance																	
ρcce	80	80	80	80	70	70	70	70	50	50	50	30	30	30	10	10	10
ρw	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
RCR																	
1	0.923	0.929	0.935	0.94	0.933	0.939	0.943	0.948	0.956	0.96	0.963	0.973	0.976	0.979	0.989	0.991	0.993
2	0.931	0.942	0.95	0.958	0.94	0.949	0.957	0.963	0.962	0.968	0.974	0.976	0.98	0.985	0.988	0.991	0.995
3	0.939	0.951	0.961	0.969	0.945	0.957	0.966	0.973	0.967	0.975	0.981	0.978	0.983	0.988	0.988	0.992	0.996
4	0.944	0.958	0.969	0.978	0.95	0.963	0.973	0.98	0.972	0.98	0.986	0.98	0.986	0.991	0.987	0.992	0.996
5	0.949	0.964	0.976	0.983	0.954	0.968	0.978	0.985	0.975	0.983	0.989	0.981	0.988	0.993	0.987	0.992	0.997
6	0.953	0.969	0.98	0.986	0.958	0.972	0.982	0.989	0.977	0.985	0.992	0.982	0.989	0.995	0.987	0.993	0.997
7	0.957	0.973	0.983	0.991	0.961	0.975	0.985	0.991	0.979	0.987	0.994	0.983	0.99	0.996	0.987	0.993	0.998
8	0.96	0.976	0.986	0.993	0.963	0.977	0.987	0.993	0.981	0.988	0.995	0.984	0.991	0.997	0.987	0.994	0.998
9	0.963	0.978	0.987	0.994	0.965	0.979	0.989	0.994	0.983	0.99	0.996	0.985	0.992	0.998	0.988	0.994	0.999
10	0.965	0.98	0.989	0.995	0.967	0.981	0.99	0.995	0.984	0.991	0.997	0.986	0.993	0.998	0.988	0.994	0.999

Begin with room dimensions, surface reflectances, desired mounting and work plane heights, and the CU table for the desired luminaire.

(i) Calculate the room cavity ratio (RCR).

(ii) Calculate the effective floor and ceiling cavity reflectances (ρ_{fce} and ρ_{cce}) using Equations 2.2 and 2.3.

(iii) Using the effective ceiling cavity reflectance (ρ_{cce}) and the wall reflectance (ρ_w) determine the CU for the specific luminaire using the equivalent of Table 2-1. Note that this will likely require linear regression analysis to determine the exact CU value based upon the predominantly non-ideal values of ρ_{cce} and ρ_w.

(iv) If the effective floor cavity reflectance (ρ_{fce}) is not 20% then the floor cavity correction factor is determined using tables 2-2, 2-3, and 2-4. Again linear regression is employed using the non-ideal values of ρ_{cce} and ρ_w, however there is the additional complication of regression between two values of correction factor resulting from an intermediate value of floor cavity reflectance ρ_{fce}. The correction factor for an equivalent table corresponding to an effective floor cavity reflectance of 20% would be 1.0 by definition.

(v) The CU determined in step (iii) is then multiplied by the correction factor determined in step (iv) resulting in a final CU.

Table 2-4: Multiplying Factors for 0% Floor Cavity Reflectance [4]

For 0% Effective Floor Cavity Reflectance																	
ρcce	80	80	80	80	70	70	70	70	50	50	50	30	30	30	10	10	10
ρw	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
RCR																	
1	0.859	0.87	0.879	0.886	0.873	0.884	0.893	0.901	0.916	0.923	0.929	0.948	0.954	0.96	0.979	0.983	0.987
2	0.871	0.887	0.903	0.919	0.886	0.902	0.916	0.928	0.926	0.938	0.949	0.954	0.963	0.971	0.978	0.983	0.991
3	0.882	0.904	0.915	0.942	0.898	0.918	0.934	0.947	0.936	0.95	0.964	0.958	0.969	0.979	0.976	0.984	0.993
4	0.893	0.919	0.941	0.958	0.908	0.93	0.948	0.961	0.945	0.961	0.974	0.961	0.974	0.984	0.975	0.985	0.994
5	0.903	0.931	0.953	0.969	0.914	0.939	0.958	0.97	0.951	0.967	0.98	0.964	0.977	0.988	0.975	0.985	0.995
6	0.911	0.94	0.961	0.976	0.92	0.945	0.965	0.977	0.955	0.972	0.985	0.966	0.979	0.991	0.975	0.986	0.996
7	0.917	0.947	0.967	0.981	0.924	0.95	0.97	0.982	0.959	0.975	0.988	0.968	0.981	0.993	0.975	0.987	0.997
8	0.922	0.953	0.971	0.985	0.929	0.955	0.975	0.986	0.963	0.978	0.991	0.97	0.983	0.995	0.976	0.988	0.998
9	0.928	0.958	0.975	0.988	0.933	0.959	0.98	0.989	0.966	0.98	0.993	0.971	0.985	0.996	0.976	0.988	0.998
10	0.933	0.962	0.979	0.991	0.937	0.963	0.983	0.992	0.969	0.982	0.995	0.973	0.987	0.997	0.977	0.989	0.999

2.4.2 Light Loss Factors

Once the CU has been determined for a given lighting scenario it is necessary to project those circumstances that will further alter or attenuate the amount of luminous flux that will reach the work plane surface. The Illuminating Engineering Society identifies the following items as those that contribute to what is referred to as the Total Light Loss Factor (LLF) [4].

- Luminaire Ambient Temperature (AT)
- Voltage to Luminaire (LV)
- Ballast Factor (BF)
- Luminaire Surface Depreciation (LSD)
- Room Surface Dirt Depreciation (RSDD)
- Luminaire Dirt Depreciation (LDD)
- Burnouts (LBO)
- Lamp Lumen Depreciation (LLD)

The first four items are categorized as being *non-recoverable*, meaning that conventional maintenance will not tend to improve or correct these shortcomings. The last four items however are considered to be *recoverable*, meaning that conventional maintenance can either improve or totally eradicate the negative effects of each [17]. Lamp Lumen Depreciation (LLD) and Burnouts (LBO) are corrected or improved by individual or group lamp replacement, whereas Room Surface Dirt Depreciation (RSDD) and Luminaire Dirt Depreciation (LDD) are corrected by cleaning [18]. The LLF is determined by multiplying all of the aforementioned factors together as shown in Equation 2.4.

$$LLF=AT \times LV \times BF \times LSD \times RSDD \times LBO \times LLD \times LDD \quad (2.4)$$

The loss factor due to variations in ambient temperature (AT) is primarily a concern when using fluorescent sources. Linear fluorescent lamps are optimized to produce maximum luminous flux when the bulb wall temperature is either 25ºC (T-12 lamps) or 35ºC (T-8 and T-5 lamps) [9]. Temperatures on either side of these ranges will reduce lamp output and thus reduce the illumination on the work plane. In the case of HID lamps the effects of temperature variation upon luminous output level are not noticeably significant, however with these lamps there are concerns regarding reliable ignition and material thermal limits. As a result, the AT factor would be equal to 1.0 when utilizing HID sources.

The loss factor accounting for low line voltage at the luminaire (LV) is a factor that is customarily not introduced unless low illuminance readings are discovered. A common end-user assumption is that line and branch voltages are consistent and very close to rated values when in reality these quantities may be off by more than ±5% of nominal levels. This variation can have a profound affect upon the amount of light that is produced from a luminaire when it is equipped with at line frequency (magnetic) ballast. In the case of HID luminaires equipped with conventional regulating ballasts, it is customary to anticipate a 1.5% reduction in light output for every 1% reduction in luminaire supply voltage. Therefore, if the branch circuit voltage is 5% below nominal then a 7.5% reduction in light output would not be unexpected. In the case of incandescent sources, which are not the focus of this research, the light output also drops in some cases 3% with every 1% reduction in voltage [6]. The only lighting products that are somewhat immune to this problem are those that employ electronic ballasting circuits as opposed to line frequency ballasts. Electronic ballasts are essentially switch-mode AC-to-AC converters with closed loop control and active front ends. These ballast topologies have the capability to regulate lamp output to a nearly constant level regardless of the supply voltage variation. HID luminaires employing line frequency ballasts above the 175W level it would be appropriate to enter a LV loss factor as described by Equations 2.5 and 2.6.

$$LV = 1 - \left[\left(1 - \frac{\text{Line Voltage @ Luminaire}}{\text{Rated Luminaire Voltage}}\right) \times 1.5\right] \left(\text{regulating ballast types}\right) \tag{2.5}$$

$$LV = 1 - \left[\left(1 - \frac{\text{Line Voltage @ Luminaire}}{\text{Rated Luminaire Voltage}}\right) \times 3.0\right] \left(\text{non-regulating ballast types}\right) \tag{2.6}$$

Ballast Factor (BF) is a loss factor that accounts for the inability of the lamp to operate at rated power levels due to either ballast design or functional mismatches between the ballast and the lamp. In the former case this factor compensates for ballasts that fall outside the window of what would be considered nominal. This does not mean that these ballasts do not meet the functional and compatibility requirements set forth by the American National Standards Institute (ANSI), but it does mean that the lamp will not operate at rated power and therefore will not generate the anticipated amount of luminous flux [19]. Ballasts and lamps are analog circuit elements that suffer from the same manufacturing inconsistencies as other devices. Variations in lamp characteristics and ballasts parameter tolerances are commonplace, and as a result it is not the norm for a lamp to operate at rated power. For this reason there are acceptable windows of operation to which lighting systems are held, and in an idealistic sense one would expect that some systems would operate above rated levels which would offset those that operate at a less that rated level. Unfortunately, for both the lighting designer and the customer, the norm is that the majority of HID lighting systems operate below rated power levels thus moving the mean of the distribution below rated output. The BF multiplier accounts for the effect of this shift upon overall light levels. Common ballast factors for non-electronic lighting systems are in the range of 0.9 to 0.95, where electronic fluorescent systems in some cases tout ballast factors well above 1.0.

The LSD factor represents the degradation of the materials used in the construction of the luminaire. It includes the discoloring (yellowing) of plastics and the degradation of surface finishes. This factor, although acknowledged in the lighting community, has no published value [6].

Luminaire Dirt Depreciation (LDD) and Room Surface Dirt Depreciation (RSDD) have been quantified in the form of tables that are presented by the IESNA. The process is simplified however by the use of Equation 2.7 to determine the percent dirt depreciation and then using this value, along with knowledge of the luminaire distribution type, to determine the LDD and RSDD [6].

$$\%\,\text{Dirt Depreciation} = 100(1 - e^{-At^{B}}) \qquad (2.7)$$

The values of A and B are listed in Table 2-5 where the luminaire distribution type refers to the categorization of how the luminous flux is distributed or delivered from the luminaire. The distribution types (classifications) are direct, semi-direct, direct-indirect, semi-indirect and indirect. Referring to Equation 2.7 and Table 2-5, the values of A and B are functions of not only the luminaire maintenance category, but also of the relative cleanliness of the environment.

Since this research concentrates on the industrial case, the values of A and B used in the determination of LDD will always be based upon maintenance category III. Maintenance categories are published by the luminaire manufacturers and are a function of whether or not the luminaire is enclosed, the type of optical assembly, and the amounts of upward and downward lumens [6]. The direct effect of dirt upon the luminaire optical assembly (LDD) is determined through the use of Equation 2.8 where the values of A and B are retrieved from Table 2-5 (cat. III).

$$LDD = e^{-At^{B}} \tag{2.8}$$

For a category III luminaire the value of B is always taken to be 0.70, where the value of A is dependent upon the relative cleanliness of the environment. It should be noted that there are assumed to be no changes in the light distribution of a luminaire based upon the deposition of dirt, only a reduction in overall output [20].

Table 2-5: Constants for Use in Determining RSDD and LDD (Cat. III and V) [6]

Luminaire Maintenance Category	B	A				
		Very Clean	Clean	Medium	Dirty	Very Dirty
III	0.70	0.079	0.106	0.143	0.184	0.236
V	0.53	0.078	0.128	0.190	0.249	0.321

Studies have shown that the parameters (A and B) used in the determination of RSDD are consistent with those of maintenance category V [6]. With the amount of dirt depreciation calculated using Equation 2.7 and the applicable values from Table 2-5, an additional table is used in the determination of the RSDD. Table 2-6 presents the RSDD values for varying room cavity ratios and dirt depreciation percentages. Note that these values are applicable for luminaires of the direct distribution variety which are the only ones being considered in this dissertation.

Table 2-6: RSDD Values for Direct Luminaire Classification [6]

% Dirt Depreciation	10	20	30	40
RCR				
1	98	96	94	92
2	98	96	94	92
3	98	95	93	90
5	97	94	91	89
7	97	94	90	87
10	96	92	87	83

It should be mentioned that cleaning a dirty luminaire will not completely restore its initial optical performance. Studies have been performed determine the amount of LDD that cannot be recovered, however a universal method for projecting this quantity has not been established [20]. Consistent with other lighting design protocols, this non-recoverable element of LDD is not considered in this research.

The loss factor attributed to lamp failures is referred to as simply lamp burnout (LBO). Lamp replacement strategies fall into one of two categories: group relamping and spot relamping, each of which has varied effects upon the performance of the lighting application. Group relamping is typically performed at some point after the lamps have reached their rated service life, or when a boost in overall light levels is desired. Spot relamping refers to ongoing maintenance of the lighting installation to prevent illumination levels in a specific area from falling below acceptable levels. The LBO factor refers to those lumens lost in the overall lighting application that are only recovered when relamping is performed. It is customary to use the formula shown as Equation 2.9 when determining this quantity.

$$\text{LBO} = \frac{\text{Total \# of Lamps - \# of Acceptable Failures}}{\text{Total \# of Lamps}} \qquad (2.9)$$

The quantity calculated using Equation 2.9 is a simple ratio that expresses the minimum percentage of functioning lamps that is acceptable before spot relamping is performed.

The final loss factor is Lamp Lumen Depreciation (LLD), also referred to as Lumen Maintenance. This quantity is an indication of the expected reduction in luminous flux generated by a lamp over its operating life. Different source families (MH, HPS, fluorescent, etc.) exhibit different values of LLD as often do different power levels within the specific family group. Although lamp manufacturer's monitor the performance of their products, the LLD values that they publish for a given product are approximations based upon historical data. In fact, the lumen depreciation of a specific source falls within a band of acceptability which broadens with time, however a single value of depreciation is generally published which is intended to represent the overall mean of the performance of the production group. There are often two quantities published by lamp manufacturers relating to the depreciation of luminous output over time. The first is the mean lumen factor, which is the factor of interest in this research, is the percent of rated lumens that should be expected once 40% (MH) or 50% (HPS) of rated operating life is reached. This factor is primarily used in lighting design and economic studies [6]. The second value is the LLD is the percent of the rated lumens that should be anticipated at 70% of rated life, which is chosen because that is considered to be one of the standard points where group relamping should be performed [21].

When all of these factors are represented as functions with respect to time their effect upon lighting levels may be further explored. Figure 2-1 illustrates the effects of certain loss factors upon illumination levels over time. In this representation the LV, BF, AT and LSD factors are assumed to be unity so as to not overcomplicate the figure. This example is based upon a group lamp replacement occurring every 18 months with luminaire cleaning occurring at the same time. The area is cleaned every nine months which gives rise to the incremental improvement in LLF at months 9 and 27.

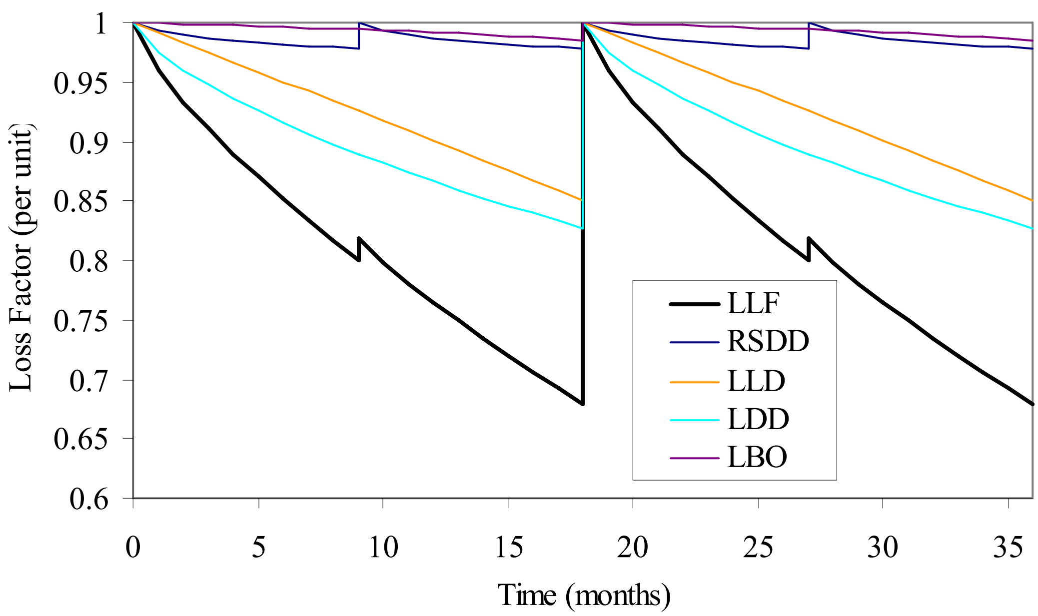


Figure 2-1: Effect of Loss Factors upon Illumination Levels

2.4.3 Luminaire Requirement (Quantity)

Upon determining the CU and minimum LLF values, the minimum number of luminaires required to provide the desired level of illumination may be determined. The formula for determining this quantity is shown in Equation 2.10 [5].

$$N = \#\text{of Luminaires} = \frac{A_{wp} \times E_{wp}}{\Phi_L \times CU \times LLF} \tag{2.10}$$

Referring to Equation 2.10, A_{wp} is the area of the work plane in square feet, E_{wp} is the desired level of illumination in footcandles, and Φ_L is the initial lamp output rating in lumens. It should be noted that if the luminaire being employed has more than one lamp, as would be the case in many fluorescent luminaires, then the calculation is performed using Equation 2.11.

$$N = \#\text{of Luminaires} = \frac{A_{wp} \times E_{wp}}{\Phi_L \times (\#\text{ lamps/luminaire}) \times CU \times LLF} \tag{2.11}$$

The quantity of luminaires needed to illuminate the target area (work plane) is reasonably approximated using the Lumen Method by way of Equation 2.10 or 2.11, however the strategy to implement the design has yet to be finalized.

2.4.4 Luminaire Mounting Configuration (Layout)

At this stage, based upon the goals of the lighting application it has been determined that a minimum quantity of specific lighting products will be employed using the lumen method. The mounting height is known based upon its need for use when determining the CU. The mounting height is defined as the distance that the luminaire optical aperture is located above the floor (i.e. the distance from the floor to the bottom of the luminaire optical assembly). The next decision to be made concerns the mounting configuration of the luminaires to achieve acceptable levels of uniformity based upon the defined mounting height, room dimensions, and luminaire quantity. The goal of the arrangement of the luminaires is typically not only to achieve the required amount of illuminance upon the work plane, but to also meet some criteria for the uniformity of this illumination. Commonly this criterion is a ratio of the maximum level of illuminance that is recorded at any point on the work plane to the minimum level recorded at any point, which is generally termed the *Max to Min Ratio*. An average level to minimum level ratio is sometimes employed as well. Perfect uniformity is not achievable, however if the maximum and minimum values of illumination in the room are not more or less than one sixth that of the mean (min to max ratio of 1.4), then the uniformity is generally considered acceptable [4]. For an industrial lighting layout, as well as many other indoor applications, a rectangular configuration is routinely employed. This allows for the maintaining of equal spacing between luminaires which is desirable when trying to reduce the max to min ratio. A layout similar to that being discussed is shown in Figure 2-2.

In this example layout the horizontal and vertical spacings, S_1 and S_2 respectively, may be of equal magnitude. If it is assumed that S_1 and S_2 will be of equal magnitude, then an approximate spacing for a given target area is shown in Equation 2.12 [7].

$$S_{approx} = \sqrt{\frac{A_{wp}}{N}} = \sqrt{\frac{f_w \times f_d}{N}} \tag{2.12}$$

In Equation 2.12, A_{wp} is the area of the room (square feet) and N is the number of luminaires that are to be mounted. The spacing from the outer luminaires to the walls, denoted as S_W, is typically one-third that of the luminaire to luminaire spacing [4]. If S_W is too great the outermost areas of the space may be under-illuminated, however if it is too small an effect referred to as "scalloping" would be more pronounced. Although scalloping is not a functional problem it is considered by many end users to be undesirable. It should be noted that these spacings are intended to be starting points, which is where the design process begins to stray from the objective to the subjective.

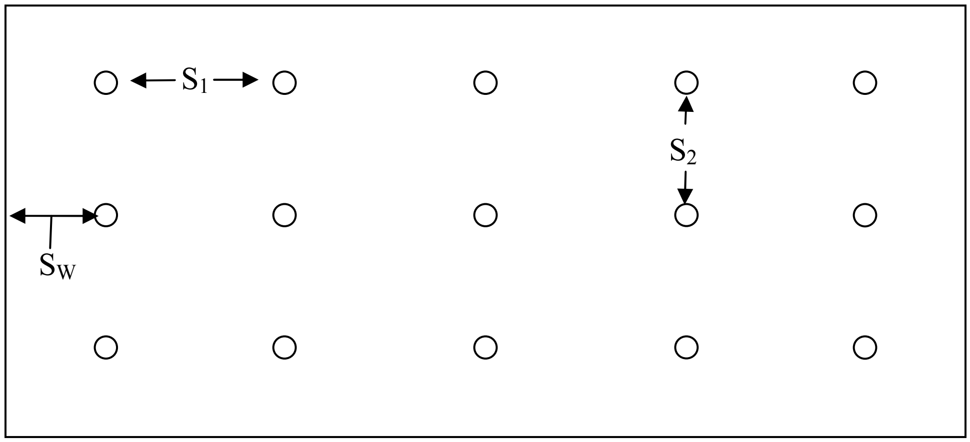


Figure 2-2: Example Luminaire Layout for Rectangular Application

As it pertains to the application of lighting, the discussion of the artistic design element normally arises - the artistic aspect of the design being the placement of luminaires to achieve a desired aesthetic. As stated previously, in industrial applications the goal is to place sufficient quantities of light upon the work plane as well as maintaining some acceptable level of uniformity. To achieve this end the designer typically begins with an initial spacing, such as the one determined from equation 2.12, and then proceeds to alter luminaire placements to achieve the desired lighting uniformity. For a rectangular workspace it is normal for there to be a mounting arrangement that is proportional to the room dimensions. For example, if a room is 50 feet wide and 80 feet deep, it is common that the ratio of rows to columns is 80 divided by 50, or 1.6. The shortcoming of this approach is that it often leads the designer to employ more luminaires than are required per Equation 2.11 to achieve layout symmetry. In the 50 foot by 80 foot example the designer may opt to use 40 luminaires at a spacing of approximately 10 feet, however the quantity of luminaires required to sufficiently illuminate the space as determined by Equation

2.10 may be only 36. The obvious issues associated with using more luminaires than the application requires are higher installation, operating, and maintenance costs in addition to the wasting of energy.

A final topic of importance with regard to luminaire layout is the *spacing criterion*. This is a specification that is a refinement of the older *spacing to mounting height ratio* for predicting acceptable uniformity of illumination [7]. This value is typically included with the photometric report and is used as a quality check for the lighting designer. If the spacing at a given mounting height is too great for a specific luminaire type, an inadequate overlapping of the luminous beam patterns emitted from the luminaire optical assemblies will result. Alternatively, this may also be viewed as a luminaire being mounted too closely to the work plane which will again cause an inadequate blending of luminous flux. In either case, the evaluation of this criterion may indicate that the luminaire chosen is not suitable for a given application at a specific mounting height. As a further illustration of this refer to Figure 2-3.

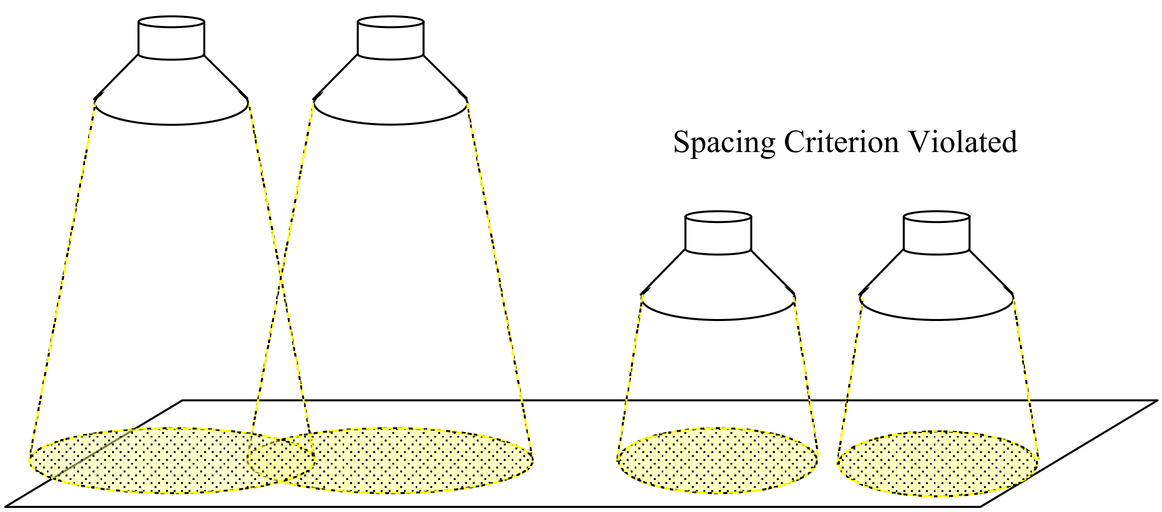


Figure 2-3: Illustration of Spacing Criterion Violation

2.5 Lighting System Costs

It has become common practice to evaluate the value of a lighting system based upon simple payback criteria [22]. This method of financial analysis determines the savings per year of a new lighting project relative to an existing or other reference lighting project with the same performance specifications. It is often the case that the savings per year is based upon improved lighting system efficacy and possibly some contribution from reduced maintenance expenses. If the projected savings per year offsets the initial cost to acquire and install the proposed lighting system over an acceptable period of time (i.e. return on investment), then the lighting design may be considered for implementation. The shortcoming of this method is that it does not consider the true cost of the lighting system over the lifespan of the project, which should include the effects of return and inflationary factors. A more complete set cost criteria used in selecting a system include the available budget, initial system cost, projected LCC, and the dollar value benefits to the customer [23]. This research assumes that available funds are not limited and that intangible customer benefits should not be used as a basis for economic decisions. In other words the methods presented in this document do not weight lighting system designs based upon user preferences. If the user objects to the color of certain HID sources, then luminaires equipped with those sources should be omitted from the design process.

Regardless of the type of lighting system that is employed, the total cost may be separated into the following categories:

- Acquisition and Installation Cost
- Operating Cost
- Maintenance Cost
- Disposal Cost

Acquisition and Installation Cost is simply the cost of luminaires and lamps as well as the labor and extra materials required for installation of the lighting system. The Operating Cost over the life of the project is simply the cost of the energy to power the luminaires as well as the additional HVAC operating cost needed to offset the heat generated by the lighting system. A general rule that is employed in this analysis is that three watts of lighting requires one watt of HVAC capacity [24]. Maintenance Cost is the cost to re-lamp and clean all of the luminaires. Luminaires normally have no salvage value and therefore the final cost or Disposal Cost is simply the dollar amount required to remove and dispose of all lighting materials at the end of the project.

Figure 2-4 presents a chart representing the total cost of ownership over a four year period of an individual 400W MH luminaire used in an industrial application. The facility operates 24 hours per day – 365 days per year. This example lighting project is based upon the following assumptions and is not corrected for inflation or rate of return.

- Luminaire and lamp cost is $70
- Installation cost is $20
- Maintenance cost is $40
- Annual operating cost is $326
- Additional HVAC annual operating cost of $109 (one-third of operating cost)

The aggregate of these costs over the period demonstrates that the cost of ownership is primarily composed of the cost of energy, which in this case is 93% of the total cost. Figure 2-5 presents a breakdown of the costs over the four year period.

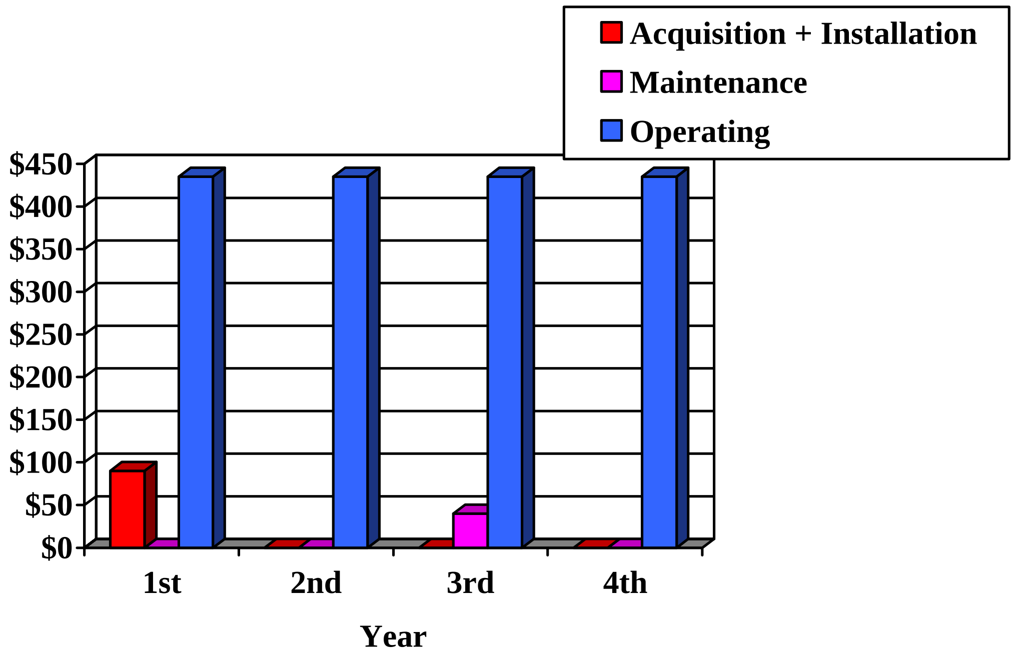


Figure 2-4: Example Lighting Project - Individual Luminaire Annual Costs

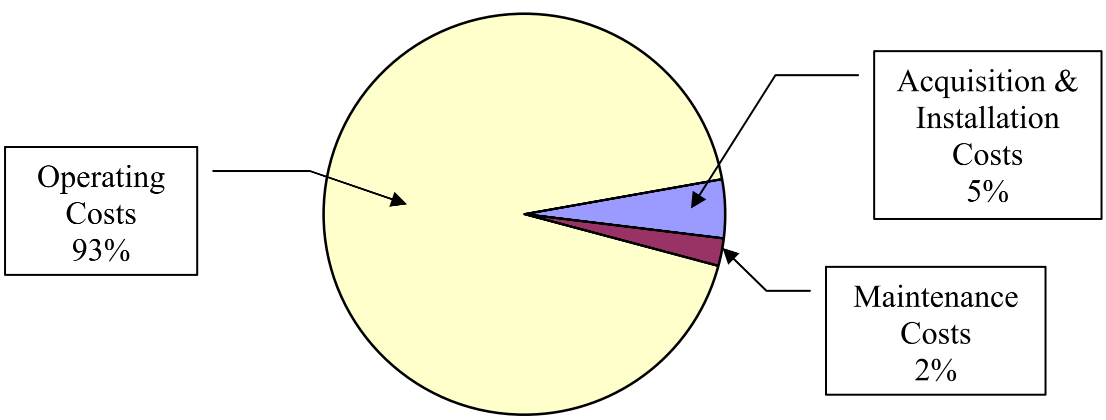


Figure 2-5: Example Lighting Project - Single Luminaire Aggregate Costs of Over 4–Year Period

2.5.1 Life-Cycle Costing

Life-Cycle Costing is a financial analysis strategy for determining the overall cost associated with a complex system [25]. This overall analysis uses all cash flow events, annual rates of return, and inflation rates to determine a single present or an equivalent annualized cost for a project. Figure 2-6 presents a cash flow diagram of an arbitrary lighting project that may be used to illustrate the process of determining life-cycle cost (LCC). An equivalent present day cost may be determined by using the rules governing the time value of money to convert all of the annual operating, maintenance, and scrap expenses to lump sum amounts in year zero and add these values to the expense of acquisition and installation. In this illustration the resulting total cost is the present day LCC of the project over a projected project life of twenty years.

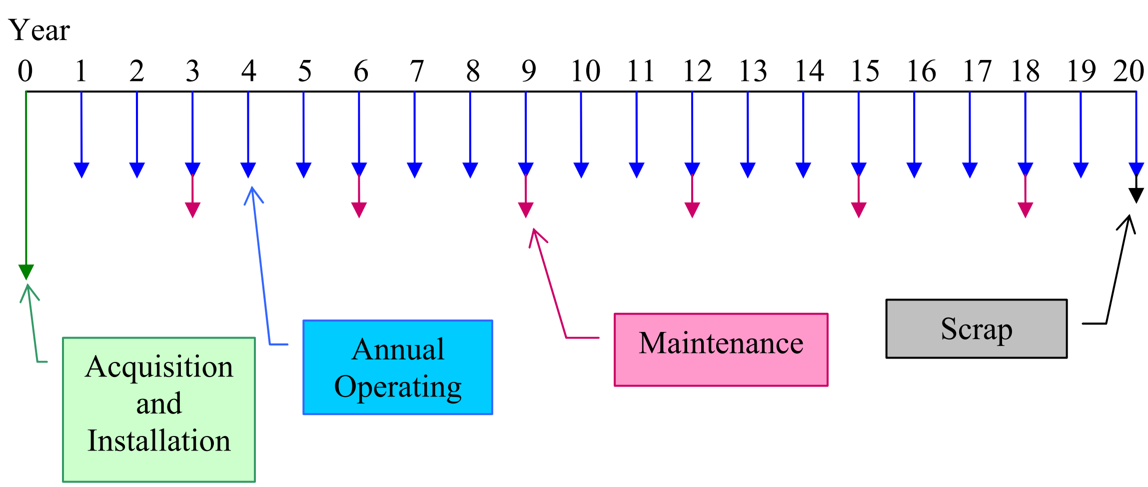


Figure 2-6: Lighting System Cash Flow Diagram

The financial formulae required for analysis of a lighting system are those used to determine the uniform present worth (UPW) and single present worth (SPW) factors. These factors are defined by Equations 2-13 and 2-14 where **i** is the annual rate of return [25].

$$UPW = (P/A, i, n) = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (2.13)$$

$$SPW = (P/F, i, n) = \frac{1}{(1 + i)^n} \quad (2.14)$$

However, to include the effects of inflation an effective or "real" interest rate is needed which considers the increasing cost of energy. The effective interest rate (k) is determined using Equation 2.15 considering the annual rate of inflation (g) [26].

$$k = \left(\frac{1+ i}{1+ g}\right) - 1 = \frac{(i - g)}{(1+g)} \quad (2.15)$$

Substituting the effective interest rate for the interest rate in either the UPW or SPW formulae, the effects of inflation are also included in the resulting year zero cost projections.

2.6 Lighting and the Environment

The impact of discharge lighting upon the environment extends from the effects resulting from the generation of electrical energy to the disposal of hazardous materials. As a result no analysis of lighting maintenance and energy usage should be made without addressing the environmental implications.

2.6.1 Greenhouse Gas Emissions

One of the fundamental topics pertaining to the relationship between electrical energy and the environment is the emission of greenhouse gasses and their contributions to global warming. Of all the greenhouse gasses, carbon dioxide (CO_2) is the compound that most contributes to the increase in global warming via the greenhouse effect. This material, which has been estimated to have contributed to 66% of global warming over the period 1880 to 1980, is a naturally occurring by-product of animal respiration; however it is in the generation and conversion of energy that has created dramatic increases in CO_2 concentration levels in the years since the industrial revolution [27]. Between 1990 and 2006 there has been an estimated domestic increase in CO_2 emissions of 18.0% from all sources [28]. Of the CO_2 emissions contributed by the United States, approximately 41% are directly attributed to the combustion of fossil fuels for the generation of electric power, which is up from 38.3% of the total in 1990 [28]. In the short term, to reduce the growth of CO_2 emissions from industrialized nations it is imperative that energy usage be reduced which, as mentioned previously, will prolong the planet's fossil fuel reserves and retard the emission and build-up of greenhouse gasses. The amount of CO_2 created as a result of the generation of electrical energy has been quantified as 7.78×10^{-4} metric tons per kilowatt-hour and is referred to as the eGRID non-baseload national average emissions rate [29].

As stated previously, artificial lighting is responsible for consuming approximately 22% of the electrical energy generated in the United States, second only to the amount of energy consumed by electric machinery [1]. If less lighting energy is wasted, then it follows that energy demand should fall based upon consistent user requirements. Generally speaking, wasted lighting energy is defined as that electrical energy that is consumed by the lighting system which is not converted into visible energy. Unfortunately, the more efficient the lighting system in converting electrical energy to visible energy, in general, the greater the acquisition cost. As a result, the relationship between acquisition cost and performance is a major obstacle in an effort to convince users to install more efficient lighting equipment.

2.6.2 Mercury Emissions and Disposal

The vast majority of discharge lamps, both low-pressure and high-pressure, contain varying amounts of mercury. This naturally occurring element has long been known to cause health problems, specifically mercury pneumonitis, in humans who encounter the vaporized form of the material in sufficient quantities for extended periods of time [30]. This is the primary reason for the classification of many lamps as universal waste, which must be handled and disposed of under stricter guidelines than conventional waste materials. In addition to the mercury that is directly attributed to discharge lamps (lamp content), there is the quantity which is released into the environment through the combustion of fossil fuels to supply the energy for lighting system operation. Through an analysis of varying forms of fossil fuels it was estimated that 54 nanograms of mercury is released in vapor form for every watt-hour of electrical energy that is generated [30]. This quantity of material must be included in any analysis of the contribution made by artificial lighting to the planet's environmental state.

3 Development of Model and Software Tools for HID Industrial Lighting Design

3.1 Design Strategy

In order to curtail the consumption of energy and LCC for a lighting project, a set of programs have been developed to determine the most efficient lighting design for an arbitrary industrial lighting application. The application in this case is treated as a general area lighting problem which allows for the exclusion of physical obstructions. The design algorithm presented is based upon the calculation of average illuminance, previously presented in Chapter 2, which is the calculation of the number of luminaires required to provide a sufficient amount luminous flux to illuminate a specified area to a prescribed level. This is accomplished by the determination and application of a quantity known as the Coefficient of Utilization (CU), which is defined as the ratio of the luminous flux (lumens) delivered from a luminaire received on the work plane to the lumens emitted by the luminaire's lamp(s) alone [4]. This makes the CU for a given luminaire a function of the luminaire efficiency as well as external factors such as the physical characteristics of the space to be illuminated; more specifically the luminaire mounting height and surface reflectances of the walls, floor and ceiling. The development of equations and algorithms which are considered to be original contributions are described in this chapter, whereas a discussion of the creation and interaction of all software tools developed to support this research is presented in Appendix A. A diagram illustrating the differences between the standard industrial lighting design strategy and the design strategy developed as part of this research is presented in Figure 3-1. The fields which are yellow indicate design elements which are shared by both design strategies. The fields which are green indicate changes that have been introduced to support the study of industrial lighting system efficiency and life-cycle cost, as well as the successful layout of all designs that are created.

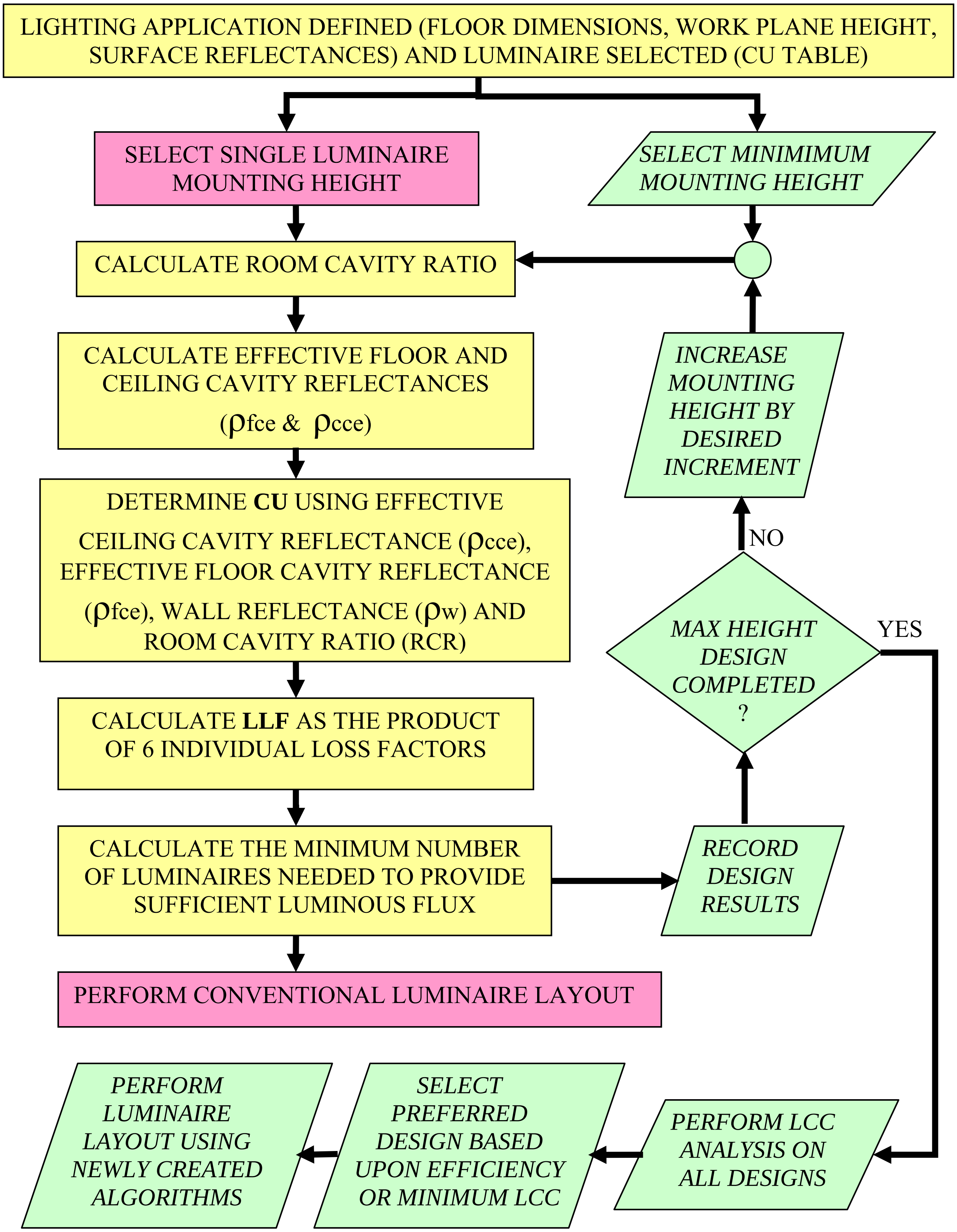


Figure 3-1: Industrial Lighting Design Strategy Comparison

3.2 Lamp Mortality and Lamp Lumen Depreciation

The lamp mortality (LBO) equation given in Equation 2.9 was deemed to be unsatisfactory for the purpose of this research. This equation is based upon the number of acceptable outages which the user is willing to tolerate before lamp replacements are performed. In actuality, lamp failure rates are a matter of record and the number of anticipated outages prior to group relamping may be predicted using lamp manufacturers published mortality data [31] [32]. The published mortality data for both MH and HPS lamp families were manually transferred to a spreadsheet for the purpose of performing regression analysis resulting in equations which would be suitable for use by the software. Figure 3-2 shows a MH lamp family mortality characteristic. The data points extracted from the published data are shown as circles, and the solid curve is the third order polynomial equation used by the software to calculate the LBO factor used in the determination of the overall light loss factor (LLF). Equation 3.1 is used by the developed software for all designs employing MH lamps, where *y* is percent of lamps surviving and *x* is the percent of rated lamp life.

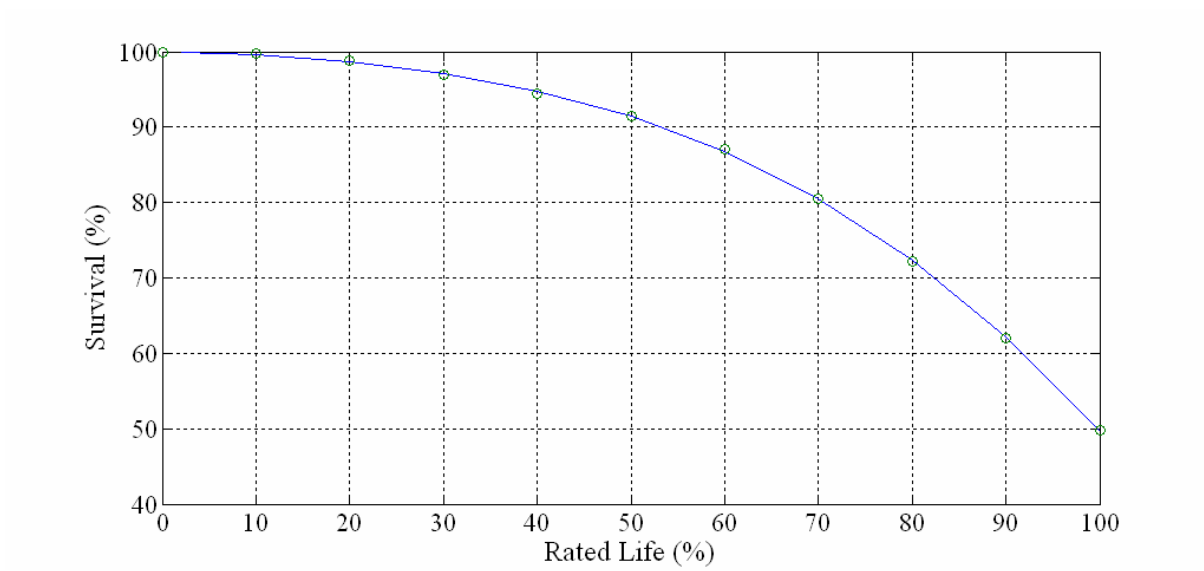


Figure 3-2: Typical Metal-Halide Lamp Mortality Characteristic Data (O) and Third Order Polynomial Regression [31]

$$y = \left(-4.1472 \times 10^{-5}\right) x^3 + \left(-3.9627 \times 10^{-4}\right) x^2 + \left(-5.0282 \times 10^{-2}\right) x + 100 \qquad (3.1)$$

For all HPS sources, Equation 3.2 is the mortality equation used where Figure 3-3 illustrates the comparable mortality characteristic.

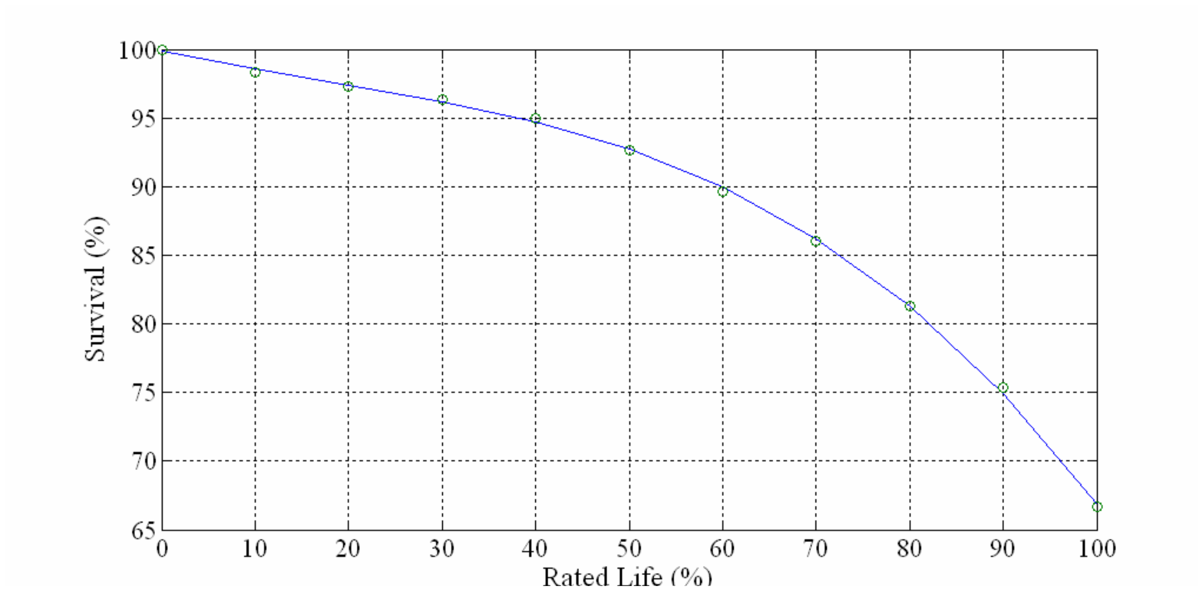


Figure 3-3 Typical High-Pressure Sodium Lamp Mortality Characteristic Data (O) and Third Order Polynomial Regression [32]

$$y = \left(-3.8401 \times 10^{-5}\right) x^3 + \left(2.0381 \times 10^{-3}\right) x^2 + \left(-1.4984 \times 10^{-1}\right) x + 100 \qquad (3.2)$$

Using the number of operating hours per month, and dividing this value by the rated lamp life, a monthly lamp life reduction is determined and substituted for *x* in Equations 3.1 and 3.2. This allows for the generation of an array depicting the progression of lamp failures throughout the life-cycle of a lighting project.

For the purposes of this research LLD is projected to be a linear or piecewise linear function. LLD curves are published for all HID lamps, and these curves generally take on a decaying exponential characteristic. Some of these published LLD characteristics are in the form of ranges as shown in Figure 3-4 to account for variability in lamp performance.

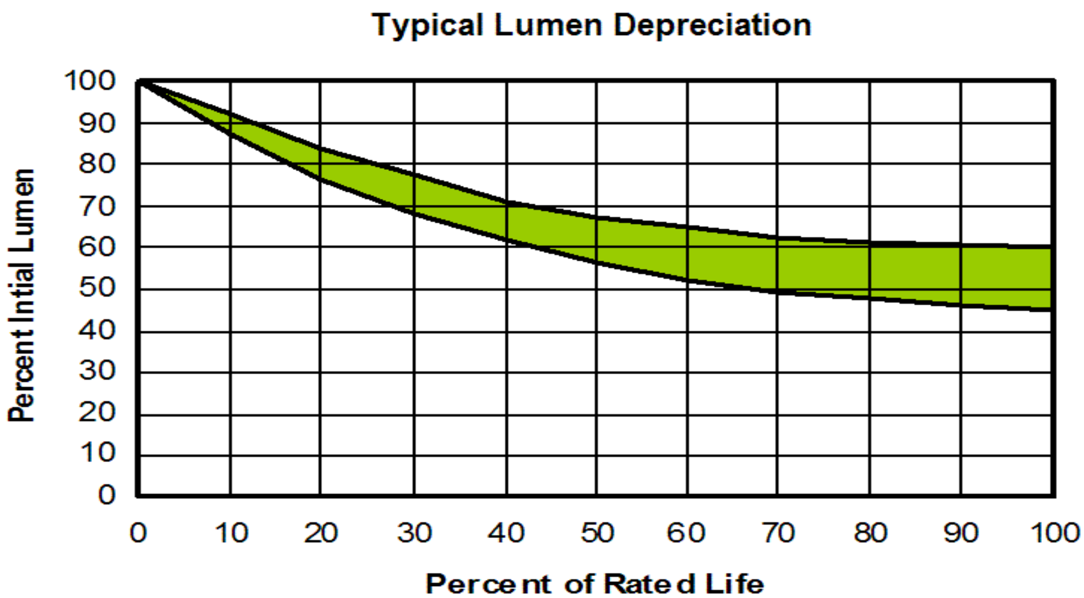


Figure 3-4: Example LLD Characteristic for Metal-Halide Lamps [33]

Lamp performance data recorded at the Rector Field House located on the main campus of Virginia Tech yielded the LLD results presented in Figure 3-5 [2]. The results of this study indicate that the use of MR ballasts to operate MH lamps does promote improved lumen maintenance. It was concluded that this improvement in LLD results from a lower lamp current crest factor relative to that which is present when CWA ballasts are employed. Lamp current crest factor being the ratio of the peak lamp current level measured on a half-cycle basis to the root-mean-squared (RMS) lamp current level. The data recorded for this study serves as a basis for the LLD characteristic employed by the developed software in those applications where MR ballasts are used in conjunction with MH lamps.

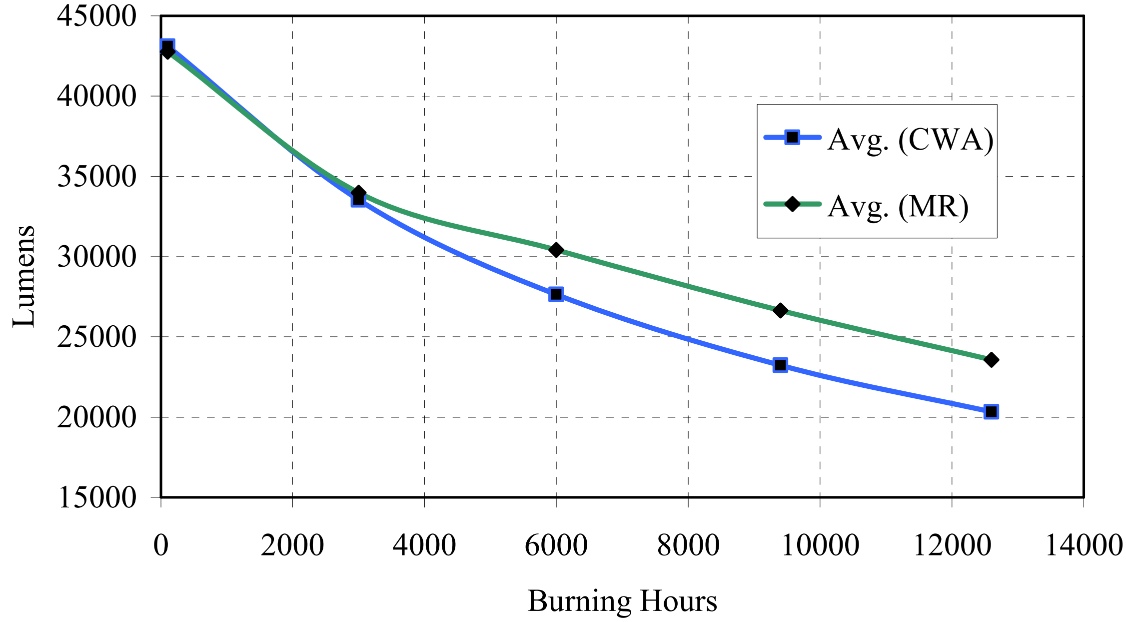


Figure 3-5: Lumen Depreciation of 400W M.H. Lamps – Rector Field House [2]

This LLD data presented in Figure 3-5 loosely supports the published data, however over isolated periods the depreciation characteristic appears to be more linear than exponential, especially noted in the case where the magnetically regulating (MR) ballasts were employed. Given this nearly piecewise linear characteristic for LLD and the allowable range of LLD performance as illustrated in Figure 3-4, the method employed for projecting this factor is one of linear regression. Referring to Figure 3-6, the initial lumens, mean lumens, and rated lamp life are shown in a simplified linear relationship. The mean lumen point relative to rated lamp life depends upon the lamp family – 40% for MH and 50% for HPS [32]. Figure 3-7 illustrates the LLD characteristic employed by the software. Initial lumens, mean lumens, and lamp life are all quantities which are published by the manufacturer of the lamp in question.

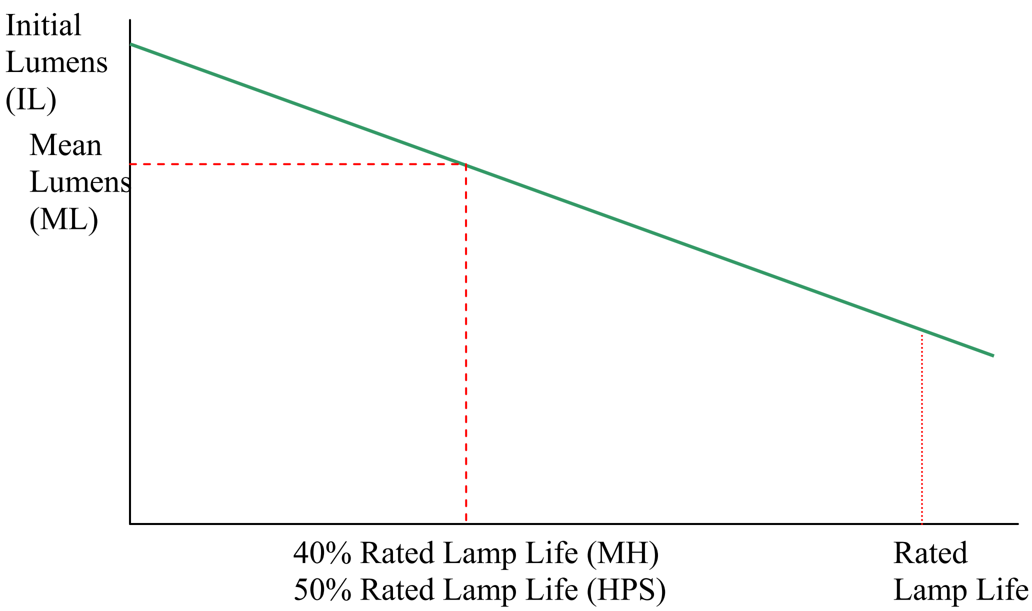


Figure 3-6: Linear LLD Characteristic

An equation relating these quantities to lamp operating hours is developed by the normalization of this plot which is shown in Figure 3-7. The slope of the normalized linear characteristic is given by either Equation 3.3 or Equation 3.4, depending upon the lamp family of interest.

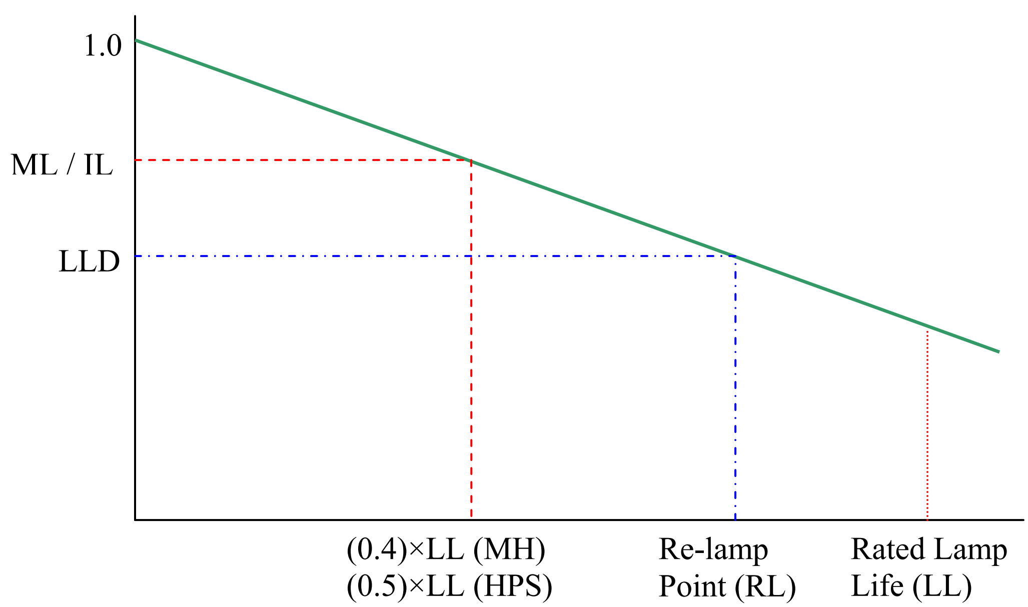


Figure 3-7: Illustration for the Development of LLD Equation

$$\text{Slope} = \left(\frac{\text{ML}}{\text{IL}} - 1.0\right) \Big/ (0.4 \times \text{LL}) \qquad \text{MH} \tag{3.3}$$

$$\text{Slope} = \left(\frac{\text{ML}}{\text{IL}} - 1.0\right) \Big/ (0.5 \times \text{LL}) \qquad \text{HPS} \tag{3.4}$$

The LLD factor is simply the magnitude of the slope multiplied by the planned number of operating hours prior to group re-lamping as shown in Equation 3.5.

$$\text{LLD} = \left| \left(\frac{\text{ML}}{\text{IL}} - 1.0\right) \times \text{RL} \Big/ (\mathit{dfact} \times \text{LL}) \right| \tag{3.5}$$

In the above equation the re-lamping point (RL) is in hours, and the mean lumen factor (*dfact*) in the case of MH sources is 0.4, and in the case of HPS sources it is assigned a value of 0.5. For the purpose of generating an array corresponding to the running reduction of lamp output on a monthly basis, a running total of operating hours is substituted for the variable RL. If the LLD is plotted over time the result is a sawtooth characteristic resulting from the lamps being replaced on a group basis over the life of the project.

In cases where magnetically regulating ballasts are used, data acquired at the Rector Field House indicates that an improvement in LLD is realized over that of lamps operated with constant wattage autotransformer (CWA) ballasts [2]. Using this data the projected improvement in LLD may be approximated by increasing the original characteristic, presented in Figure 3-7, on a piecewise linear basis as illustrated in Figure 3-8.

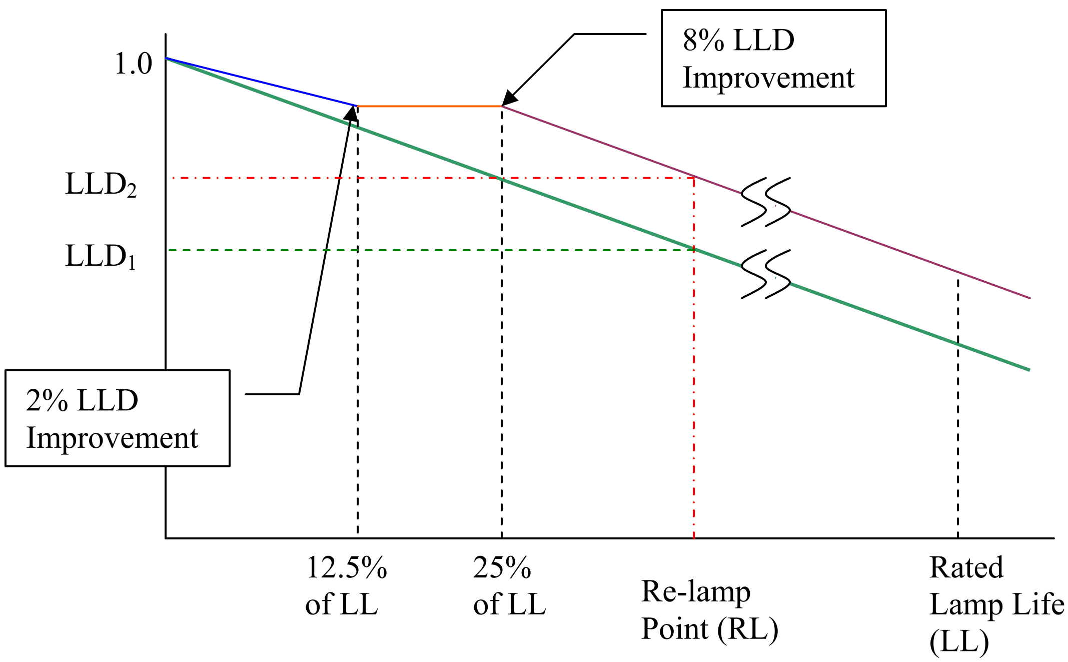


Figure 3-8: LLD Improvement using Magnetically Regulating Ballasts

The process of determining the LLD improvement is performed by adding the appropriate percentage over the three lamp life domains; 0 to 12.5%, 12.5+% to 25%, and 25+%. The equations used are given as Equation 3.6, Equation 3.7 and Equation 3.8.

$$LLD_2 = LLD_1 + \left(\frac{RL \times 0.02}{0.125 \times LL}\right) \quad \left[0 < RL < (0.125)LL\right] \tag{3.6}$$

$$LLD_2 = LLD_1 + 0.02 + \left(\frac{(RL - 0.125 \times LL) \times 0.06}{0.125 \times LL}\right)\left[(0.125)LL < RL < (0.25)LL\right] \tag{3.7}$$

$$LLD_2 = LLD_1 + 0.08 \quad \left[RL > (0.25)LL\right] \tag{3.8}$$

3.3 Industrial Lighting Life-Cycle Cost Analysis

Section 2.5 presented the topic of life-cycle costing (LCC). Using the quantities resulting from Equations 2.13, 2.14, and 2.15, a program has been developed that calculates the present worth (year 0) life-cycle costs for a lighting installation. This LCC is the summation of the present worth costs associated with acquisition and installation (*PWAI*), operating (*PWOPER*), maintenance (*PWMAIN*), and disposal (*PWDISP*) of the lighting system.

Equation 3.9 is used to determine the present worth of the acquisition and installation costs associated with an industrial lighting project. This cost is based upon the number of luminaires (*nol*), the individual luminaire cost (*lumcost*), the individual lamp cost (*lmpcost*), the additional installation material cost on a per unit basis (*admat*), the time in hours needed to install an individual luminaire (*insttime*), and the hourly labor rate associated with the installation of an individual luminaire (*instcost*).

$$PWAI = \left(lumcost + lmpcost + admat + \left(insttime \times instcost\right)\right) \times nol \qquad (3.9)$$

Utilizing the effective interest rate (k), which is determined using Equation 2.15, the present worth of the operating expenses may be determined using Equation 3.13. Equations 3.10 through 3.12 define the intermediate variables which are used in Equation 3.13.

$$yrlumnrg = \left(\frac{nol \times lumpwer}{1000}\right) \times \left(hrspwk \times 52\right) \qquad (3.10)$$

$$yrhvacnrg = \frac{yrlumnrg}{hvacfctr} \qquad (3.11)$$

$$upw = \frac{(1+k)^{prjlife} - 1}{k \times (1+k)^{prjlife}} \qquad (3.12)$$

$$PWOPER = (yrlumnrg + yrhvacnrg) \times nrgcost \times upw \qquad (3.13)$$

Equation 3.14 is used to determine the base cost of performing maintenance (*mbase*) which includes luminaire re-lamping and cleaning for the entire installation.

$$mbase = nol \times (lmpcost + (mntcost \times mnttime) + dspcost + clnmatl) \qquad (3.14)$$

Since maintenance costs associated with HID lighting systems are typically not incurred on an annual basis, the present value formula must be modified to reflect the desired time interval using the annual interest and inflation rates. Considering a hypothetical 3 year maintenance interval over a 20 year service life, the present value of the maintenance expense would be the inflated maintenance costs in years 3, 6, 9, 12, 15, and 18, all of which are moved (projected) back to year 0 using the single present worth factor (SPW) given in Equation 2.14. As a result, the present worth of the maintenance expenses (*PWMAIN*), shown in Equation 3.15, considering the current annual interest rate (i) would be the summation of the costs incurred in the years previously mentioned.

$$\begin{aligned} PWMAIN = {} & mbase_3(\text{P/F, i, 3}) + mbase_6(\text{P/F, i, 6}) + mbase_9(\text{P/F, i, 9}) + \\ & mbase_{12}(\text{P/F, i, 12}) + mbase_{15}(\text{P/F, i, 15}) + mbase_{18}(\text{P/F, i, 18}) \end{aligned} \qquad (3.15)$$

Considering the inflation of wages and materials, the maintenance costs $mbase_3$, $mbase_6$, etc. can be related to the base maintenance cost (*mbase*) using an inflation factor $(1+g)^n$, where g is the annual rate of inflation. This substitution results in a modified equation for *PWMAIN* as given in Equation 3.16 where *ry* is the maintenance cycle time in years.

$$PWMAIN = mbase\left[\left(\frac{1+g}{1+i}\right)^{ry} + \left(\frac{1+g}{1+i}\right)^{2ry} + \left(\frac{1+g}{1+i}\right)^{3ry} + \left(\frac{1+g}{1+i}\right)^{4ry} + \left(\frac{1+g}{1+i}\right)^{5ry} + \left(\frac{1+g}{1+i}\right)^{6ry}\right] \quad (3.16)$$

The same equivalent interest rate may be employed as given in Equation 2.15, giving a new appearance to the formula for *PWMAIN* as given in Equation 3.17.

$$PWMAIN = mbase\left[\left(\frac{1}{1+k}\right)^{ry} + \left(\frac{1}{1+k}\right)^{2ry} + \left(\frac{1}{1+k}\right)^{3ry} + \left(\frac{1}{1+k}\right)^{4ry} + \left(\frac{1}{1+k}\right)^{5ry} + \left(\frac{1}{1+k}\right)^{6ry}\right] \quad (3.17)$$

If a new periodic maintenance based interest rate is introduced (q), which is related to the effective interest rate (k) by the equation $(1+q) = (1+k)^{ry}$, the formula for *PWMAIN* may be further simplified as shown in Equation 3.18.

$$PWMAIN = mbase\left[\left(\frac{1}{1+q}\right) + \left(\frac{1}{1+q}\right)^{2} + \left(\frac{1}{1+q}\right)^{3} + \left(\frac{1}{1+q}\right)^{4} + \left(\frac{1}{1+q}\right)^{5} + \left(\frac{1}{1+q}\right)^{6}\right] \quad (3.18)$$

The summation of terms within the brackets mirrors the uniform present worth formula for the number of maintenance intervals of interest. As a result the uniform present worth factor may be used with some slight adjustments to the input variables. The relationship between the newly created interest rate (q) and the inflation and interest rates may be determined as given in Equation 3.19.

$$q = \left(\frac{1+i}{1+g}\right)^{ry} - 1 = \left(1+k\right)^{ry} - 1 \quad (3.19)$$

One goal of this research was to develop the means for determining lighting project LCC based upon variations in maintenance intervals on a monthly basis. As a result, the calculation to determine *PWMAIN* has been converted to utilize monthly as opposed to annual time increments. This is accomplished by determining equivalent monthly interest and inflation rates (*mintrate* and *minfrate*) as presented in Equation 3.20 and Equation 3.21.

$$mintrate = 100 \times \left(\left(1 + \frac{intrate}{100} \right)^{(1/12)} - 1 \right) \qquad (3.20)$$

$$minfrate = 100 \times \left(\left(1 + \frac{infrate}{100} \right)^{(1/12)} - 1 \right) \qquad (3.21)$$

The effective monthly interest rate (*kmint*) and the effective monthly rate based upon maintenance (*qeff*) are determined using Equation 3.22 and Equation 3.23 where *r* is the maintenance interval in months.

$$kmint = \frac{(mintrate/100) - (minfrate/100)}{1 + (minfrate/100)} = 0.01 \times \frac{(mintrate) - (minfrate)}{100 + (minfrate)} \qquad (3.22)$$

$$qeff \;\; = (1 + kmint)^{r} - 1 \qquad (3.23)$$

Presented as Equation 3.24, the incorporation of the result of Equation 3.23 into the present worth formula for maintenance expenses results in the present worth formula for all routine maintenance expenses when events are measured in terms of months. The number of periods used to determine the UPW factor is the truncated value of the life of the project life (*prjmnths*) divided by the maintenance interval (*r*), both of which are in months.

$$PWMAIN = mbase\left(\text{P/A}, qeff, \text{Truncate}\left(\frac{prjmnths}{r}\right)\right) = mbase\left[\frac{(1+qeff)^{\text{Truncate}\left(\frac{prjmnths}{r}\right)} - 1}{qeff\,(1+qeff)^{\text{Truncate}\left(\frac{prjmnths}{r}\right)}}\right] \quad (3.24)$$

Lighting systems do not generally have any salvage value, therefore at the end of service life the only cash flow is negative and is typically referred to as disposal cost. The determination of the disposal cost at the end of the life of the project is simply the sum of the labor costs required to remove the luminaires and the cost of disposal, which may or may not include hazardous waste charges. If the cost to scrap a single luminaire (labor and disposal cost) in present day dollars is multiplied by the total number of luminaires the result is the base disposal cost for the lighting project. The present value of the disposal cost (*PWDISP*) is given in Equation 3.25 using the single value present worth factor.

$$PWDISP = nol \times \left(\left(scrptime \times mntcost \right) + dspcost \right) \times \left(\frac{1}{1+\text{k}} \right)^{prjlife} \quad (3.25)$$

The present worth of the LCC, given by Equation 3.26, is the summation of the four values determined by Equations 3.9, 3.13, 3.24, and 3.25.

$$LCC = PWAI + PWOPER + PWMAIN + PWDISP \quad (3.26)$$

3.4 Determination of Luminaire Mounting Locations

The task of determining the number of luminaires required to meet illumination requirements is a somewhat tedious but straightforward process. Being able to distribute the luminaires to provide acceptable uniformity of illumination without the need for additional luminaires is another matter. The developed software provides solutions to this problem, as discussed in section 2.4.4, through the use of two independent luminaire layout algorithms designed to distribute any number of luminaires over a rectangular target area. By way of photometric simulations, the layouts generated have proven successful in providing desired illumination levels, and have also proven to be comparable in uniformity to layouts generated by commercial design software.

3.4.1 Layout Algorithm *"layoutA1"*

This luminaire placement strategy begins by assuming a *symmetrical layout* with all columns being of equal length and containing the same number of luminaires; and all rows being of equal length and containing the same number of luminaires. Based upon the difference between the number of luminaires used in the symmetrical design and the actual number of required luminaires (*nl*), certain columns in the symmetrical design are shortened by one luminaire until the required number of luminaires is achieved. This requires that the inter-luminaire spacing be adjusted to correct for the luminaires which are removed. The algorithm first calculates an initial spacing (S) based upon a symmetrical layout, an example of which is shown in Figure 3-9. An assumption is made that the luminaires on the outermost edge will be one-third of a luminaire spacing distance (S/3) from the outer wall. Based upon this diagram is obvious that the total area may be subdivided into three types of smaller areas; a large block (I) that has an area of S^2, a

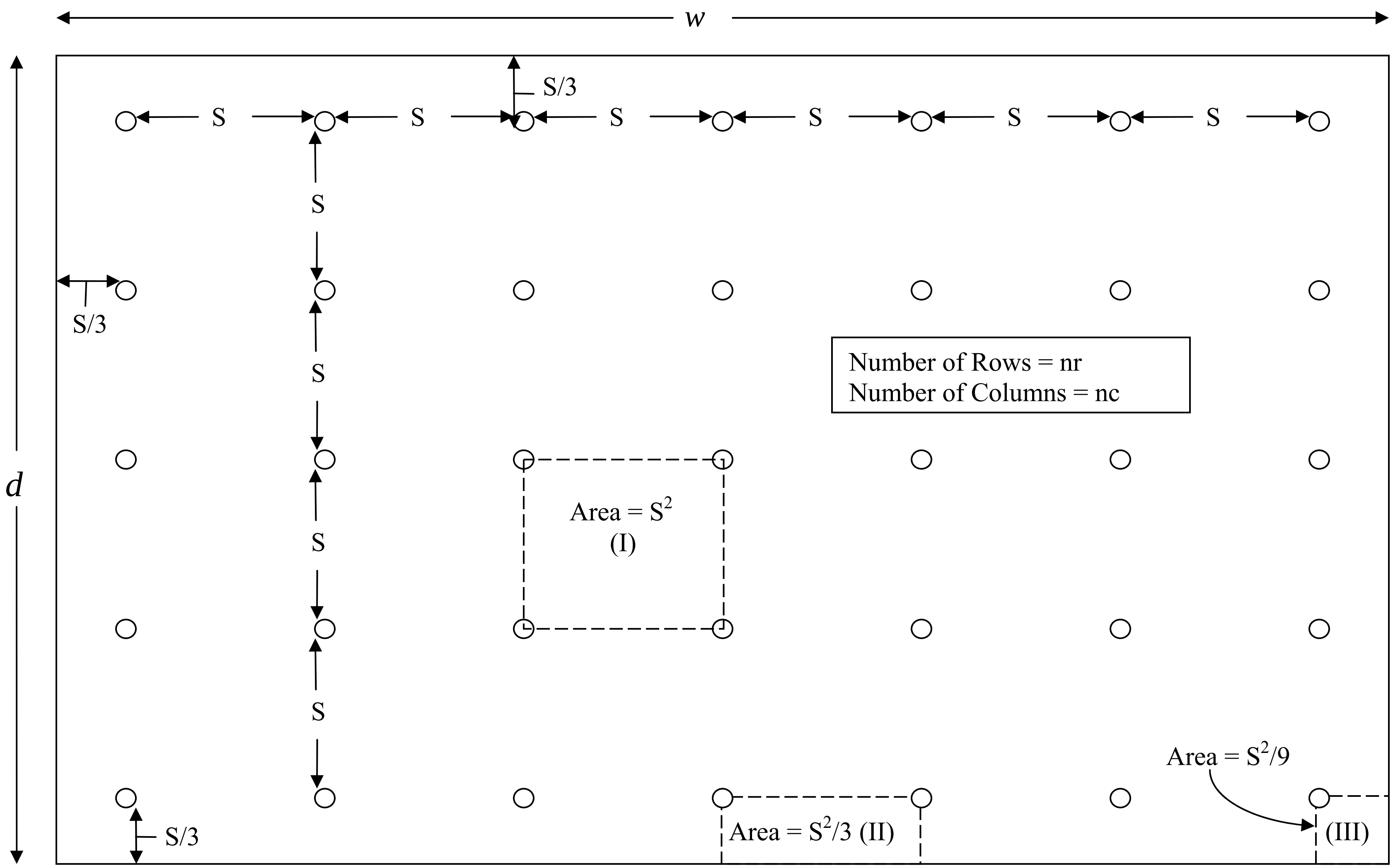


Figure 3-9: Development of Equation to Determine Initial Luminaire Spacings

smaller rectangle (II) that has an area of $S^2/3$, and a small block (III) with an area of $S^2/9$. The relationship between these areas, the total floor area, and the spacing (S) may be derived by developing equations for each of these smaller areas (I, II and III) and calculating their contribution to the total area. Equations 3.27 through 3.29 express these relationships.

$$\text{Total Area (I)} = (\text{nr-1})\times(\text{nc-1})\times S^2 \tag{3.27}$$

$$\text{Total Area (II)} = 2\times\left[(\text{nr-1})\left(\frac{S^2}{3}\right)+(\text{nc-1})\left(\frac{S^2}{3}\right)\right] \tag{3.28}$$

$$\text{Total Area (III)} = 4\times\left(\frac{S^2}{9}\right) \tag{3.29}$$

The total floor area is the summation of Equations 3.27 through 3.29, and is the same quantity as the floor width (*w*) multiplied by the floor depth (*d*). This relationship is shown in Equation 3.30 with the number of luminaires (*nl*) being the product of the number of rows and columns (nr, nc).

$$\text{Total Area} = w\times d = S^2\left(nl - \frac{(\text{nc}+\text{nr})}{3} + \frac{1}{9}\right) \tag{3.30}$$

Equations 3.31 and Equation 3.32 describe the relationships between the number of columns and the floor width, and the number of rows and the floor depth.

$$w = (\text{nc - 1})S + \left(\frac{2}{3}\right)S \tag{3.31}$$

$$d = (\text{nr - 1})S + \left(\frac{2}{3}\right)S \tag{3.32}$$

Rearranging these equations yields Equations 3.33 and 3.34.

$$\text{nc} = \frac{w}{\text{S}} + \frac{1}{3} \tag{3.33}$$

$$\text{nr} = \frac{d}{\text{S}} + \frac{1}{3} \tag{3.34}$$

Adding Equations 3.33 and 3.34 results in Equation 3.35.

$$\text{nc} + \text{nr} = \frac{(w + d)}{\text{S}} + \frac{2}{3} \tag{3.35}$$

As shown in Equation 3.36, by substituting Equation 3.35 into Equation 3.30 a quadratic equation is formed that describes the relationship between the number of luminaires, the room dimensions and the initial spacing.

$$w \times d = \text{S}^2\left(nl - \left(\frac{1}{3}\right)\left(\frac{(w + d)}{\text{S}} + \frac{2}{3}\right) + \frac{1}{9}\right) = \text{S}^2\left(nl - \frac{(w + d)}{3\text{S}} - \frac{1}{9}\right)$$

$$\text{S}^2\left(nli - \frac{1}{9}\right) - \text{S}\left(\frac{w + d}{3}\right) - (w \times d) = 0 \tag{3.36}$$

An initial luminaire quantity (*nli*) is determined through the selection of initial row and column values, with the solution of Equation 3.36 yielding an initial spacing that will satisfy the logistical constraints of Figure 3-9 and accommodate the desired number of luminaires. Note that the number of luminaires used in Equation 3.36 will not necessarily be the actual number of luminaires that are to be placed. The determination of initial luminaire quantity is accomplished by first plotting the function $nr \times nc = nl$ for the number of required luminaires as specified by the calling program.

Dividing Equation 3.33 by Equation 3.34 results in Equation 3.47.

$$\frac{\text{nc}}{\text{nr}} = \frac{\left(\frac{w}{\text{S}}+\frac{1}{3}\right)}{\left(\frac{d}{\text{S}}+\frac{1}{3}\right)} \simeq \frac{w}{d} \text{ (as } w \text{ and } d \rightarrow \infty \text{, or as S} \rightarrow 0\text{)} \tag{3.37}$$

Substituting into Equation 3.37 the relationship that the number of luminaires is equal to the product of the number of rows and number of columns, Equations 3.38 and 3.39 emerge.

$$\text{nr} \simeq \sqrt{nl \times \left(\frac{d}{w}\right)} \tag{3.38}$$

$$\text{nc} \simeq \sqrt{nl \times \left(\frac{w}{d}\right)} \tag{3.39}$$

To illustrate the determination process, Figure 3-10 is presented which contains a plot of the function $\text{nr} \times \text{nc} = 25$,with the value of 25 being arbitrarily chosen for this example. The initial value of luminaires (*nli*) to be used in equation 3.36 may be determined graphically by focusing upon the area of the plot in the vicinity of the initial number of rows (*irval*) and the initial number of columns (*icval*). These initial values are determined by solving Equations 3.38 and 3.39, using the actual number of required luminaires (*nl*) and the room dimensions.

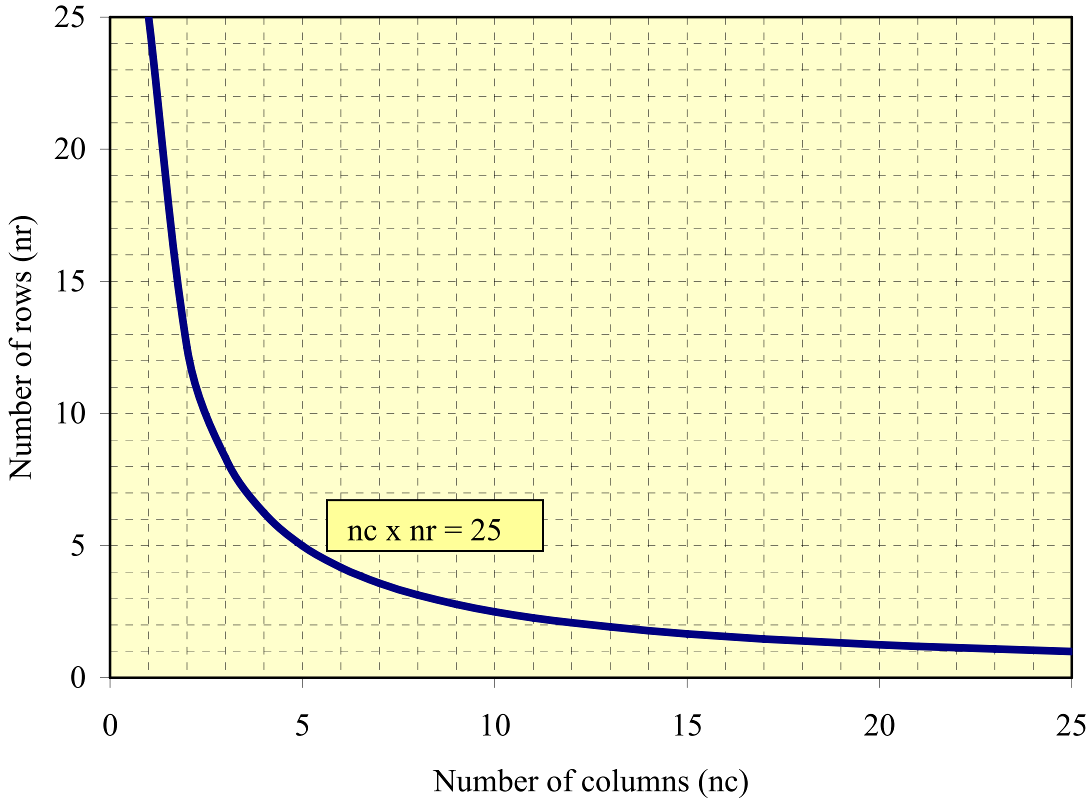


Figure 3-10: Plot of Function nl = nr × nc = 25

Using the initial row and column values as a basis, a section of the plot area of Figure 3-10 may be isolated to determine a best fit row to column ratio. As an example, for a quantity of 25 luminaires and a layout area which has a width of 100 feet and a depth of 230 feet, the initial row and column quantities based upon Equations 3.38 and 3.39 would be 7.6 and 3.3 respectively. Figure 3-11 presents the area of the previous figure in the vicinity of these initial row and column values (*irval* and *icval*). These values will lie upon the curve corresponding to the number of luminaires, which again in this example is 25. Since the number of rows and columns are integers, the four possibilities closest to the point of interest are labeled A through D. Points labeled M and N indicate the intersections of the function with the rectangular boundary A-B-C-

D. Since this luminaire placement algorithm removes selected luminaires from an initially overpopulated rectangular symmetric layout, the initial number of luminaires must be greater than the desired quantity. For this reason only those points to the right of the plot of the function are considered feasible. In this example points C and D are located to the right of the curve in what is labeled in Figure 3-11 as the *Feasible Region*.

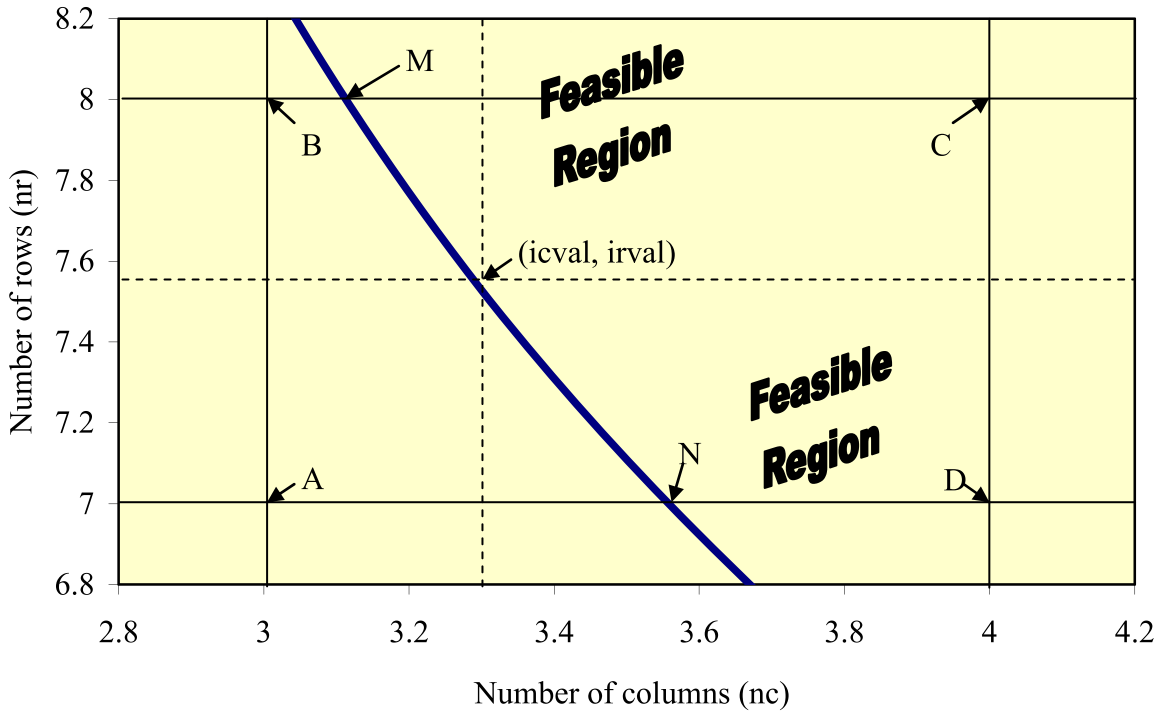


Figure 3-11: Detail of Figure 3-10

The choice of the initial values for the number of rows (*nri*) and columns (*nci*) to be used in the rectangular layout is made by evaluating the distance between points C and M, and D and N. The measurement is this case is conducted along the horizontal since the vertical, or column value of four is common to both points of interest. The shortest of these distances will indicate which of the points, and therefore corresponding initial numbers of rows and columns will be used in the layout process. It follows that the minimum of these two distances will be the smallest value of the product of the initial row and column quantities, corresponding to points C and D, both of which are located in the feasible region.

Once the initial row, column, and luminaire values (*nri, nci, nli*) are determined the value of *nli* substituted into Equation 3.36 and a revised initial spacing (*si*) is determined by solving the quadratic equation. Based upon the substitution of this revised initial spacing, revised row (*nr*) and column (*nc*) quantities may be calculated through the use of Equations 3.33 and 3.34, with these quantities being rounded down to the nearest integer to ensure that the outermost luminaires placements are within the target layout area. If the product of *nr* and *nc* is less than the actual number of luminaires desired the revised spacing is reduced by one percent, resulting in a new reduced spacing (*sn*), and the calculation of row and column quantities is repeated. When the product of rows and columns satisfies the constraint this new value of reduced spacing (*sn*) is used as the spacing for all further calculations requiring that quantity.

The luminaire quantity to be removed (*dl*) from the rectangular layout is determined using Equation 3.40.

$$dl = (\mathrm{nc} \times \mathrm{nr}) - nl \qquad (3.40)$$

This algorithm (*layoutA1*) is based upon the removal or addition of single luminaires from specified columns, therefore if the number of luminaires to be removed exceeds the number of columns in the rectangular layout then the number of rows (*nr*) is reduced by one and the number of luminaires to be removed is recalculated using Equation 3.40. Assuming that the number of luminaires to be removed is less than one-half of the number of columns, the columns to be shortened by removing a single luminaire are selected based upon one of the following procedures.

1. If the number of luminaires to be removed is an even:
   (i) Beginning with the center column if the number of columns is odd, or column that is just to the left of center if the number of columns is even, subtract one from this column number and remove a single luminaire from the resulting column.
   (ii) Increase the column number by two and remove a luminaire from that column.
   (iii) Decrease the column number by four and remove a luminaire from the resulting column.
   (iv) Increase the column number by six and remove a luminaire, etc.
   (v) This process repeats until the quantity of luminaires being removed is exhausted.

2. If the number of luminaires to be removed is odd:
   (i) Beginning with the center column if the number of columns is odd, or column that is just to the left of center if the number of columns is even, remove a single luminaire.
   (ii) Increase the column number by two and remove a luminaire from that column.
   (iii) Decrease the column number by four and remove a luminaire from the resulting column.
   (iv) Increase the column number by six and remove a luminaire, etc.
   (v) This process repeats until the quantity of luminaires being removed is exhausted.

The results of the chosen procedure are stored in an array (*shortcol*) which is subsequently used to generate the coordinates of the luminaires. Examples of the realization of this algorithm for the four possible cases are illustrated in Figures 3-12 and 3-13.

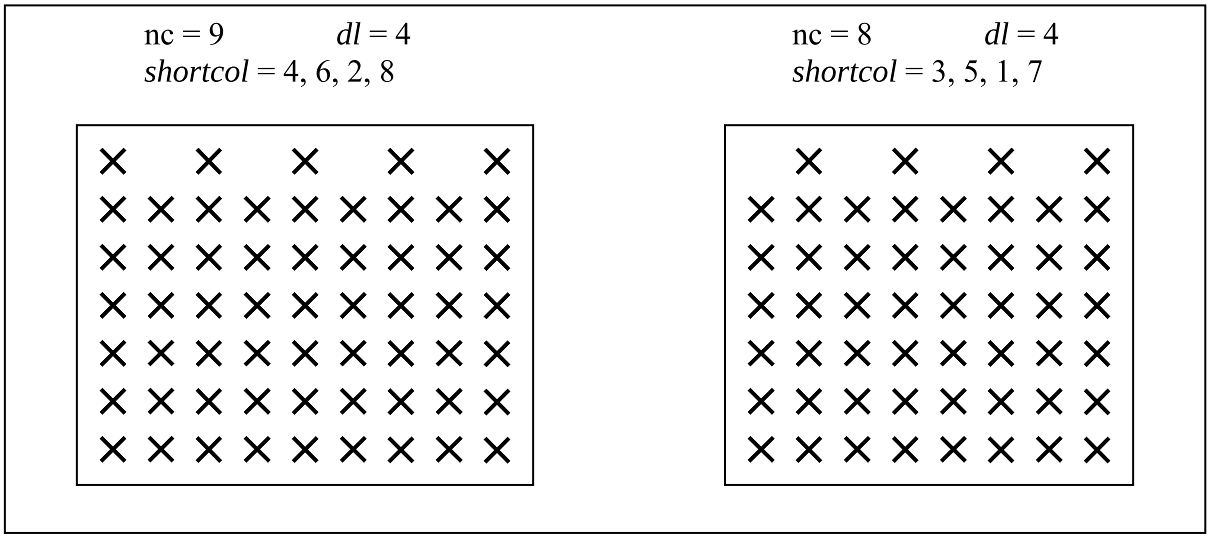


Figure 3-12: Results of Column Shortening Procedure when Quantity of Luminaires to be Removed is Even

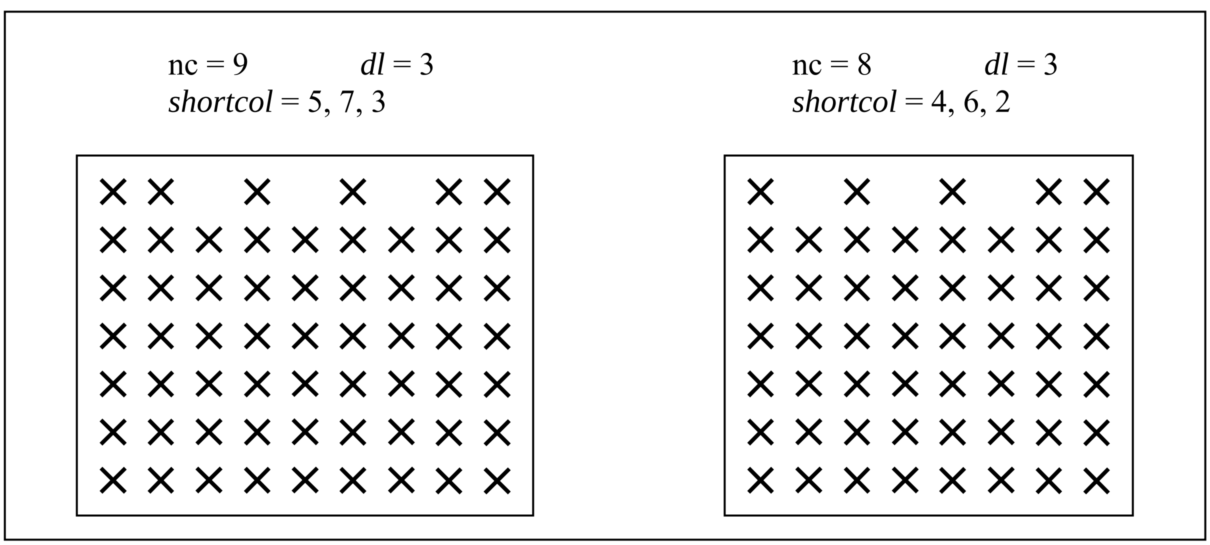


Figure 3-13: Results of Column Shortening Procedure when Quantity of Luminaires to be Removed is Odd

Once the columns to be shortened have been determined, it is required that they be centered by shifting one half of a luminaire spacing to achieve a greater level of uniformity of illumination as shown in Figure 3-14. The challenge however is that this shifting results in an increased spacing between the luminaires in the shortened columns and those in adjacent columns thus exceeding the current spacing level (*sn*). It is therefore necessary to reduce the spacing between the shortened columns and the columns on either side, which is illustrated in Figure 3-15. For each shortened column, with the exception one located in the first or last position, there will be two column gaps that will need to be compressed. These spacings will need to be reduced by a factor of 0.866, which is the cosine of the angle 26.565º (arctan (0.5/1)).

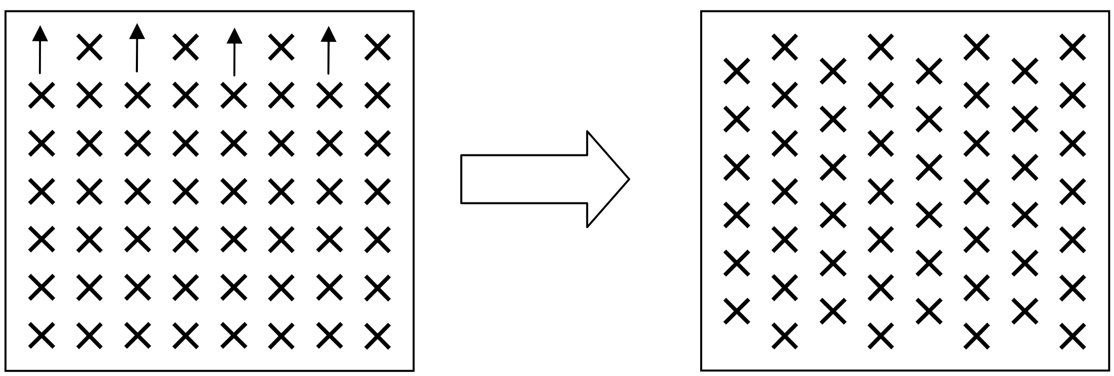


Figure 3-14: Centering of Shortened Columns

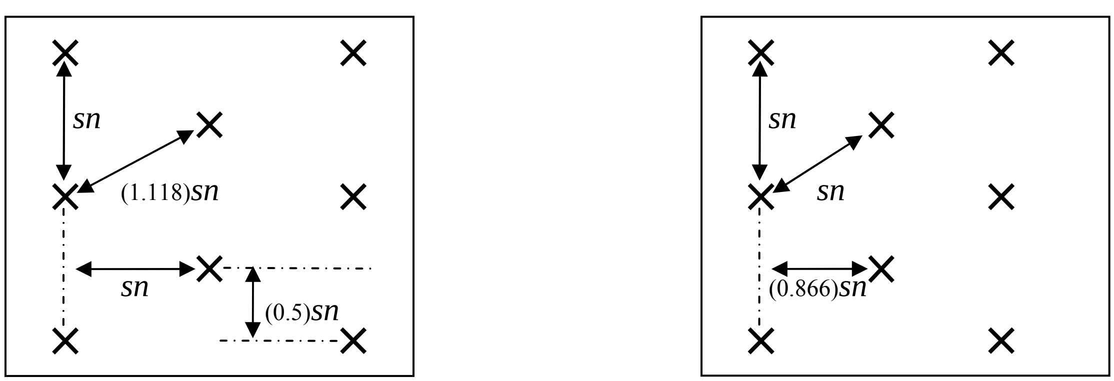


Figure 3-15: Adjusting of Columns Spacing in Vicinity of Shortened Columns

The probable result of this manipulation is a layout that no longer sufficiently fills the layout area, and as a result a revision to the overall luminaire spacing is required which will satisfy the lighting application from a uniformity perspective. The development of an equation to determine this new spacing is illustrated with the help of Figure 3-16.

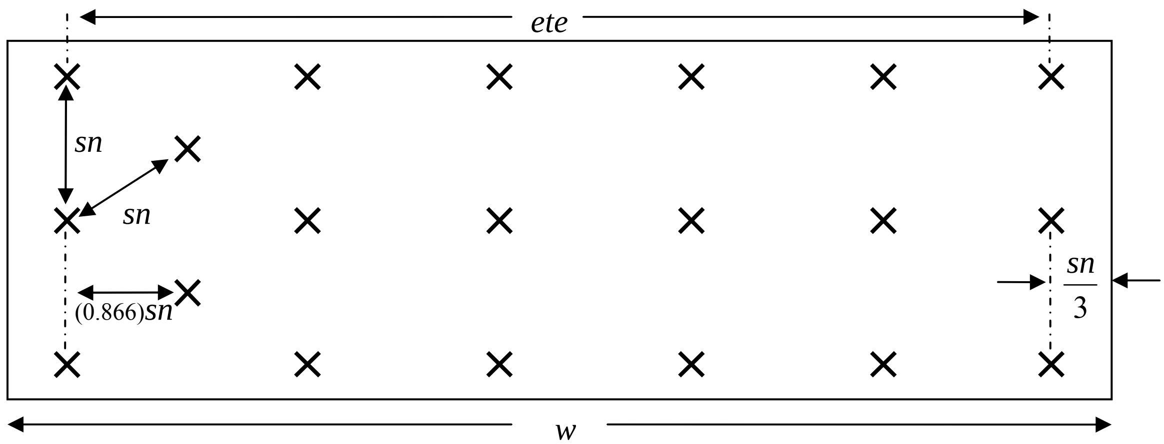


Figure 3-16: Development of Revised Luminaire Spacing

Referring to Figure 3-16, the goal is to maintain a third of a spacing distance between both the leftmost and rightmost columns and their corresponding boundaries. From the spatial relationships of Figure 3-16, both Equations 3.41 and 3.42 emerge, where *ete* is the distance between the first and last columns.

$$w = ete + \left(\frac{2}{3}\right)sn \qquad (3.41)$$

$$ete = (2 \times dl \times 0.866)sn + (\text{nc} - (2 \times dl) - 1)sn \qquad \left[\text{for } dl < \frac{\text{nc}}{2}\right] \qquad (3.42)$$

In the event that one of the outer two columns is shortened, Equation 3.43 would apply.

$$ete = (\mathrm{nc} - 1) \times (0.866)sn \qquad \left[\text{for } dl = \frac{\mathrm{nc}}{2}\right] \qquad (3.43)$$

Combining Equation 3.41 with Equations 3.42 and 3.43 results in the creation of two new equations which may are used to determine a revised spacing. These are presented as Equations 3.44 and 3.55.

$$sn = \frac{w}{\mathrm{nc} - (0.268)dl - 0.333} \qquad \left[\text{for } dl < \frac{\mathrm{nc}}{2}\right] \qquad (3.44)$$

$$sn = \frac{w}{(0.866)\mathrm{nc} - 0.645} \qquad \left[\text{for } dl = \frac{\mathrm{nc}}{2}\right] \qquad (3.45)$$

Once a revised spacing has been defined, which Equations 3.44 and 3.45 ensure will be accommodated by the width of the layout area, it must be confirmed that the depth of the layout area will not be violated. The required depth based upon the revised spacing (*dreq*) is calculated using equation 3.46.

$$dreq = (\mathrm{nr} - 1)sn \qquad (3.46)$$

This revised spacing only represents the total of the distances between luminaires in a long (un-shortened) column, therefore the distance needed between the wall and the top and bottom luminaires is not included in this quantity. A further adjustment is necessary if the value of the revised spacing (*dreq*) is greater than the actual depth (*d*) less any distance between outside luminaires and adjacent walls, which is the spacing (*sn*) multiplied by a predetermined wall spacing factor (*walspace*). As mentioned previously the desired spacing from the walls is one-third the calculated luminaire spacing, however the execution of this algorithm will most often require a compromise to a reduced level. Therefore the value of wall spacing factor will be less than two-thirds but greater than two times the minimum acceptable distance, or

$$2 \times \text{min. wall distance (\% of } sn) < walspace < \frac{2}{3}.$$

The developed software evaluates whether the depth required by the layout violates the aforementioned constraints. If the target area will not accommodate the current luminaire depth requirement then spacing is reduced until the requirement is satisfied. The constraint $dreq \leq d - (walspace \times sn)$ is satisfied by incrementally reducing the new spacing (*sn*) by a reduction factor. In this case the reduction factor is defined so that the spacing is reduced in one percent increments until the constraint is satisfied.

In the event that the number of luminaires to be removed from the original rectangular layout is greater than one-half of the number of columns, a single row is removed and the appropriate number luminaires are added to specific columns. The number of luminaires to be added is then determined by Equation 3.47.

$$dl = nl - (\text{nc} \times \text{nr}) \qquad (3.47)$$

The luminaires are then placed using one of the following procedures.

1. If the number of luminaires to be added is even:
   - (i) Beginning with the center column, or column that is just to the left of center, reduce the column number by one and add a single luminaire to the resulting column.
   - (ii) Increase the column number by two and add a luminaire to that column.

(iii)Decrease the column number by four and add a luminaire to the resulting column.

(iv)Increase the column number by six and add a luminaire, etc.

(v) This process repeats until the quantity of luminaires being added is exhausted.

2. If the number of luminaires to be added is odd:

   (i) Beginning with the center column, or column that is just to the left of center, add a single luminaire to this column.

   (ii) Increase the column number by two and add a luminaire to that column.

   (iii)Decrease the column number by four and add a luminaire to the resulting column.

   (iv)Increase the column number by six and add a luminaire, etc.

   (v) This process repeats until the quantity of luminaires being added is exhausted

The results of the selected procedure are stored in an array (*longcol*) which is used in the determination of the luminaire coordinates. Examples of the results of this algorithm are presented in Figures 3-17 and 3-18.

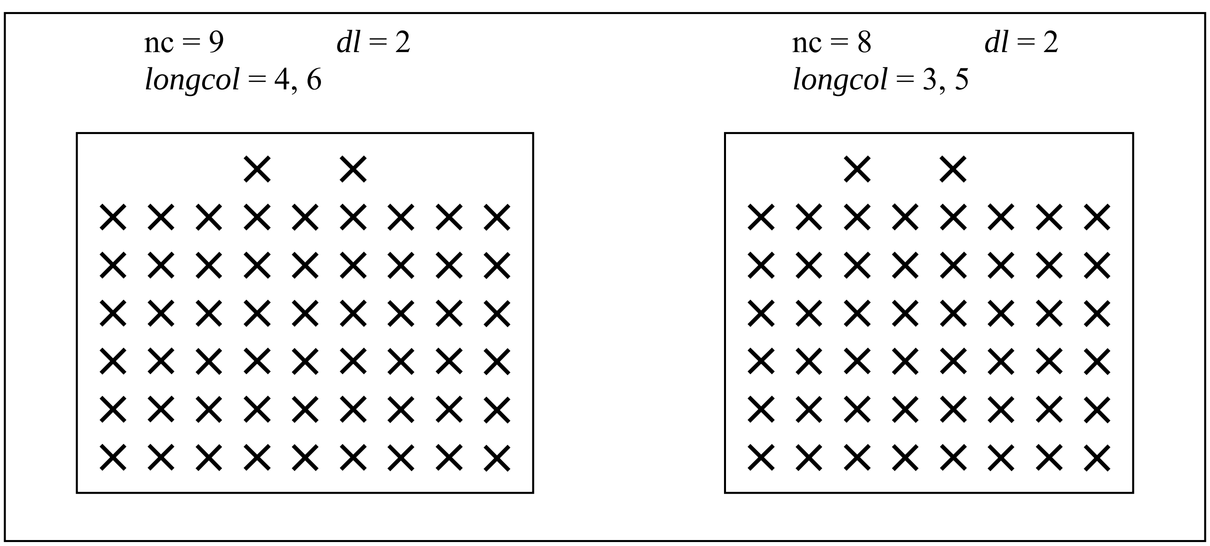


Figure 3-17: Results of Column Lengthening Procedure when Quantity of Luminaires to be Added is Even

In the same manner previously described through the use of Figures 3-14 through 3-16, the columns are shifted, spacings recalculated, and the inter-luminaire spacing is modified to compensate for reduction in the end-to-end distance. The spacing is again recalculated if the luminaires along the top and bottom of the layout exceed acceptable wall spacings and room depth requirements. Once either the columns to be lengthened or the columns to be shortened are determined by one of the two methods, a complementary array must be generated to account for all of the columns in the layout.

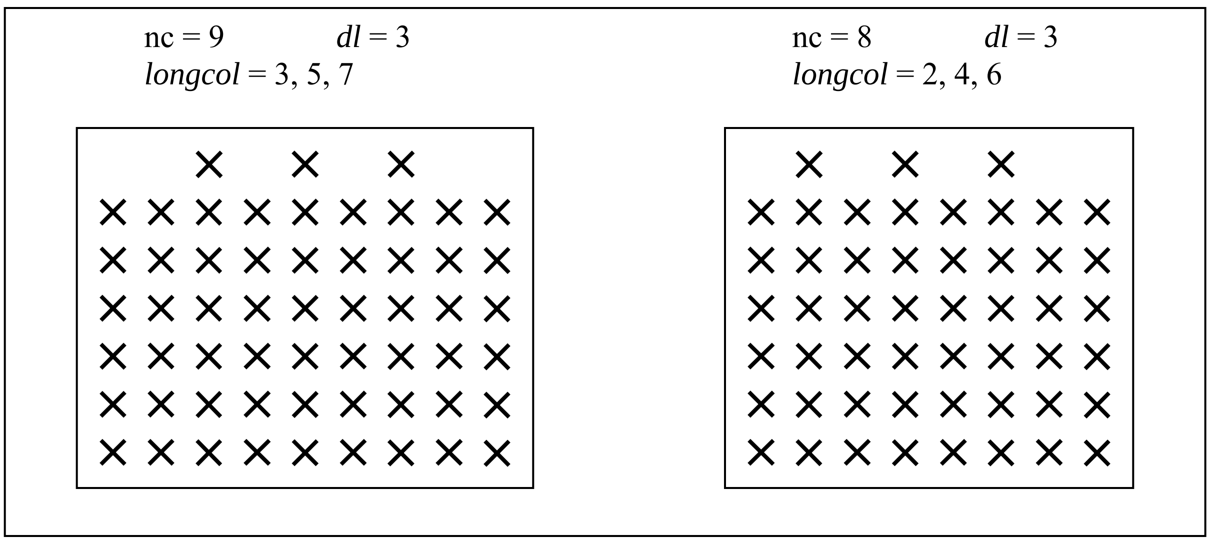


Figure 3-18: Results of Column Lengthening Procedure when Quantity of Luminaires to be Added is Odd

For example, in the case of a six column design if it is determined that the columns to be shortened are columns 1, 3, and 5 (*shortcol* = [1 3 5]), then a complementary array is generated to identify those columns that are long (*longcol* = [2 4 6]). This is performed by generating a vector containing only ones that has a length equal to the number of columns in the design, making those entries which correspond to the locations dictated by the array *shortcol* equal to zero and converting the entries to their corresponding column number and removing the zeros from the resulting array. The same would be true if the columns to be lengthened were previously determined and a vector identifying the shorter columns was required. This process is illustrated in Figure 3-19.

$$[1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1]$$
$$\Downarrow$$
$$[0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1]$$
$$\Downarrow$$
$$[0 \quad 2 \quad 0 \quad 4 \quad 0 \quad 6]$$
$$\Downarrow$$
$$longcol = [2 \quad 4 \quad 6]$$

Figure 3-19: Determination of Array (*longcol*) Based Upon Array *shortcol* = [1 3 5]

The generation of the coordinates for the luminaire locations is then performed using the column numbers issued to arrays *shortcol* and *longcol*, as well as the most recently revised luminaire spacing. Once the coordinates of the first luminaire have been determined, the locations of the remaining luminaires are calculated using these initial coordinates as a reference. The first luminaire is placed by determining its position relative to the two walls which are in closest proximity. To determine the spacing from the outer columns to the walls (*swc*), and the outer rows to the walls (*swr*), the end-to-end spacings are calculated in a manner discussed previously. By extracting the spacing term (*sn*) from Equation 3.42 it can be seen that the summation of spacing distances (*spsum*) is described by Equation 3.48.

$$spsum = \mathrm{nc} - 1 - (0.268 \times dl) \qquad \left[\text{for } dl < \frac{\mathrm{nc}}{2}\right] \tag{3.48}$$

Likewise, as presented in Equation 3.49, the extracting of the spacing (*sn*) from equation 3.43 results in the summation of spacing distances in the case when half of the columns are shortened.

$$spsum = 0.866 \times (\mathrm{nc} - 1) \qquad \left[\text{for } dl = \frac{\mathrm{nc}}{2}\right] \tag{3.49}$$

In the case where there are more shortened than elongated columns, Equation 3.48 may be re-employed noting that the value of *dl* is describing the number of long columns. Using Equations 3.48 and 3.49, along with the possibility that the layout may actually be rectangular (all rows contain same number of luminaires, all columns likewise), the spacings from the walls to the nearest luminaires may be determined as shown in Equations 3.50 and 3.51.

$$swc = \frac{(w - (spsum \times sn))}{2} \tag{3.50}$$

$$swr = \frac{(d - ((\mathrm{nr} - 1) \times sn))}{2} \tag{3.51}$$

In the event that the initial luminaire does not lie within a shortened column, then this location is determined by equating the x-coordinate to the value of *swc*, and the y-coordinate to *swr*. If however the initial luminaire is located within a shortened column, then the x-coordinate is again the value of *swc*, but the y-coordinate is offset by half of a luminaire spacing or $swr + s/2$.

Once the initial luminaire coordinates are established, all subsequent luminaire locations are determined in a row-wise manner starting from the bottom. If adjacent columns are the same length the x-coordinate of the next luminaire in the row is simply the spacing (*sn*) added to the previous x-coordinate. In the event that adjacent columns are different in length (ie. a short column and long column) then the increment (0.866)*sn* is added to previous x-coordinate. The y-coordinates are the same in a particular row unless adjacent columns differ in length. As an example, if the previous column is short and the current column is long the value of the y-coordinate is half a luminaire spacing subtracted from y-coordinate of the previous luminaire. Figure 3-20 illustrates the location assignment sequence as well as the relative spacings between luminaires which are labeled L1 through L14. This figure presents the relative spacings between luminaires lying in short columns to those in long columns.

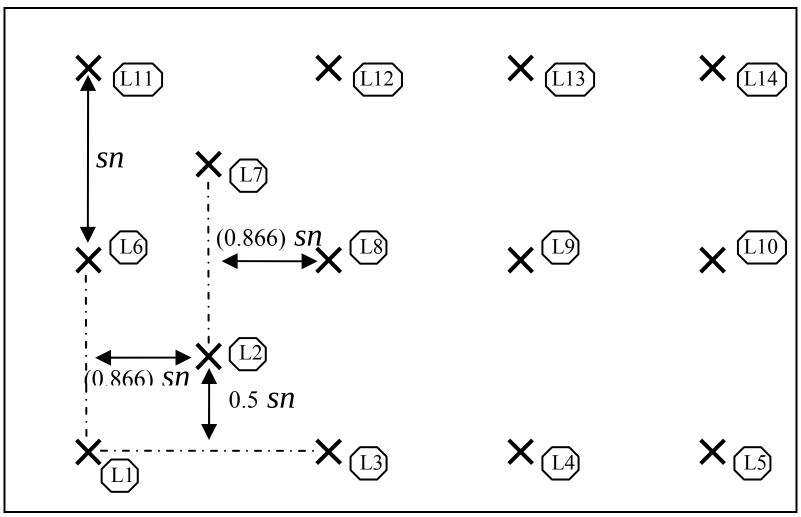


Figure 3-20: Luminaire Coordinate Development

The coordinates for each of the luminaire locations determined by this algorithm are stored in final coordinate arrays for use by a plotting program.

3.4.2 Layout Algorithm *"layoutB1"*

This second algorithm for the placement of luminaires first assumes a spacing that is smaller than that required to fill the target area. Luminaires are placed in a row-wise manner using this reduced spacing starting in the lower left corner until the end of the first or bottom row is reached. At this point the placement of luminaires continues on the next row using a hexagonal packing configuration until the quantity is exhausted, as illustrated in Figure 3-21. The luminaire spacing is then increased and the process is repeated until the space is adequately filled. This configuration of luminaire placement is extrapolated from circle packing theory which states that the densest of all planar circle packings is achieved when the hexagonal or "honeycomb" structure is employed [34]. This is significant because the greater the packing density for a circles of equal diameter, the lower the total amount of remaining area that is uncovered by the circles which, from a visual perspective, translates to a lighting layout whereby the floor area which is under-illuminated may be minimized. It should be pointed out that the circles used in the execution of the algorithm, such as those shown in Figure 3-21, represent luminaire spacings and do not reflect the actual photometric distributions of the luminaires being considered.

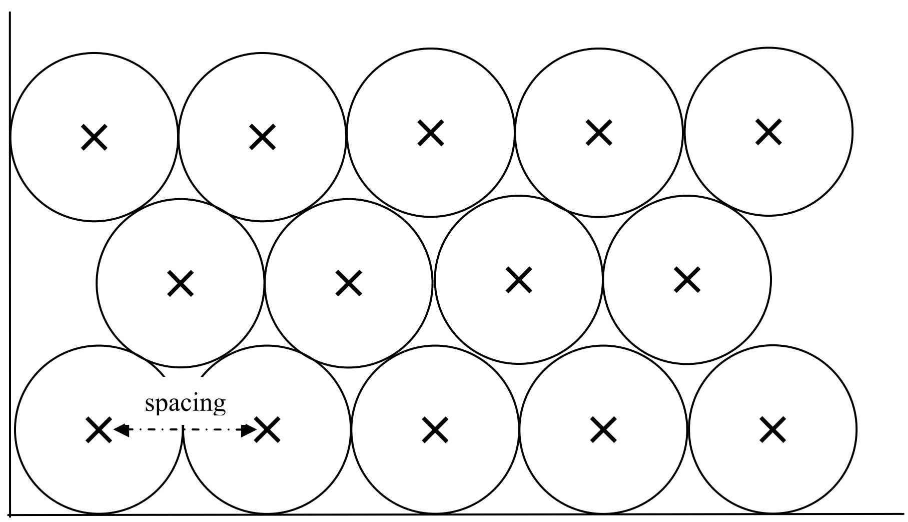


Figure 3-21: Hexagonal Packing of Circles of Equal Diameter

To account for the recommended reduced spacing between the walls and those luminaires that border them, a variable or "ghost" boundary is introduced as illustrated in Figure 3-22. This fictitious outer limit is needed for determining the location of the circles relative to the outer walls and therefore the location of the luminaires at their centers. As discussed previously, a widely accepted wall spacing target is one-third of the inter-luminaire spacing, therefore a relationship between the actual boundary and the ghost boundary may be derived in the ideal case as shown in Figure 3-23.

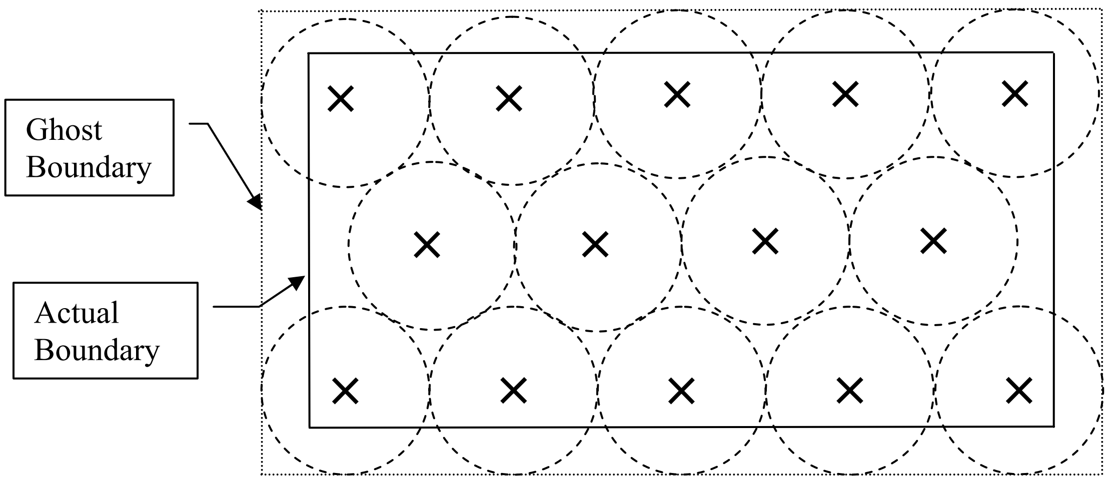


Figure 3-22: Illustration of Variable or "Ghost" Boundary

What may be determined from Figure 3-23 is that to maintain one-third of a luminaire spacing between the walls and outermost luminaires, the ghost boundary must be established by a distance of one-sixth of the luminaire spacing on the outer side of each wall. As a result the overall target area dimensions of the project are temporarily increased (*wnew* and *dnew*) by one third of the luminaire spacing (Δw and Δd) as shown in Equations 3.52 and 3.53.

$$wnew = w + \frac{S}{3} \tag{3.52}$$

$$dnew = d + \frac{S}{3} \tag{3.53}$$

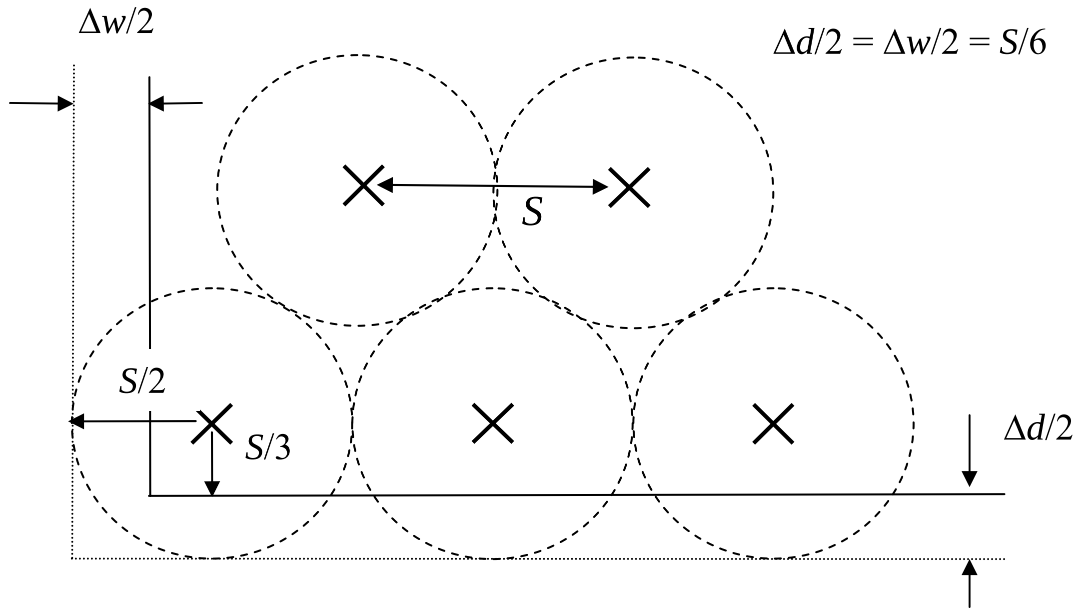


Figure 3-23: Determination of Ghost Boundary Limits

As previously stated, the algorithm begins with a calculation of an initial spacing that will not allow for a filling of the area within the ghost boundary. This value (*S*) is determined by solving for the largest root of Equation 3.36, which was developed in support of the previous algorithm, and then rounding this value down to the nearest integer. Using the relationships identified by Equations 3.52 and 3.53, the new width (*wnew*) and depth (*dnew*) boundaries are determined. The number of luminaires that will be placed in the bottom row (*brn*), is simply the truncation of the result of the ghost boundary width (*wnew*) divided by the initial spacing (*S*). A revised spacing (*snew*) is calculated based upon the ghost width (*wnew*) and the number of luminaires (*brn*), with the new spacing being greater than or equal to the initial spacing. An example of this process using an initial spacing of 12 feet is illustrated in Figure 3-32.

Initial Spacing (S) = 12 feet
Floor Width (w) = 100 feet

⇓

Ghost Width ($wnew$) $= 100 + \frac{12}{3} = 104$ feet

⇓

Bottom Row Number (brn) $= \text{floor}\left(\frac{104}{12}\right) = 8$ luminaires

⇓

New Spacing ($snew$) $= \frac{104 \text{ feet}}{8 \text{ luminaires}} = 13$ feet

Figure 3-24: Initial Luminaire Spacing Calculations (*layoutB1*)

With the bottom row now filled with circles representing the luminaire spacings, the remainder of the luminaire locations may be defined based upon the hexagonal packing configuration described earlier. The location of the luminaires in the first row along the depth of the room is one-half of the new spacing (*snew*). This quantity is also labeled $\frac{\Delta y}{2}$, which results from Δy being equated to the new spacing. The x-coordinates across the width of the target area are one-half of the new spacing for the initial luminaire followed by increments of *snew* for the balance of luminaires throughout the row. These locations along the first row are illustrated in Figure 3-25. If the direction along the depth of the room is considered the y-axis, and along the width of the room to be the x-axis, the first row of luminaires will have the x-y coordinates shown in Table 3-1.

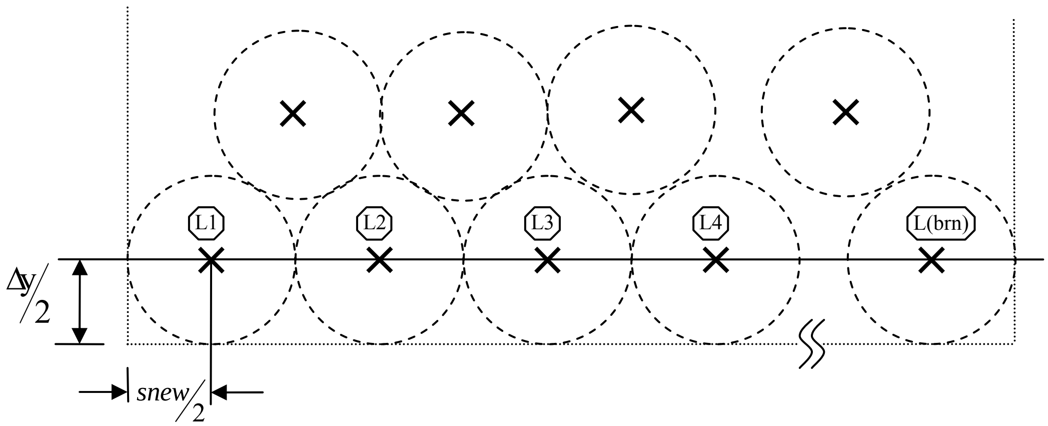


Figure 3-25: Luminaire Coordinate Determination (row 1)

Table 3-1: Coordinates of First (bottom) Row using Algorithm *layoutB1*

Luminaire	[x,y] Coordinates (feet)
L1	$\left[\frac{snew}{2}, \frac{\Delta y}{2}\right]$
L2	$\left[\frac{snew}{2} + snew, \frac{\Delta y}{2}\right]$
L3	$\left[\frac{snew}{2} + (2 \times snew), \frac{\Delta y}{2}\right]$
:	:
L(brn)	$\left[\frac{snew}{2} + ((brn - 1) \times snew), \frac{\Delta y}{2}\right]$

The coordinates of the luminaires in the second row are generated in a similar manner, however the strategy is not to nest the luminaires in the upper rows, but to space them one full luminaire spacing above the previous row. The reason for this approach is that some of the rows will be converted from short rows to long rows in later portions of the algorithm. As this operation is performed the designated rows will have their x-coordinates shifted to the left, essentially defeating the hexagonal packing configuration to accommodate luminaires whose coordinates have fallen outside of the target area. The need for this row placement or *modified hexagonal packing* strategy will become clear as the description of the algorithm progresses. The coordinate assignment convention for the second row is illustrated in Figure 3-26 and Table 3-2. The process of assigning coordinates to row pairs (rows 3 and 4, rows 5 and 6, etc.) continues in this manner until all of the luminaires have been placed.

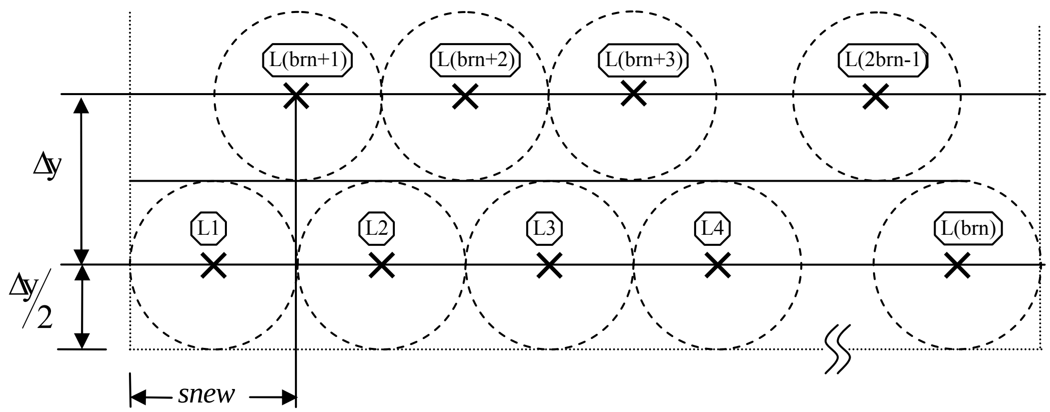


Figure 3-26: Luminaire Coordinate Determination (row 2)

In this modified hexagonal placement routine there are two types of rows - short and long. The long rows are odd numbered rows, and the short rows are even numbered rows, assuming that bottom row (row 1) is a long row and that numbering progresses from the bottom to the top of the layout area. Since the short and long rows alternate, the software executes the luminaire placements in pair groups (previously referred to as row pairs) where one pair group consists of one odd and one even row. Note that the x-coordinates will be the same for each row pair whereas the y-coordinates are incremented by the quantity Δ*y*.

Table 3-2: Coordinates of Second Row using Algorithm *layoutB1*

Luminaire	[x,y] Coordinates (feet)
L(brn+1)	$\left[\mathrm{L1(x)} + \frac{snew}{2}, \mathrm{L1(y)} + \Delta \mathrm{y}\right]$
L(brn+2)	$\left[\mathrm{L2(x)} + \frac{snew}{2}, \mathrm{L2(y)} + \Delta \mathrm{y}\right]$
L(brn+3)	$\left[\mathrm{L3(x)} + \frac{snew}{2}, \mathrm{L3(y)} + \Delta \mathrm{y}\right]$
:	:
L(2brn-1)	$\left[\mathrm{L}\left(\mathrm{brn\text{-}1}\right)\mathrm{(x)} + \frac{snew}{2}, \mathrm{L}\left(\mathrm{brn\text{-}1}\right)\mathrm{(y)} + \Delta \mathrm{y}\right]$

With the locations of all luminaires calculated, the arrays containing x and y-coordinates are transformed to the original layout area (i.e. removing the ghost boundary) using the relationships given in Equations 3.54 and 3.55.

$$xactual = \mathrm{x} - \frac{wnew - w}{2} \tag{3.54}$$

$$yactual = \mathrm{y} - \frac{dnew - d}{2} \tag{3.55}$$

A test is then performed to determine whether or not the final luminaire is within one spacing distance of the upper right corner of the layout area, thus determining if the area has been adequately filled. If this test is passed then the layout algorithm is complete, however if test fails the original spacing (*S*) is increased by a predetermined increment of one-tenth of a foot and the algorithm is repeated.

Repeated trials of this algorithm using various room dimensions and luminaire quantities have suggested that in the majority of cases the increased spacing and repeated execution of the algorithm results in the location of one or more of the final luminaires falling outside the bounds of the layout area. In this event the number of luminaires that are placed outside of the layout area is determined and this quantity is used to shift certain even-numbered (short) rows to the left (negative x-direction) for the purpose of adding an off-grid luminaire back to the end of the row in question. The process is illustrated in Figure 3-27. Once the off-grid luminaires have been placed, a reduction in the row spacing between short and long rows is performed much in the same manner as the previous algorithm *layoutA1*. The difference in this case being that in algorithm *layoutA1* it is the spacing between columns that is reduced. The spacing reduction method used in algorithm *layoutB1* is based upon whether a long row is bordered by a short row as well as the value of Δy. In the event that there are more luminaires located outside of the layout area than can be accommodated by the shifting of the short rows, a scaling factor (*yspace*) is employed to reduce the spacing between long and short rows thus pulling off-grid luminaires back within the bounds of the target area. Initially this factor is assigned a value of one, but under these circumstances it is reduced by a preset value (10%) which reduces the inter-row spacing (Δy) by that percentage during each iteration. This reduction of row spacings continues until all of the off-grid luminaires are placed within the layout boundaries.

To facilitate the determination of final luminaire coordinates a matrix (*coordact*) is created that contains the coordinates of each luminaire as well as their corresponding row number. Once the row shifting is completed, and off-grid luminaires are placed back within the layout area as illustrated in Figure 3-27, the coordinates of the layout are revised and placed in a new matrix (*coordshift*). Using the y-coordinate location of each luminaire as the primary sorting criteria and the x-coordinate as the secondary sorting criteria, the matrix (*coordshift*) is re-sequenced by row location and given a new identification (*coordsort*).

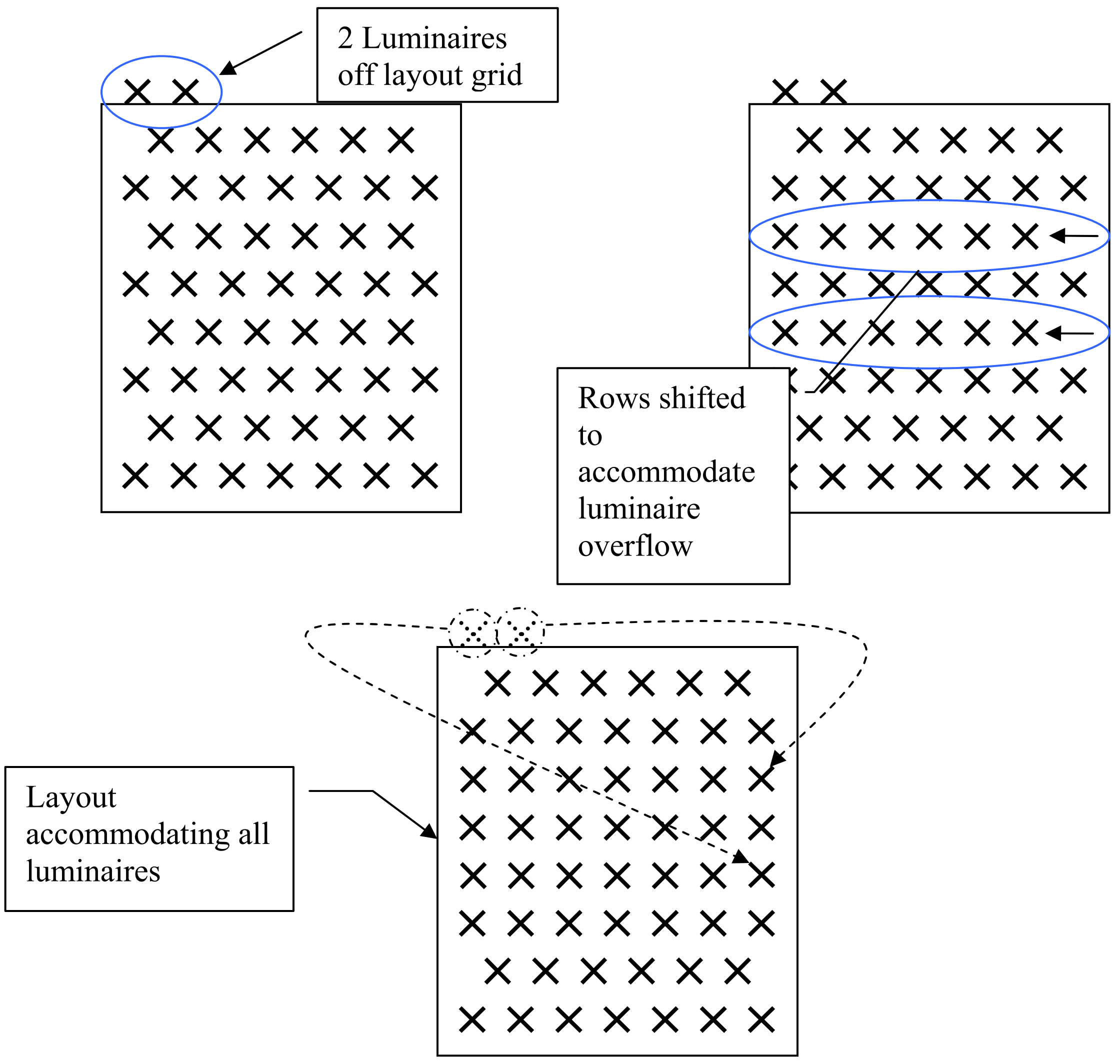


Figure 3-27: Luminaire Overflow Compensation used in Algorithm *layoutB1*

This process of retrieving luminaires that are off of the layout grid is illustrated in Figure 3-28 for an example layout area of 40 feet by 40 feet requiring the placement of 12 luminaires. Referring to the matrix (table) in the upper left corner labeled *coordact*, it is apparent that the final two luminaires (hi-lighted) are located off of the layout grid. The x-coordinates of the second and fourth row luminaires are shifted to the left and the x-coordinates of the off-grid luminaires area changed to the values corresponding to the rightmost luminaire locations in the first row. The y-coordinates of the off-grid luminaires are given the same values as those rows which were shifted, with all resulting coordinates are placed in the matrix *coordshift*. The matrix is then sorted as discussed above moving the result to the matrix *coordsort*. The final step is the updating of the row numbers in the third column of the matrix *coordsort*, resulting in all luminaire locations residing within the layout area.

coordact =

x	y	row
5.3333	5.3333	1
20	5.3333	1
34.667	5.3333	1
12.667	16.025	2
27.333	16.025	2
5.3333	26.717	3
20	26.717	3
34.667	26.717	3
12.667	37.409	4
27.333	37.409	4
5.3333	***48.101***	***5***
20	***48.101***	***5***

coordshift =

x	y	row
5.3333	5.3333	1
20	5.3333	1
34.667	5.3333	1
5.3333	16.025	**2**
20	16.025	**2**
5.3333	26.717	3
20	26.717	3
34.667	26.717	3
5.3333	37.409	**4**
20	37.409	**4**
34.667	***37.409***	***5***
34.667	***16.025***	***5***

coordsort =

x	y	row
5.3333	5.3333	1
20	5.3333	1
34.667	5.3333	1
5.3333	16.025	2
20	16.025	2
34.667	**16.025**	**5**
5.3333	26.717	3
20	26.717	3
34.667	26.717	3
5.3333	37.409	4
20	37.409	4
34.667	**37.409**	**5**

coordsort =

x	y	row
5.3333	5.3333	1
20	5.3333	1
34.667	5.3333	1
5.3333	16.025	2
20	16.025	2
34.667	16.025	2
5.3333	26.717	3
20	26.717	3
34.667	26.717	3
5.3333	37.409	4
20	37.409	4
34.667	37.409	4

Figure 3-28: Steps to Accommodate Off-Grid Luminaires

In order to maintain proper spacings between luminaire locations which have been offset in adjacent rows, it is necessary to reduce the distance between the remaining shorter rows and their longer neighboring rows. This is equivalent of changing the layout as shown in Figure 3-26 to the hexagonally packed configuration of Figure 3-25. This may be accomplished by shifting the y-coordinates of the short rows by an incremental distance (*dy*) which is defined in Equation 3.56.

$$dy = \Delta y \times (1 - 0.866) = 0.134 \times \Delta y \qquad (3.56)$$

Once the short row has been relocated by the incremental distance (*dy*), all rows above are shifted by twice this amount to account for the reduced spacings on both sides of the short row. Any subsequent short rows are located and the process is repeated until all coordinate adjustments have been completed. This process is illustrated in Figure 3-29.

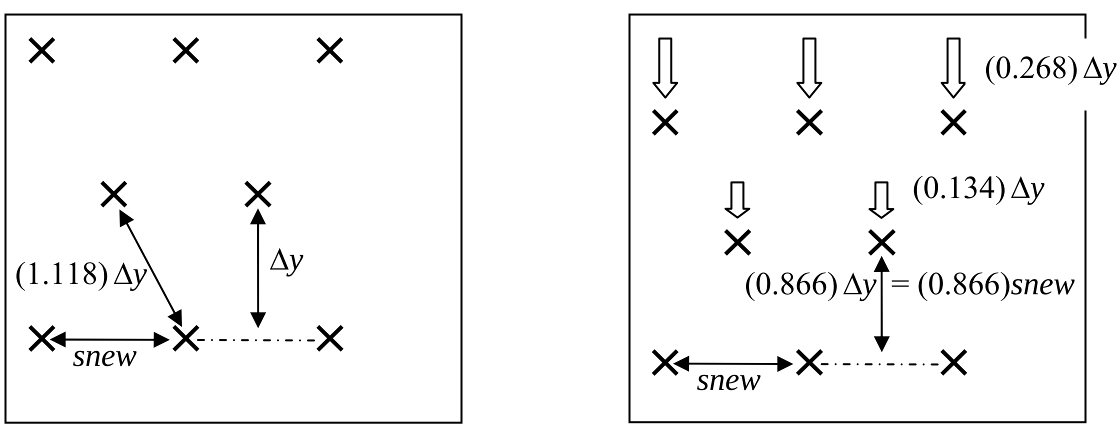


Figure 3-29: Adjusting of Row Spacing in Vicinity of Shortened Rows

To preserve symmetry of illumination with respect to the outer boundaries the layout is centered within the target area, which is accomplished by using the maximum and minimum x-coordinates to determine the distances from these locations to the horizontal walls. These distances are then compared and half of their difference is used to shift all of the luminaire locations accordingly, thus centering the design horizontally. The same process is executed in the centering of the layout vertically using distances in the y-direction.

The final step performed in the execution of this algorithm is to determine if the luminaire locations violate the spacing criterion as illustrated in Figure 2-3. This is accomplished by determining if the final spacing (*snew*) is greater than the product of the mounting height and the spacing criterion factor published for the particular luminaire. If the spacing criterion is violated then it can be concluded that the application of this algorithm coupled with the design requirements and particular luminaire photometric distribution will not generate a satisfactory luminaire layout.

4 Validation of Model for HID Industrial Lighting Design

4.1 Introduction

To evaluate the accuracy and impact of lighting designs performed using the developed software, it is necessary to simulate the optical and electrical performance of a test design and compare it to design performed using commercially available lighting design software. LitePro® is a lighting design software package offered by Columbia Lighting which is currently a division of Hubbell Lighting Incorporated [35]. This software has the ability to perform both indoor and outdoor lighting analysis using the *point-by-point method* of illuminance calculation, as well as perform indoor designs based upon the *zonal cavity method*. For the purpose of evaluating the software developed to support this research, zonal cavity design calculations will be performed using both the developed software and LitePro® for three different lighting application scenarios, and the optical performance of both designs will be evaluated using the point-by-point analysis features provided by LitePro®. The use of LitePro® as it pertains to this research is illustrated in Appendix B, which includes a detailed step-by-step example design and analysis based upon the industrial lighting scenario presented in section 4.2.

4.2 Analysis of 50’ × 100’ Industrial Lighting Application (Scenario #1)

The first test of the software is the design for an area with a 2-to-1 aspect ratio. It is an industrial area with a three foot work plane height and a ceiling which is 40 feet above the floor. The desired maintained illuminance level is 30 footcandles, which is the level that is generally recommended for visual tasks of high contrast and large size in industrial lighting applications [5]. Three MH lamp power levels were used in the design process: 400 watts, 350 watts, and

200 watts. Using the values given in Table 4-1 the designs were performed using the developed software yielding the results shown in Figure 4-1.

Table 4-1: Industrial Scenario #1 Specifications

Dimensions of Floor Area (W x D)	50’ x 100’
Ceiling Height (feet)	40
Work Plane Height (feet)	3
Maintained Illumination Level (fc)	30
Maximum Mounting Height (feet)	37
Minimum Mounting Height (feet)	28
Ceiling Reflectance (%)	50
Wall Reflectances (%)	50
Floor Reflectance (%)	20
Cleanliness of Area (1 – 5[cleanest])	3
Lamp Type	Metal-Halide
Possible Lamp Power Levels (watts)	400, 350, 200
Lamp Initial Lumen Ratings	44,000; 37,000; 21,000 [36]
Lamp Mean Lumen Ratings	35,000; 29,000; 16,800 [36]
Rated Lamp Life (hours)	20,000; 20,000; 15,000 [36]
Luminaire Voltage (rms volts)	277
Actual Luminaire Voltage (rms volts)	277
Ballast Type	Constant Wattage Autotransformer (CWA)
Area Cleaning Period (years)	2
Operating Hours per Lamp Start (hours)	10
Operating Hours per Year (hours)	2,600
Re-lamp/Luminaire Cleaning Cycle (operating hours)	12,000
Unit Luminaire Cost (w/o lamp)	$150
Unit Lamp Cost	$35 (all types)

Original designs were performed for each of the three MH lamp power levels at 10 different mounting heights resulting in a total of 30 designs. These designs were sorted by the program on the basis of power demand and LCC, both in ascending order. The top three designs in each of these categories (lowest power demand and lowest LCC) are displayed as shown in Figure 4-1 along with a summary of the project specifications. The user is then given a choice of which of these six designs is to be passed to the luminaire layout program. For this example the design labeled A (DesignID A) in Figure 4-1 was chosen since it provided the lowest power demand

and consequently it is the same as design D which provides the lowest LCC. The luminaire layout results generated by the developed software for design A are presented in Figure 4-2.

Floor Width (feet)	50	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	100	Annual Interest Rate (percent)	5
Ceiling Height (feet)	40	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	28	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	37	Hourly Installation Rate ($/Hr)	100
Design Levels	10	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	50	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	3	Economic Life of Project (Yrs)	10
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	12000
Hours per Lamp Start	10	Luminaire Cleaning Cycle (Hrs)	12000
Operating Hours per Year	2600	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	277		
Actual Voltage (Vrms)	277		
Ballast Type	CWA		
Area Cleaning Interval (months)	24		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	400	400	400
Lamp Type	MH	MH	MH
No. of Luminaires	16	17	17
Mounting Height	28	29	30
LLF	0.3599	0.3596	0.3593
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	7328	7786	7786
LCC	$ 23983.32	$ 25482.28	$ 25482.28
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	400	400	400
Lamp Type	MH	MH	MH
No. of Luminaires	16	17	17
Mounting Height	28	29	30
LLF	0.3599	0.3596	0.3593
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	7328	7786	7786
LCC	$ 23983.32	$ 25482.28	$ 25482.28
Design ID	D	E	F

Figure 4-1: Results Generated for Industrial Scenario #1

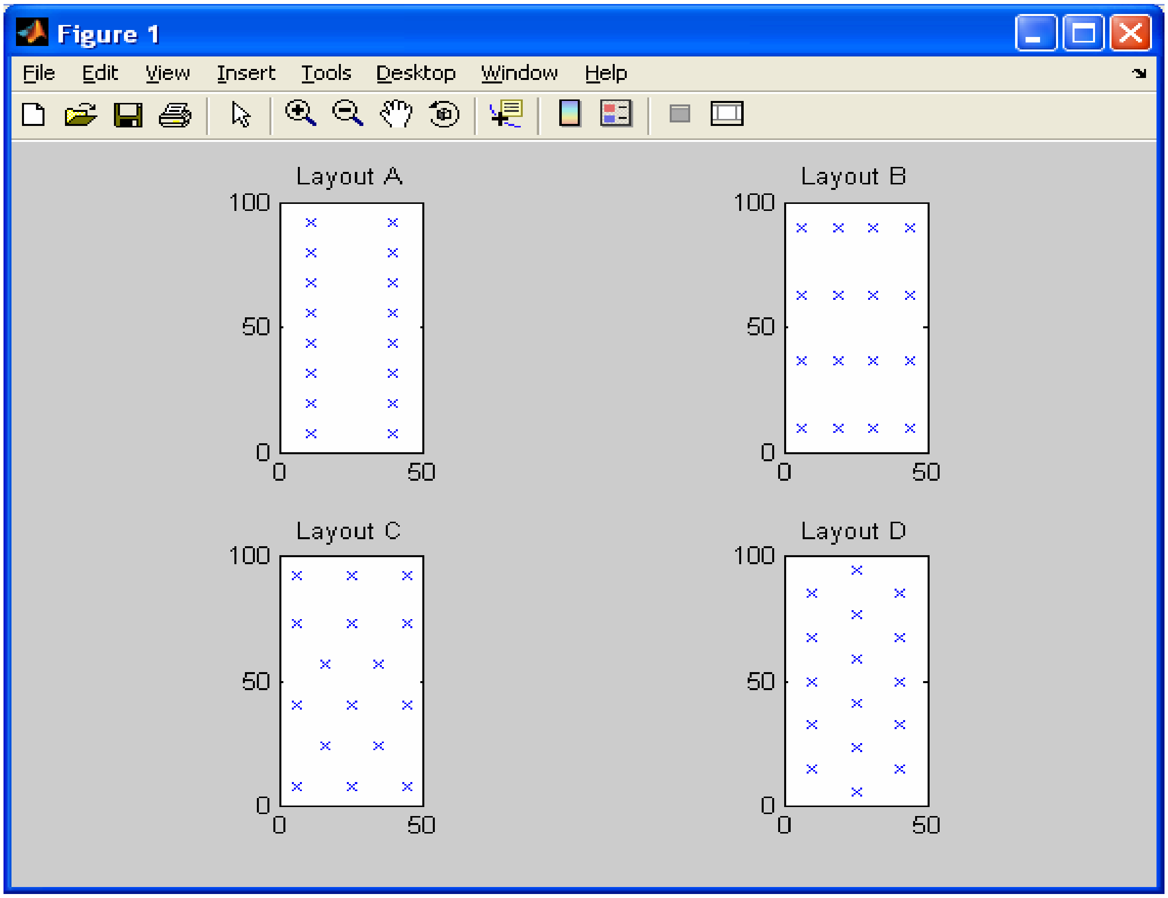


Figure 4-2: Layout Possibilities for Industrial Scenario #1, Design A

The luminaire layout program provides four possible layout configurations based upon the number of luminaires and the floor dimensions of the area in question. Two of the layouts are created by layout algorithm *layoutA1* and the others by algorithm *layoutB1*, both of which were discussed in section 3.4. At this point the user has the choice of one of the four layouts since the most preferable design is not always provided by the same algorithm and the same floor orientation. The software allows for the selection of the preferred layout option keeping in mind that the selection may have a profound impact upon the quality of the lighting project, specifically the uniformity of illumination. In general, for high-bay and low-bay photometric distributions, the layout providing the highest level of uniformity is that design which places the luminaires in the most equidistant locations from neighboring luminaires. Of the four layouts presented in Figure 4-2, Layout B displays two characteristics which are preferable for general area lighting designs. The row-to-row and column-to-columns spacings appear to be consistent, and uniformity of spacing around the perimeter appears consistent. Upon selecting Layout B, a window confirming the choice appears as shown in Figure 4-3.

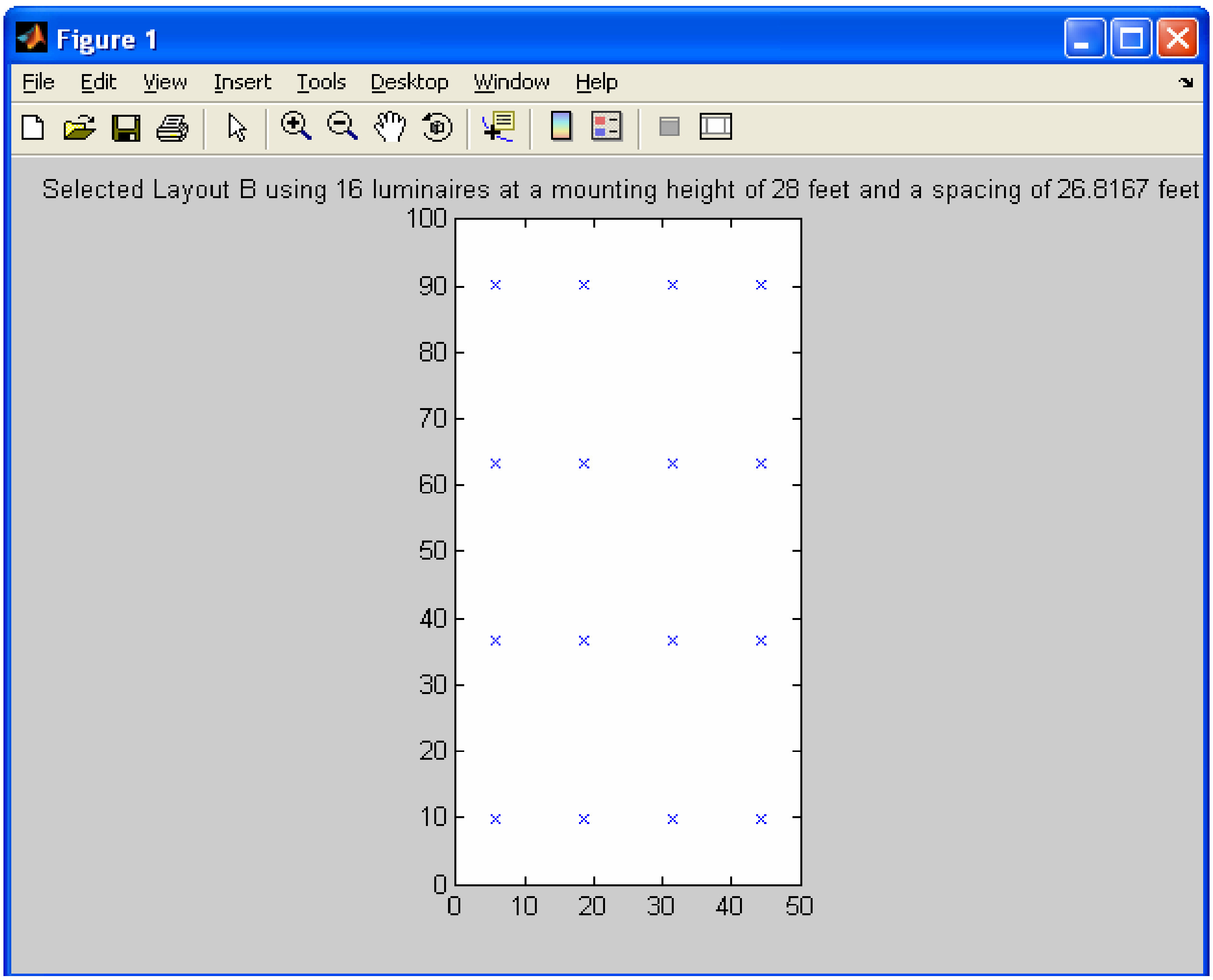


Figure 4-3: Selected Layout Confirmation – Industrial Scenario #1, Design A, Layout B

Assuming that the user is satisfied with the chosen layout, a design summary is made available which contains luminaire coordinates as will as a summary of key design results as shown in Figure 4-4.

Layout for Design A. The coordinates for a 28 foot mounting height using the 400W are:

coordinates =

5.7605	9.775
5.7605	36.592
5.7605	63.408
5.7605	90.225
18.587	9.775
18.587	36.592
18.587	63.408
18.587	90.225
31.413	9.775
31.413	36.592
31.413	63.408
31.413	90.225
44.239	9.775
44.239	36.592
44.239	63.408
44.239	90.225

Design Summary

Lamp Power	400
Lamp Type	MH
Luminaire	BL400HXBIMED
No. of Luminaires	16
Mounting Height	28
Re-Lamp (months)	55
Luminaire Cleaning (mos.)	55
Area Cleaning (yrs.)	2
Room Cavity Ratio	3.7500
Coef. of Util.	0.5951
LLF	0.3599
Total Power (W)	7328
LCC	$ 23983.32

Figure 4-4: Luminaire Coordinates and Design Summary – Industrial Scenario #1, Design A, Layout B

A listing of design summaries is offered which provides insight into the merits and demerits of each of the 30 designs that were performed. First to be displayed, as shown in Figure 4-5, is a ranked listing of designs based upon LCC which is sorted in ascending order.

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	LCC
400	1	16	28	0.35988	23983
400	1	17	29	0.35959	25482
400	1	17	30	0.35931	25482
400	1	17	31	0.35902	25482
400	1	17	32	0.35874	25482
400	1	18	33	0.35846	26981
400	1	18	34	0.35817	26981
400	1	18	35	0.35789	26981
400	1	18	36	0.3576	26981
350	1	20	28	0.35088	27308
350	1	20	29	0.3506	27308
400	1	19	37	0.35751	28480
350	1	21	30	0.35032	28673
350	1	21	31	0.35005	28673
350	1	21	32	0.34977	28673
350	1	21	33	0.34949	28673
350	1	22	34	0.34922	30038
350	1	22	35	0.34894	30038
350	1	22	36	0.34866	30038
350	1	23	37	0.34857	31404
200	1	48	28	0.26127	46966
200	1	49	29	0.26106	47944
200	1	50	30	0.26085	48923
200	1	50	31	0.26065	48923
200	1	51	32	0.26044	49901
200	1	52	33	0.26023	50880
200	1	53	34	0.26003	51858
200	1	54	35	0.25982	52836
200	1	54	36	0.25962	52836
200	1	55	37	0.25955	53815

Figure 4-5: Ranked Summary of Designs Based upon LCC – Industrial Scenario #1

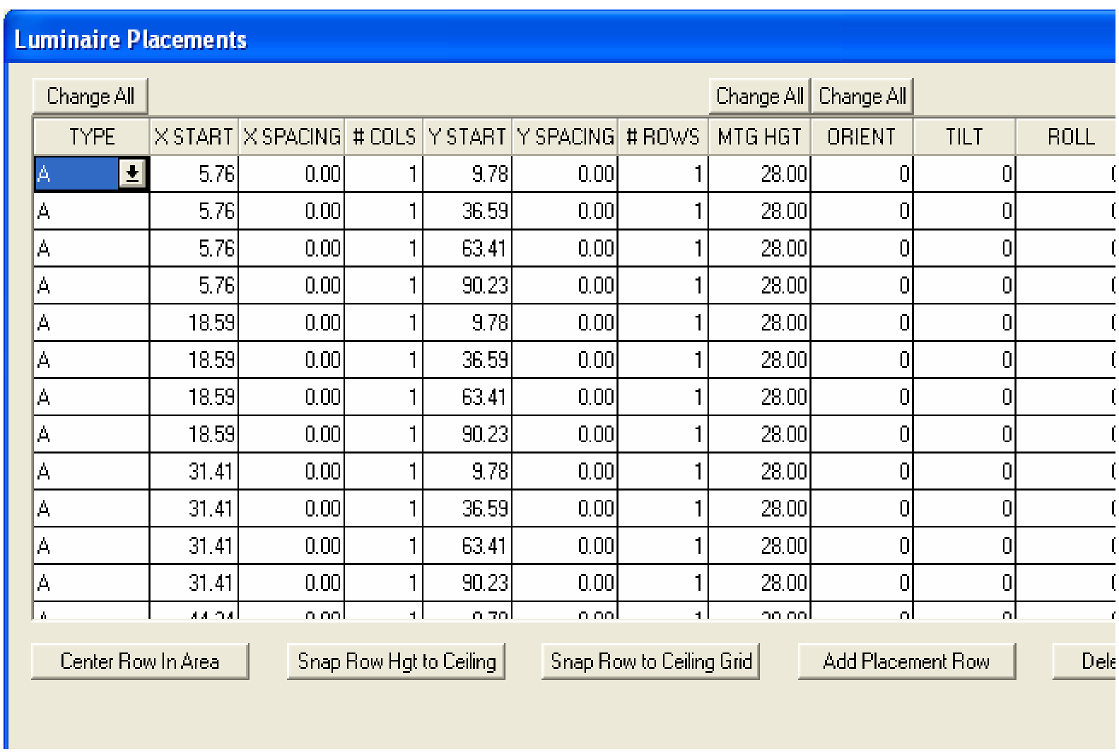
A second list is displayed as shown in Figure 4-6 which is similar to that shown in Figure 4-5, however ranking in this case is based upon total power demand. Upon review of the summary data it becomes apparent why the luminaires equipped with lower power lamps did not compare favorably with the 400W designs. The needed quantity of luminaires for the lower lamp power options inflates the LCC due to the increased energy demand, the relationships of which were discussed in section 2.5.

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	TOTAL POWER (W)
400	1	16	28	0.35988	7328
400	1	17	29	0.35959	7786
400	1	17	30	0.35931	7786
400	1	17	31	0.35902	7786
400†	1	17	32	0.35874	7786
350	1	20	28	0.35088	8000
350	1	20	29	0.3506	8000
400	1	18	33	0.35846	8244
400	1	18	34	0.35817	8244
400	1	18	35	0.35789	8244
400	1	18	36	0.3576	8244
350	1	21	30	0.35032	8400
350	1	21	31	0.35005	8400
350	1	21	32	0.34977	8400
350	1	21	33	0.34949	8400
400	1	19	37	0.35751	8702
350	1	22	34	0.34922	8800
350	1	22	35	0.34894	8800
350	1	22	36	0.34866	8800
350	1	23	37	0.34857	9200
200	1	48	28	0.26127	11136
200	1	49	29	0.26106	11368
200	1	50	30	0.26085	11600
200	1	50	31	0.26065	11600
200	1	51	32	0.26044	11832
200	1	52	33	0.26023	12064
200	1	53	34	0.26003	12296
200	1	54	35	0.25982	12528
200	1	54	36	0.25962	12528
200	1	55	37	0.25955	12760

Figure 4-6: Ranked Summary of Designs Based upon Power Demand – Industrial Scenario #1

A benefit of presenting all of the design possibilities in this manner is the ability to perform certain "what-if" analyses. For example, if it was discovered that the minimum mounting height requirement needed to be increased to 32 feet, then it is convenient to look at the listings and determine that the preferred design scenario for minimizing energy consumption is the design that employs 17, 400W luminaires with a mounting height of 32 feet (†).

For the purpose of evaluating the optical performance of the design generated by the developed software a new layout needs to be created within the LitePro® program, the use of which is illustrated in Appendix B. A method which works well is to begin with the design and layout that is generated by LitePro® (refer to Figure B-11 in Appendix B), making certain that the design parameters are consistent with those of the original design, followed by the removal and repositioning of luminaires to achieve the design and layout of Figure 4-3. This is accomplished by selecting the existing area under the Project Contents window, selecting Copy Area, and pasting it to a new area which is this case is named *IMASTERG2*. By opening the Luminaire Placement window the coordinates for the original design, which are listed in Figure 4-4, may be manually entered. Upon making the coordinate changes and removing two luminaires from the list, the lower energy design generated by the developed software may be evaluated. Figures 4-7 and 4-8 illustrate the results of the layout modifications.



TYPE	X START	X SPACING	# COLS	Y START	Y SPACING	# ROWS	MTG HGT	ORIENT	TILT	ROLL
A	5.76	0.00	1	9.78	0.00	1	28.00	0	0	
A	5.76	0.00	1	36.59	0.00	1	28.00	0	0	
A	5.76	0.00	1	63.41	0.00	1	28.00	0	0	
A	5.76	0.00	1	90.23	0.00	1	28.00	0	0	
A	18.59	0.00	1	9.78	0.00	1	28.00	0	0	
A	18.59	0.00	1	36.59	0.00	1	28.00	0	0	
A	18.59	0.00	1	63.41	0.00	1	28.00	0	0	
A	18.59	0.00	1	90.23	0.00	1	28.00	0	0	
A	31.41	0.00	1	9.78	0.00	1	28.00	0	0	
A	31.41	0.00	1	36.59	0.00	1	28.00	0	0	
A	31.41	0.00	1	63.41	0.00	1	28.00	0	0	
A	31.41	0.00	1	90.23	0.00	1	28.00	0	0	

Figure 4-7: Coordinates for Luminaires, Original Design – Industrial Scenario #1 [35]
(Used with the permission of Hubbell Incorporated)

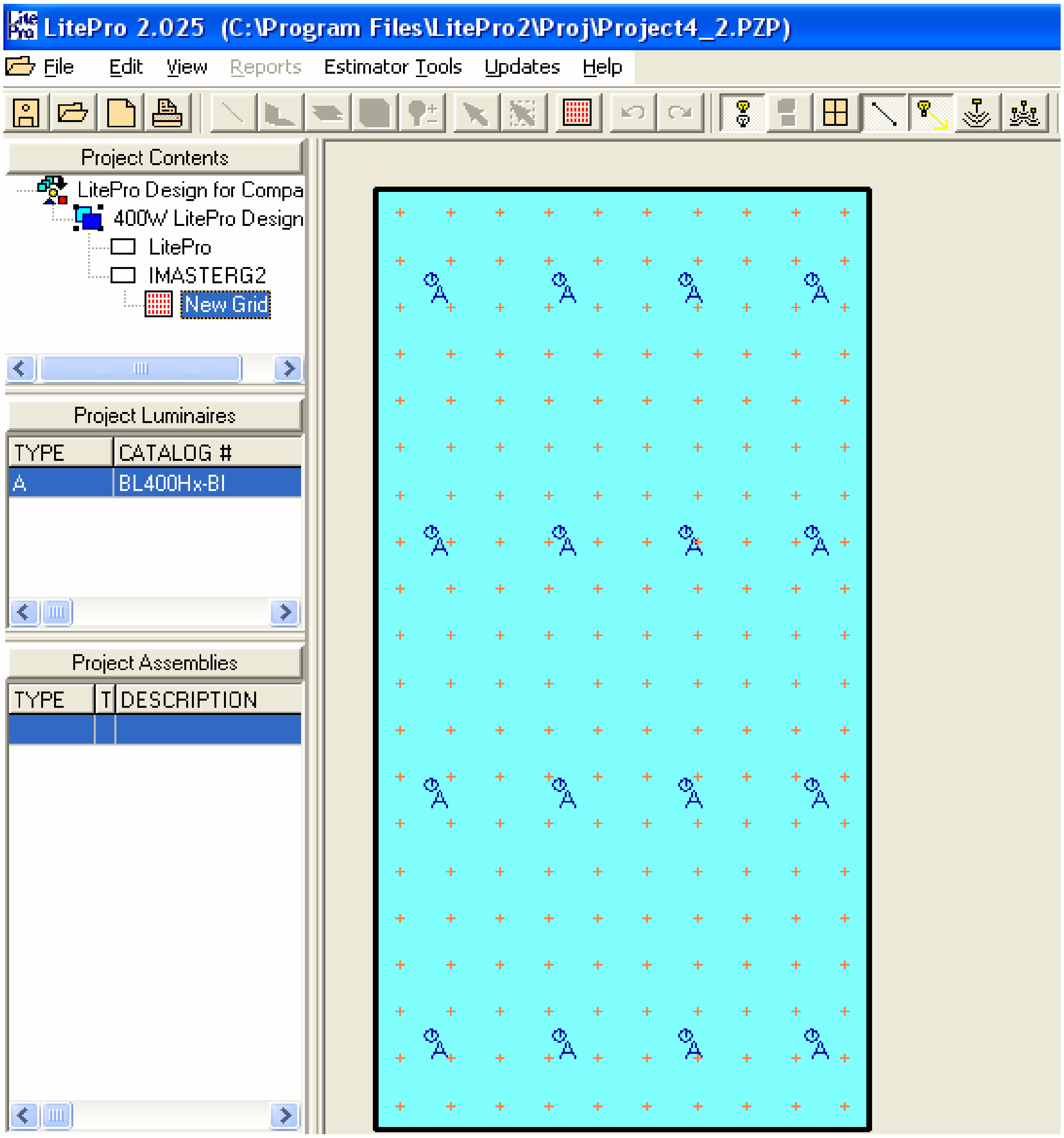


Figure 4-8: Layout Provided by Developed Software – Industrial Scenario #1 [35]
(Used with the permission of Hubbell Incorporated)

The optical performance of the design and layout provided by the developed software is determined by running the point-by-point analysis, the results of which are shown in Figure 4-9. It should be noted that no other changes to the analysis were made since luminaires, mounting heights, lamps, ballasts, etc. were the same for both the LitePro® and original designs.

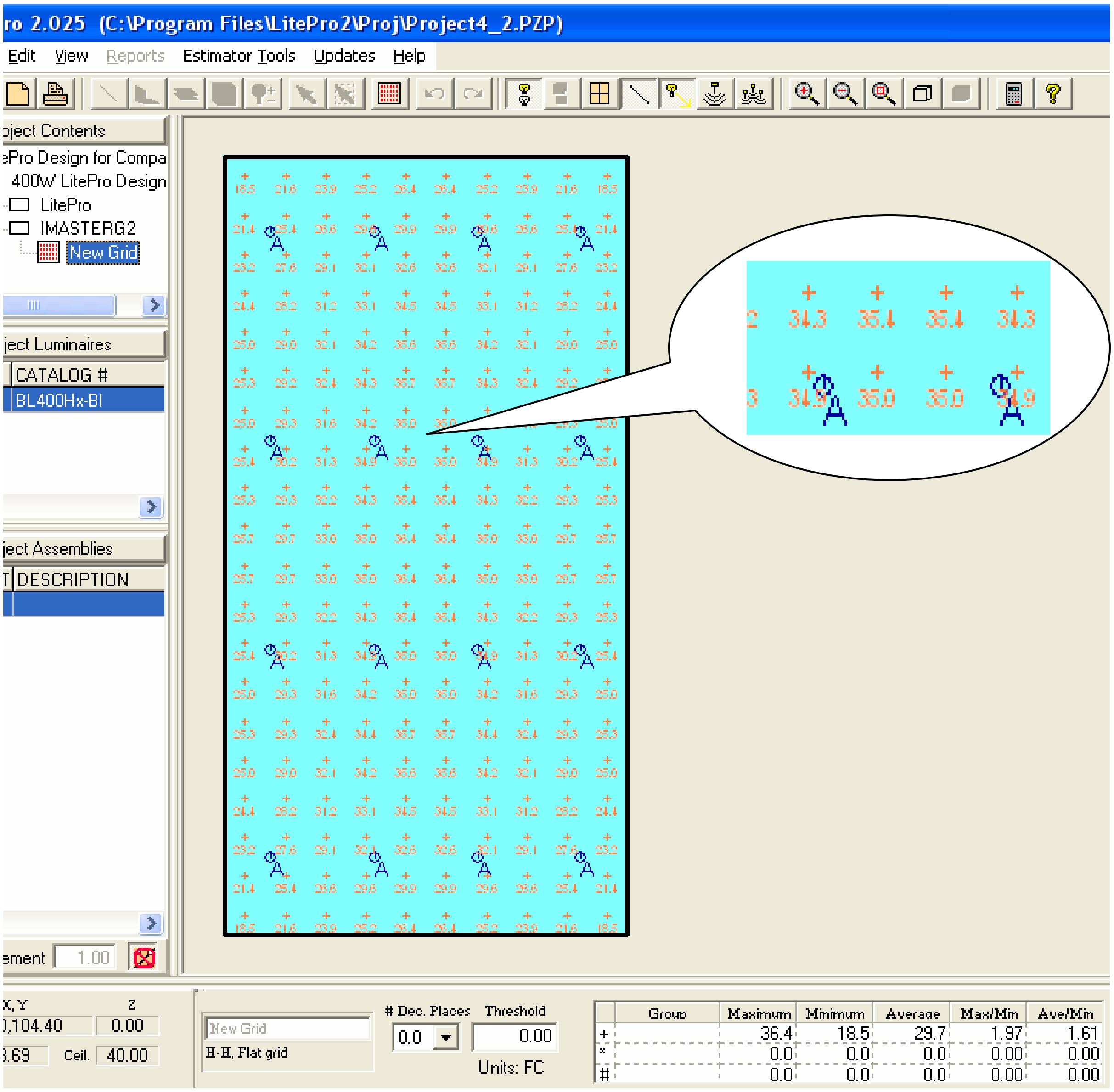


Figure 4-9: Point-by-point Analysis, Original Design – Industrial Scenario #1 [35]
(Used with the permission of Hubbell Incorporated)

A summary of the photometric analysis of both designs are presented in Table 4-2. Primary differences between the two simulations are that the design offered by the developed software results in an average maintained illumination level that is 13.6% lower than that provided by LitePro®, although both designs are predicted to meet the 30 footcandle maintained illuminance requirement to within 1%. The power demand of the original design is 11.1% lower than that of the LitePro® design which equates to the percentage of energy that could be saved. There is also an improvement in the uniformity of illumination when the original design is employed – a 1.97 max/min ratio versus the 2.31 max/min ratio offered by the LitePro® design.

Table 4-2: Summary of Lighting Design Simulation – Industrial Scenario #1

Design	No. of Luminaires	Avg. Maintained Illumination Level (fc)	Max / Min Ratio	Lighting System Power Demand (W)	Power Density (W/ft^2)
LitePro®	18	34.40	2.31	8,244	1.65
Original	16	29.71	1.97	7,328	1.47
Reduction	11.1%	13.6%	14.7%	11.1%	10.9%

A final observation is one concerning the cost of the project over its life. The LCC for the design provided by the developed software is predicted to be $23,983.32 as shown in Figure 4-4. The data presented in Figure 4-5 provides LCC information for the design provided by LitePro®, which is determined by noting the LCC for the 400W solution mounted at a height of 33 feet. The luminaire quantity in this case is the same as that of the design provided by LitePro® and results in a LCC of $26,981 reflecting an increase of $2,998 or 12.5% over that of the original design provided by the developed software. If it is determined that the uniformity is not acceptable, another of design may be selected such as design B shown in Figure 4-1. This design adds an additional luminaire, which will increase costs and lower the overall efficacy of the lighting design. However the additional luminaire combined with the greater mounting height will tend to improve the uniformity of illumination.

4.3 Demonstration of Spacing Criteria Violation (Scenario #2)

A feature incorporated into luminaire layout program prevents the layout of a design which violates the spacing criteria as discussed in section 2.4.4. To illustrate the case where luminaire spacings become to large to provide acceptable uniformity the lighting project used in Scenario #1 will again be employed. The spacing violation may be encountered for several reasons including mounting heights which are too close to the work plane, luminaires that have optical distributions that are too narrow for the application, and the reduction of required luminaires to cover the desired target area. For this example the third of these situations will be chosen, being accomplished by improving the LLF employed in Scenario #1 which results in a decrease of the quantity of luminaires to an unsatisfactory level for the lowest targeted mounting height.

By using the same lamps and luminaire types employed in Scenario #1, and increasing the frequency of maintenance (lamp replacement, luminaire cleaning, and room cleaning), the LLF has been substantially improved (increased) thus reducing the number of luminaires that are required per the lumen method. The specifications addressing these changes are given in Table 4-3, and the top results of the designs based upon this scenario (Scenario #2) are presented in Figure 4-10. Note that the number of luminaires needed for design A (and D) are 50% less than those corresponding to Scenario #1, the results of which were presented in Figure 4-1. This reduction is solely the result of improving the LLF by increased cleaning frequency and lamp replacement, which is a topic of analysis in a subsequent section of this dissertation.

The luminaire layout for design A (or D) is given in Figure 4-11. Note that Layout B appears blank with a header “Layout B is not viable due to spacing criteria violation”. The other layouts presented for this design are viable based upon the published spacing criteria, which for this particular luminaire is 1.3.

Table 4-3: Industrial Scenario #2 Specifications

Dimensions of Floor Area (W x D)	50' x 100'
Ceiling Height (feet)	40
Work Plane Height (feet)	3
Maintained Illumination Level (fc)	30
Maximum Mounting Height (feet)	37
Minimum Mounting Height (feet)	28
Ceiling Reflectance (%)	50
Wall Reflectances (%)	50
Floor Reflectance (%)	20
Cleanliness of Area (1 – 5[cleanest])	3
Lamp Type	Metal-Halide
Possible Lamp Power Levels (watts)	400, 350, 200
Lamp Initial Lumen Ratings	44,000; 37,000; 21,000 [36]
Lamp Mean Lumen Ratings	35,000; 29,000; 16,800 [36]
Rated Lamp Life (hours)	20,000; 20,000; 15,000 [36]
Luminaire Voltage (rms volts)	277
Actual Luminaire Voltage (rms volts)	277
Ballast Type	Constant Wattage Autotransformer (CWA)
Area Cleaning Period (years)	**1**†
Operating Hours per Lamp Start (hours)	10
Operating Hours per Year (hours)	2,600
Re-lamp/Luminaire Cleaning Cycle (operating hours)	**2,600**†
Unit Luminaire Cost (w/o lamp)	$150
Unit Lamp Cost	$35 (all types)

† - Quantities that differ from those of Scenario #1

If design B were selected as shown in Figure 4-10, which may be the case if the additional overhead clearance is desired, then the corresponding layout possibilities are presented in Figure 4-12. In this example the raising of the mounting height by one foot allows Layout B to satisfy the spacing criteria. Additional simulations could be performed to determine whether the optical performance of Layout B is superior to Layout C, etc. An illumination analysis is not provided since this section in included merely to point out the function of software in preventing the generation of layouts which violate the spacing criteria constraint.

Floor Width (feet)	50	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	100	Annual Interest Rate (percent)	5
Ceiling Height (feet)	40	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	28	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	37	Hourly Installation Rate ($/Hr)	100
Design Levels	10	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	50	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	3	Economic Life of Project (Yrs)	10
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	2600
Hours per Lamp Start	10	Luminaire Cleaning Cycle (Hrs)	2600
Operating Hours per Year	2600	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	277		
Actual Voltage (Vrms)	277		
Ballast Type	CWA		
Area Cleaning Interval (months)	12		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	400	400	350
Lamp Type	MH	MH	MH
No. of Luminaires	8	8	10
Mounting Height	28	29	28
LLF	0.7276	0.7271	0.7247
Coef. of Util.	0.5951	0.5864	0.5951
Total Power (W)	3664	3664	4000
LCC	$ 15324.71	$ 15324.71	$ 17820.08
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	400	400	400
Lamp Type	MH	MH	MH
No. of Luminaires	8	8	9
Mounting Height	28	29	30
LLF	0.7276	0.7271	0.7265
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	3664	3664	4122
LCC	$ 15324.71	$ 15324.71	$ 17240.30
Design ID	D	E	F

Figure 4-10: Results Generated for Industrial Scenario #2

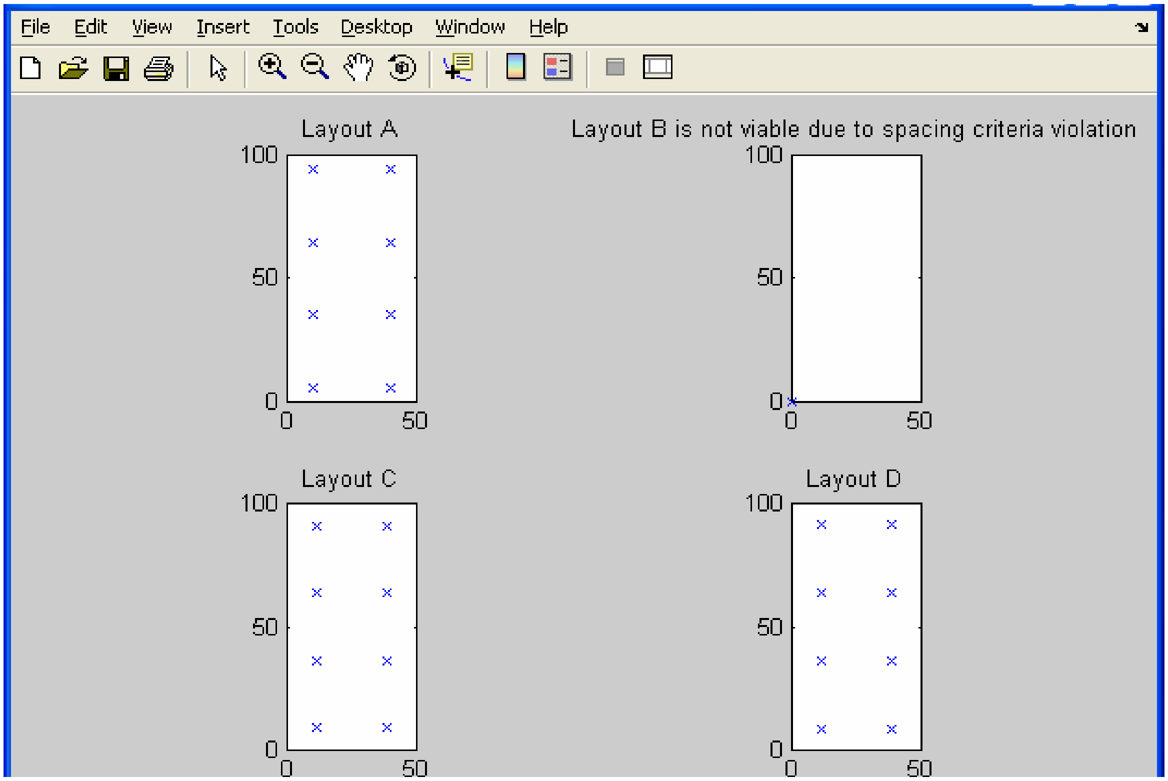


Figure 4-11: Layout Possibilities for Industrial Scenario #2, Design A

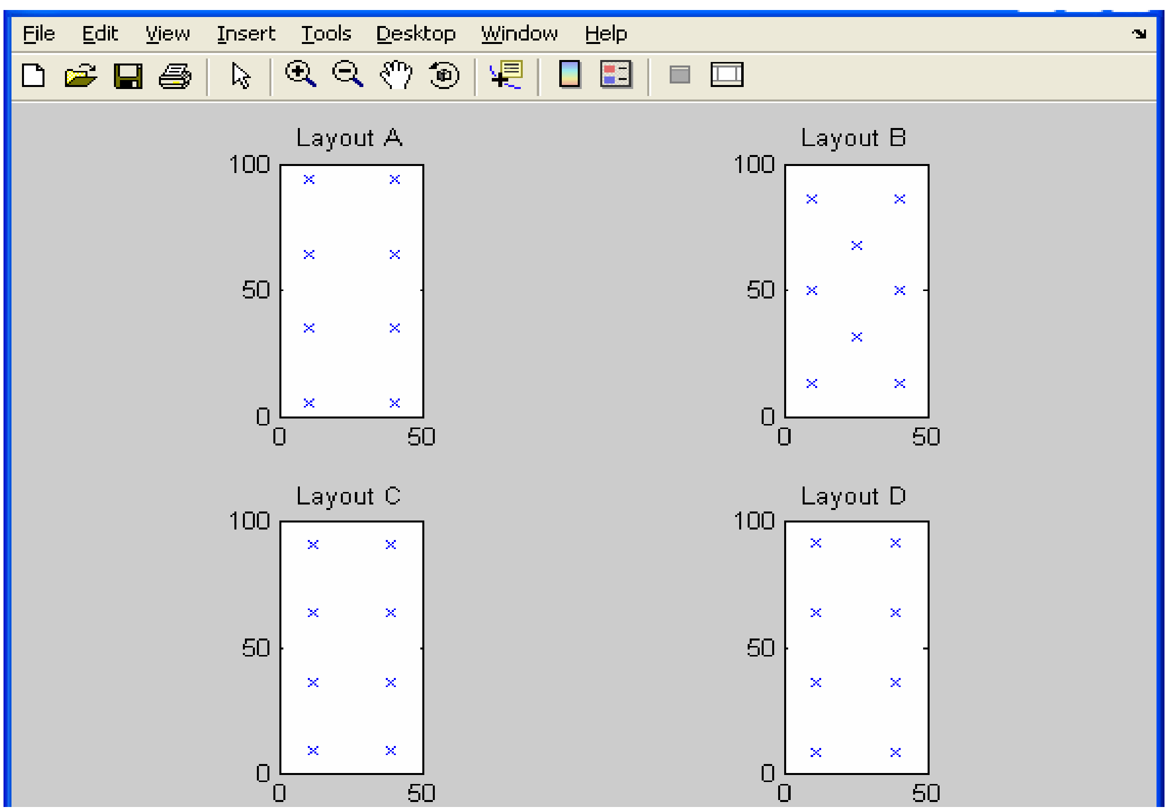


Figure 4-12: Layout Possibilities for Industrial Scenario #2, Design B

4.4 Analysis of a 200’ × 200’ Industrial Lighting Application (Scenario #3)

A final example differs from those presented in the first two scenarios. This example targets a larger area and will employ both MH and HPS sources which are operated using MR ballasts. The scenario specifications are given in Table 4-4.

Table 4-4: Industrial Scenario #3 Specifications

Dimensions of Floor Area (W x D)	200’ x 200’
Ceiling Height (feet)	35
Work Plane Height (feet)	3
Maintained Illumination Level (fc)	30
Maximum Mounting Height (feet)	32
Minimum Mounting Height (feet)	24
Ceiling Reflectance (%)	80
Wall Reflectances (%)	50
Floor Reflectance (%)	20
Cleanliness of Area (1 – 5[cleanest])	4
Lamp Type	Metal-Halide, *High-Pressure Sodium*
Possible Lamp Power Levels (watts)	400
Lamp Initial Lumen Ratings	44,000; *51,000* [36] [37]
Lamp Mean Lumen Ratings	35,000; *45,000*; [36] [37]
Rated Lamp Life (hours)	20,000; *24,000*; [36] [37]
Luminaire Voltage (rms volts)	480
Actual Luminaire Voltage (rms volts)	456
Ballast Type	Magnetic Regulator
Area Cleaning Period (years)	1
Operating Hours per Lamp Start (hours)	20
Operating Hours per Year (hours)	7280
Re-lamp/Luminaire Cleaning Cycle (operating hours)	14,000
Unit Luminaire Cost (w/o lamp)	$200
Unit Lamp Cost	$35 (MH); $25 (HPS)

This lighting application is for an industrial facility measuring 200 feet by 200 feet. The permissible mounting heights are between 24 and 32 feet with a ceiling height of 35 feet. Designs based upon both 400W MH and HPS lamps will be performed with the anticipation that the lighting branch circuit voltage will be 5% below nominal. This facility operates on a two-shift, seven day per week basis resulting in 7280 operating hours per year. The planned re-lamping and luminaire cleaning interval will be 14,000 operating hours which is 70% of the rated life of the MH lamp but only 58.3% of the rated life in the case of the HPS lamp. Figure 4-13 presents the most efficient and financially attractive designs generated by the developed software.

Floor Width (feet)	200	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	200	Annual Interest Rate (percent)	5
Ceiling Height (feet)	35	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	24	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	32	Hourly Installation Rate ($/Hr)	100
Design Levels	5	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	80	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	4	Economic Life of Project (Yrs)	15
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	14000
Hours per Lamp Start	20	Luminaire Cleaning Cycle (Hrs)	14000
Operating Hours per Year	7280	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	480		
Actual Voltage (Vrms)	456		
Ballast Type	MR		
Area Cleaning Interval (months)	12		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	400	400	400
Lamp Type	HPS	HPS	HPS
No. of Luminaires	46	46	47
Mounting Height	24	26	28
LLF	0.6143	0.6143	0.6143
Coef. of Util.	0.8405	0.8337	0.8270
Total Power (W)	22540	22540	23030
LCC	$245449.16	$245449.16	$250785.02
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	400	400	400
Lamp Type	HPS	HPS	HPS
No. of Luminaires	46	46	47
Mounting Height	24	26	28
LLF	0.6143	0.6143	0.6143
Coef. of Util.	0.8405	0.8337	0.8270
Total Power (W)	22540	22540	23030
LCC	$245449.16	$245449.16	$250785.02
Design ID	D	E	F

Figure 4-13: Results Generated for Industrial Scenario #3

The HPS designs, identified as lamp type 2, are ranked as the most preferable both on the basis of LCC and power consumption. This is due to the large disparity between lamp efficacies of the two sources and the LLF associated with each. Complete ranked lists of all designs are presented in Figure 4-14 and 4-15, where MH designs are identified as lamp type 1. The proposed layout using the 400W HPS luminaires at a mounting height of 26 feet (design B) is shown in Figure 4-16. The rationale for selecting design B over design A is that both designs result in the same luminaire count, power demand and LCC, however the increased mounting height offers additional clearance from the manufacturing floor and the probability of providing improved uniformity of illumination levels.

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	LCC
400	2	46	24	0.61435	2.4545e+005
400	2	46	26	0.61435	2.4545e+005
400	2	47	28	0.61435	2.5079e+005
400	2	47	30	0.61435	2.5079e+005
400	2	48	32	0.61435	2.5612e+005
400	1	69	24	0.45708	3.5706e+005
400	1	70	26	0.45708	3.6223e+005
400	1	70	28	0.45708	3.6223e+005
400	1	71	30	0.45708	3.6741e+005
400	1	71	32	0.45708	3.6741e+005

Figure 4-14: Ranked Summary of Designs Based upon LCC – Industrial Scenario #3

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	TOTAL POWER (W)
400	2	46	24	0.61435	22540
400	2	46	26	0.61435	22540
400	2	47	28	0.61435	23030
400	2	47	30	0.61435	23030
400	2	48	32	0.61435	23520
400	1	69	24	0.45708	32085
400	1	70	26	0.45708	32550
400	1	70	28	0.45708	32550
400	1	71	30	0.45708	33015
400	1	71	32	0.45708	33015

Figure 4-15: Ranked Summary of Designs Based upon Power Demand – Industrial Scenario #3

Again utilizing the LitePro® analysis software, the selected layout may be evaluated and compared to one generated by the commercially available software. A summary of the performance of both the original design and the LitePro® design is presented in Table 4-5. The reduced number of luminaires proposed by the developed software results in a power reduction of 1470 watts or a savings of 6.1%. The penalty for this savings however is a reduction of maintained illuminance of 4.4% and a significant reduction in uniformity going from a 2.43 max-to-min ratio to one of 3.05. In this example it would be the choice of the end user to determine whether or not the energy savings that would be realized merits this reduction in optical performance.

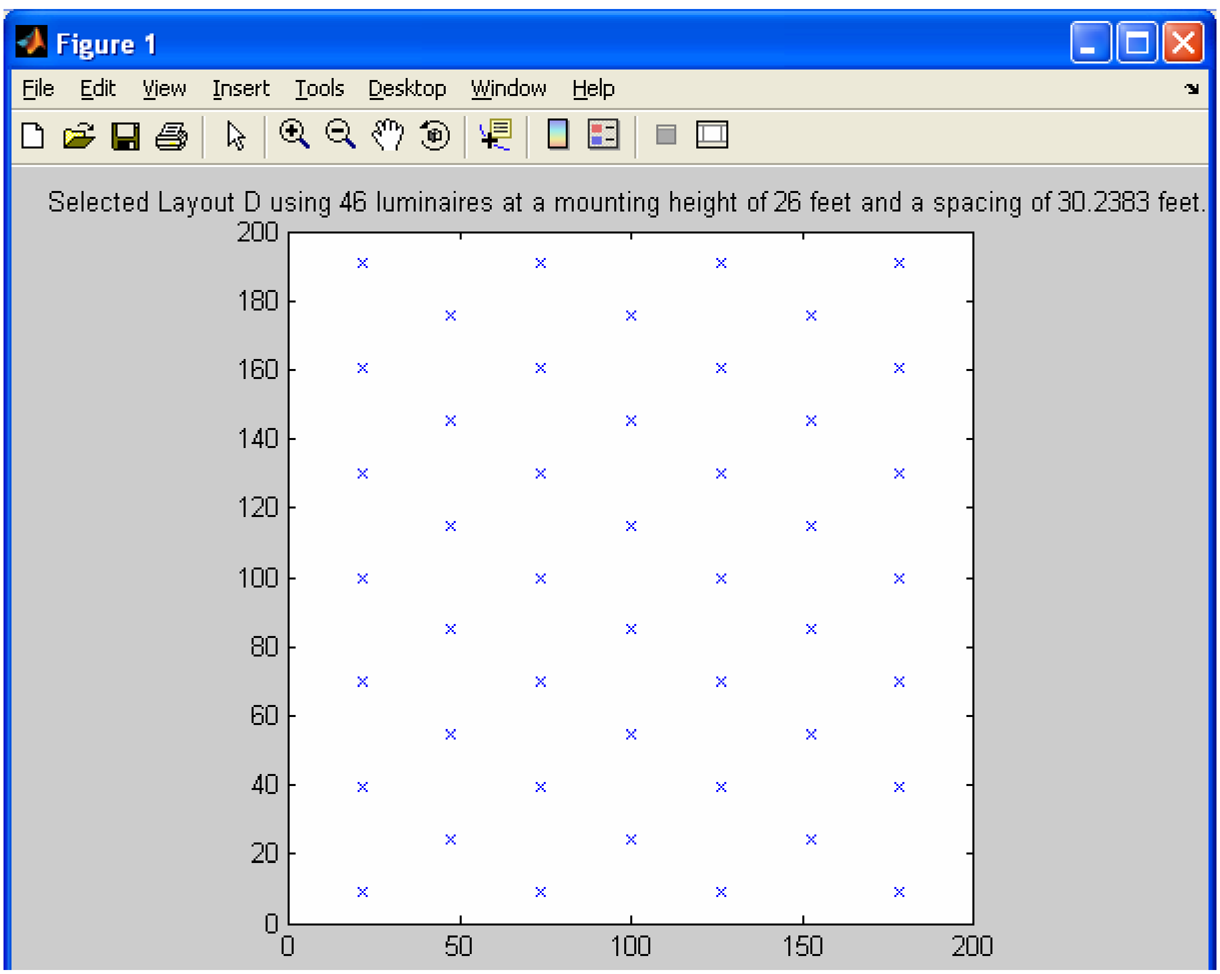


Figure 4-16: Selected Layout Confirmation – Industrial Scenario #3, Design B, Layout D

If the color and color rendering of HPS sources are not limiting considerations, as it pertains to energy and cost, the choice of industrial lighting designs that weigh both MH and HPS options will always favor HPS due to its higher efficacy, longer life, and superior lumen maintenance. One could always improve the LLF of the MH case by re-lamping on a more frequent basis to reduce the number of MH luminaires that are needed, however that step is not necessary to demonstrate the validity of the software that has been created.

Table 4-5: Summary of Lighting Design Simulation – Industrial Scenario #3

Design	No. of Luminaires	Avg. Maintained Illumination Level (fc)	Max / Min Ratio	Lighting System Power Demand (W)	Power Density (W/ft^2)
LitePro®	49	30.63	2.43	24,010	0.60
Original	46	29.27	3.05	22,540	0.56
Reduction	6.1%	4.4%	(-25.5%)	6.1%	10%

The design results presented in Table 4-5 meet the specifications (within 3%) of the lighting application with the exception of uniformity. As stated previously it is desirable that the max-to-min ratio be less than or equal to 1.4, and in both cases above these ratios well exceed this value. At this juncture there are several possibilities that the lighting designer may explore. High on this list is to simply augment the low illuminance areas with the addition of supplemental luminaires, with the penalty being the increase in energy consumption and LCC. Rectangular target areas typically display low light levels in the corners due to the lack of luminaires in the immediate vicinity. Adding several lower power luminaires, on type of which is referred to as a "wall washer", is a method that is often employed to augment illuminance levels along walls and in corners. Another option would be to investigate designs using high-output fluorescent luminaires, which is an alternative not supported by the research. A third alternative would be the use of luminaires with other photometric distributions which employ the same sources and control gear as those used in the original designs. Other alternatives could also be explored including the manual relocation of existing luminaires to increase illumination in low level areas.

The developed software is able to utilize any industrial high-bay or low-bay luminaire that has the photometric data placed in a file of the correct form as illustrated in Figure A-3 (Appendix A). The luminaires used in the original designs of this scenario (#3) exhibited photometric distributions that are categorized as *medium*. In contrast there are also *narrow* and *wide* distributions which offer the lighting designer a greater range of possibilities in satisfying the application requirements. A narrow photometric distribution exhibits a more directional downward concentration of luminous flux and it most often used when mounting heights are relatively great, and as a result these luminaires have the lowest spacing criteria limits. Wide distributions however provide more luminous flux across the horizontal plane and are not as effective at directing light downwards. Luminaires with these distributions possess greater spacing criteria values and are popular when vertical illuminance is critical such as in warehouses and large retail facilities.

Designs for this scenario (#3) were recalculated with no changes to the specifications shown in Table 4-4, and the only difference being the use of a wide distribution luminaires BL400SXBIWID and BL400MHBIWID. The results of these designs are given in Figure 4-17. Comparing these results to those of the luminaires with medium distributions in Figure 4-13, the number of luminaires required has increased in the case where the developed software was used, which is due to the lower CU values associated with the wide distribution luminaires. The design generated by LitePro® using these luminaires results in the same number of luminaires that were previously recommended. It should be noted that the mounting height has now dropped to 24 feet corresponding to designs A and D which were generated by the developed software as shown in Figure 4-17.

Floor Width (feet)	200	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	200	Annual Interest Rate (percent)	5
Ceiling Height (feet)	35	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	24	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	32	Hourly Installation Rate ($/Hr)	100
Design Levels	5	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	80	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	4	Economic Life of Project (Yrs)	15
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	14000
Hours per Lamp Start	20	Luminaire Cleaning Cycle (Hrs)	14000
Operating Hours per Year	7280	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	480		
Actual Voltage (Vrms)	456		
Ballast Type	MR		
Area Cleaning Interval (months)	12		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	400	400	400
Lamp Type	HPS	HPS	HPS
No. of Luminaires	47	48	48
Mounting Height	24	26	28
LLF	0.6143	0.6143	0.6143
Coef. of Util.	0.8199	0.8118	0.8034
Total Power (W)	23030	23520	23520
LCC	$250785.02	$256120.87	$256120.87
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	400	400	400
Lamp Type	HPS	HPS	HPS
No. of Luminaires	47	48	48
Mounting Height	24	26	28
LLF	0.6143	0.6143	0.6143
Coef. of Util.	0.8199	0.8118	0.8034
Total Power (W)	23030	23520	23520
LCC	$250785.02	$256120.87	$256120.87
Design ID	D	E	F

Figure 4-17: Results Generated for Industrial Scenario #3 – Wide Luminaire Distribution

The results of the associated illumination simulation and analysis are presented in Table 4-6, and although the uniformity increases in both design cases (original and LitePro®), the values of the max-to-min ratios remain well above recommended levels. It may be concluded that this application may be best served by the use of strategically placed supplemental luminaires to increase the illumination levels in those areas which are deficient.

Table 4-6: Summary of Lighting Design Simulation, Industrial Scenario #3 – Wide Luminaire Distribution

Design	No. of Luminaires	Avg. Maintained Illumination Level (fc)	Max / Min Ratio	Lighting System Power Demand (W)	Power Density (W/ft^2)
LitePro®	49	29.42	2.37	24,010	0.60
Original	47	28.34	2.46	23,030	0.58
Reduction	4.1%	3.7%	(-3.8%)	4.1%	3.3%

5 Simulation Analyses and Results

5.1 Impact of Lamp Selection

To illustrate the importance of lamp selection in the lighting design process consider Industrial Lighting Scenario #1, the specifications of which are given in section 4.2. A change to one of the sources will be made to illustrate the impact of lamp selection upon lighting system design and performance. This change is that the high-output 400W MH lamp will be replaced by a lower cost, lower output *universal burn* 400W MH lamp, changing the specifications as illustrated in Table 5-1.

Table 5-1: Specifications for Industrial Scenario #1 w/ Lamp Substitution

Dimensions of Floor Area (W x D)	50' x 100'
Ceiling Height (feet)	40
Work Plane Height (feet)	3
Maintained Illumination Level (fc)	30
Maximum Mounting Height (feet)	37
Minimum Mounting Height (feet)	28
Ceiling Reflectance (%)	50
Wall Reflectances (%)	50
Floor Reflectance (%)	20
Cleanliness of Area (1 – 5[cleanest])	3
Lamp Type	Metal-Halide
Possible Lamp Power Levels (watts)	400, 350, 200
Lamp Initial Lumen Ratings	**36,000**†; 37,000; 21,000 [36]
Lamp Mean Lumen Ratings	**23,000**†; 29,000; 16,800 [36]
Rated Lamp Life (hours)	20,000; 20,000; 15,000 [36]
Luminaire Voltage (rms volts)	277
Actual Luminaire Voltage (rms volts)	277
Ballast Type	Constant Wattage Autotransformer (CWA)
Area Cleaning Period (years)	2
Operating Hours per Lamp Start (hours)	10
Operating Hours per Year (hours)	2,600
Re-lamp/Luminaire Cleaning Cycle (operating hours)	12,000
Unit Luminaire Cost (w/o lamp)	$150
Unit Lamp Cost	**$30 (400W)** †, $35 (200W, 350W)

†- Quantities that differ from scenario #1, section 4.2

The term *universal burn* means that this lamp may be successfully operated in any physical orientation, making it attractive from a purchasing and stocking perspective. This less expensive lamp has an initial cost which is approximately $5 less than the 400W MH lamp used in the original example of section 4.2 [37]. The new 400W MH lamp has the same life rating as the higher-output lamp, however it has an initial output rating of 36,000 lumens and a mean lumen rating of 23,000, both of which are significantly lower than the ratings of the more expensive 400W lamp originally used [38]. The design process was repeated and compared to the designs presented in section 4.2, however for reasons of brevity only the key elements and results are presented. Figure 5-1 presents the most attractive designs based upon the new criteria.

The primary difference between the design results presented in Figure 5-1 and those of Figure 4-1 is that the 400W MH designs have been supplanted by designs using the 350W products from both energy consumption and LCC perspectives. Recall that the 350W MH designs were originally ranked below the higher (lamp) output 400W designs in the lists shown in Figures 4-5 and 4-6. Referring to Figure 5-2, the impact of employing the less expensive, lower output 400W MH lamp is more clearly demonstrated. Due to the reduced initial and mean lamp output levels the most preferable 400W MH designs have gone from the most favorable, as was the case in section 4.2, to the tenth position (and below) with regard to LCC. In the case of power consumption the comparison is even more striking as shown in Figure 5-3. Under these circumstances the designs using 400W luminaires with lower output lamps have become the most inefficient of all designs. Installing 400W luminaires at a mounting height of 28 feet which are equipped with the lower cost standard lamp has increased the projected power consumption from 7,328 watts, as shown in Figure 4-1, to 13,740 watts - an increase of 87.5%. The proposed layout using the 350W luminaires at a mounting height of 28 feet (design A) is shown in Figure 5-4. Again utilizing the LitePro® analysis software, the layout may be evaluated as shown in Figure 5-5.

Floor Width (feet)	50	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	100	Annual Interest Rate (percent)	5
Ceiling Height (feet)	40	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	28	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	37	Hourly Installation Rate ($/Hr)	100
Design Levels	10	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	50	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	3	Economic Life of Project (Yrs)	10
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	12000
Hours per Lamp Start	10	Luminaire Cleaning Cycle (Hrs)	12000
Operating Hours per Year	2600	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	277		
Actual Voltage (Vrms)	277		
Ballast Type	CWA		
Area Cleaning Interval (months)	24		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	350	350	350
Lamp Type	MH	MH	MH
No. of Luminaires	20	20	21
Mounting Height	28	29	30
LLF	0.3509	0.3506	0.3503
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	8000	8000	8400
LCC	$ 27307.54	$ 27307.54	$ 28672.91
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	350	350	350
Lamp Type	MH	MH	MH
No. of Luminaires	20	20	21
Mounting Height	28	29	30
LLF	0.3509	0.3506	0.3503
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	8000	8000	8400
LCC	$ 27307.54	$ 27307.54	$ 28672.91
Design ID	D	E	F

Figure 5-1: Results Generated by IMASTERG2 for Industrial Scenario #1 w/ Lamp Modification

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	LCC
350	1	20	28	0.35088	27308
350	1	20	29	0.3506	27308
350	1	21	30	0.35032	28673
350	1	21	31	0.35005	28673
350	1	21	32	0.34977	28673
350	1	21	33	0.34949	28673
350	1	22	34	0.34922	30038
350	1	22	35	0.34894	30038
350	1	22	36	0.34866	30038
350	1	23	37	0.34857	31404
400	1	30	28	0.23917	44538
400	1	30	29	0.23898	44538
400	1	31	30	0.23879	46022
400	1	31	31	0.2386	46022
200	1	48	28	0.26127	46966

Figure 5-2: Ranked Summary (partial) of Designs Based upon LCC – Industrial Scenario #1 with Lamp Modification

PWR LVL(W)	LAMP	QTY.	MTG. HGHT	LLF	TOTAL POWER (W)
350	1	20	28	0.35088	8000
350	1	20	29	0.3506	8000
350	1	21	30	0.35032	8400
350	1	21	31	0.35005	8400
350	1	21	32	0.34977	8400
350	1	21	33	0.34949	8400
350	1	22	34	0.34922	8800
350	1	22	35	0.34894	8800
350	1	22	36	0.34866	8800
350	1	23	37	0.34857	9200
200	1	48	28	0.26127	11136
200	1	49	29	0.26106	11368
200	1	50	30	0.26085	11600
200	1	50	31	0.26065	11600
200	1	51	32	0.26044	11832
200	1	52	33	0.26023	12064
200	1	53	34	0.26003	12296
200	1	54	35	0.25982	12528
200	1	54	36	0.25962	12528
200	1	55	37	0.25955	12760
400	1	30	28	0.23917	13740
400	1	30	29	0.23898	13740

Figure 5-3: Ranked Summary of Designs Based upon Power Demand – Industrial Scenario #1 with Lamp Modification

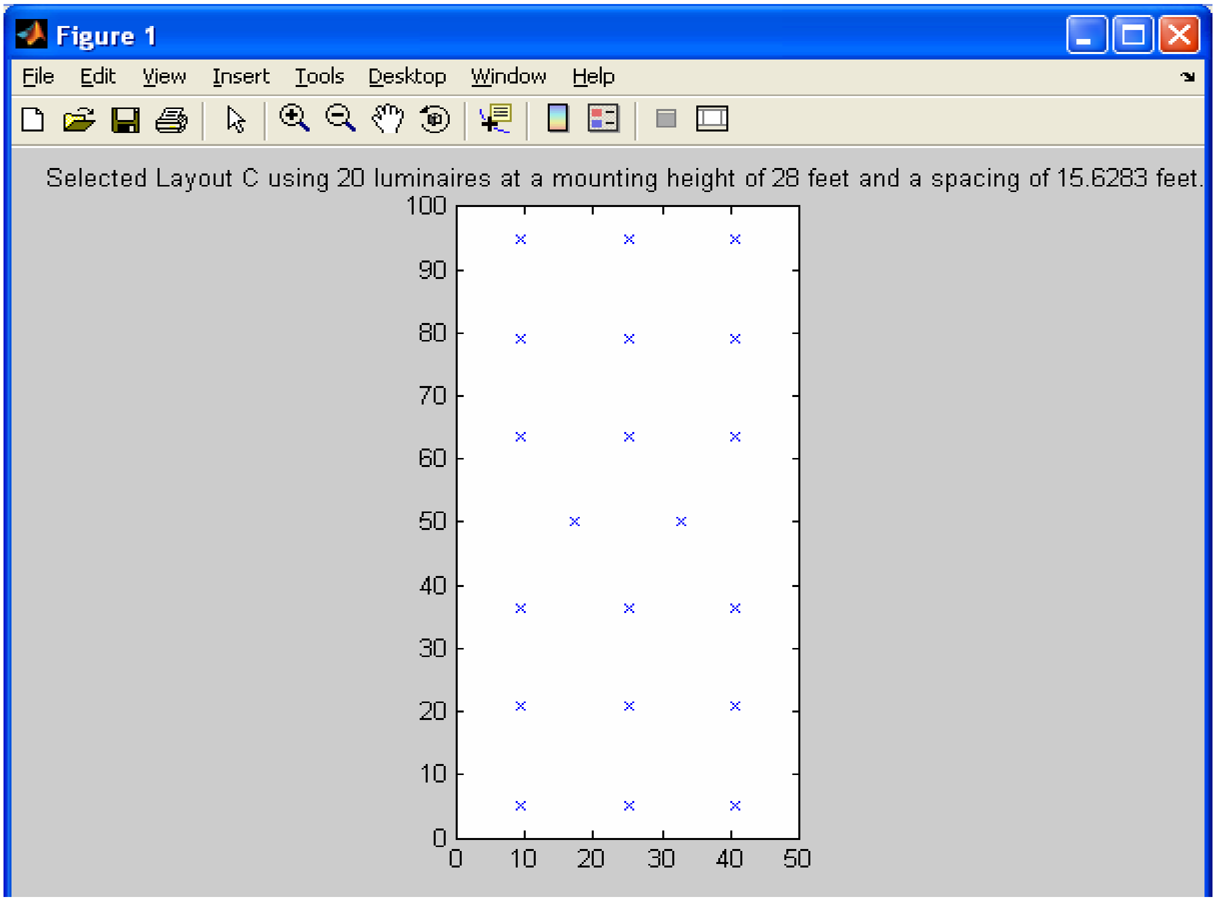


Figure 5-4: Industrial Scenario #1 with 350W Luminaire, Design A, Layout C

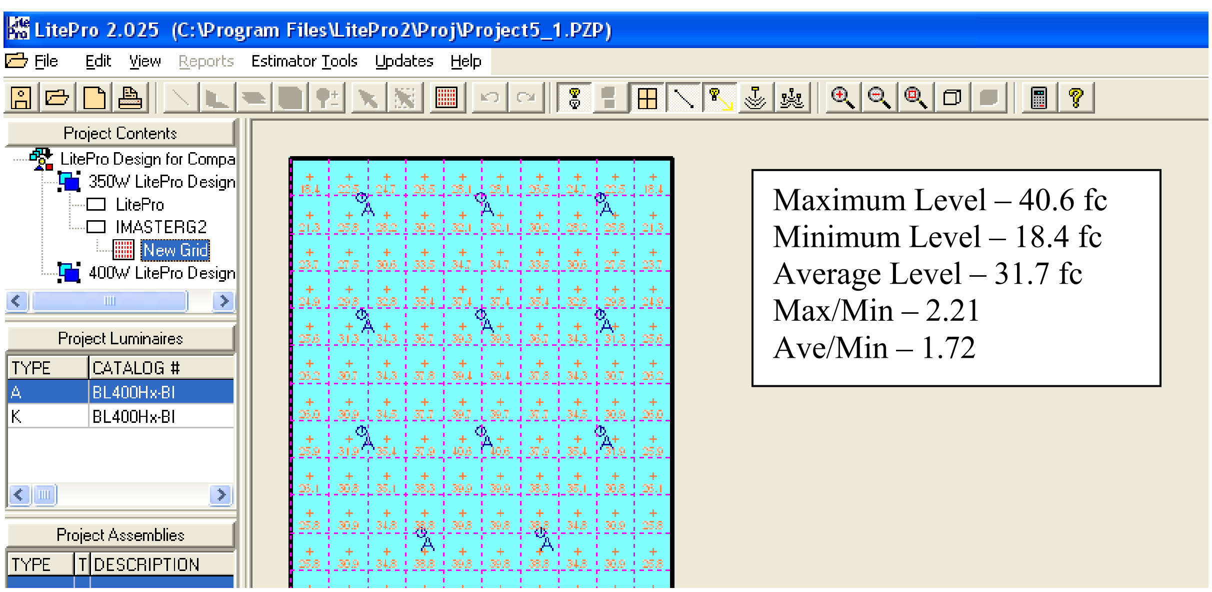


Figure 5-5: Point-by-point Analysis, Original Design (20, 350W @ 28 feet) [35]
(Used with the permission of Hubbell Incorporated)

To satisfy the lighting project requirements one may chose to use the 20 luminaires equipped with 350W MH lamps versus the 16 luminaires equipped with the higher-output 400W MH lamps for the original design of section 4.2. Table 5-2 presents the key differences between the two alternatives with the 400W data originally presented in section 4.2. These differences can be traced to the additional four luminaires that would be required which would increase the energy consumption by approximately 9.2% even though the unit luminaire input power requirement is reduced. The LCC for the lighting project will increase by $3,325 and the projected gain in maintained illumination levels would only be 2.0 footcandles.

Table 5-2: Comparison of Preferred 400W (section 4.2) and 350W (section 5.1) Designs

MH Lamp	Luminaire Qty.	Total Power (W)	LCC	Illuminance (fc)
400W (44k lumen)	16	7328	$23,983	29.7
350W (37k lumen)	20	8000	$27,308	31.7
Change	+25%	+9.2%	+13.9%	+6.7%

Another possible approach would be to install luminaires based upon the lower output 400W lamp. If the lower cost 400W MH lamp were selected, the results is 30 - 400W luminaires would be required as illustrated in Figure 5-6. Note that the maintenance and lamp replacement intervals are the same originally specified in scenario #1. A simulation of this design was performed and the key outcomes for both this design and the 400W higher output design (section 4.2) are summarized in Table 5-3.

By selecting the 36,000 lumen 400W MH lamp to satisfy Industrial Scenario #1 the result is a substantial amount of wasted energy, not to mention wasted money. Due to the lower initial lumen output and lower LLF based upon project maintenance requirements (0.23917 in Figure 5-2 versus 0.35988 in Figure 4-5), the luminaire requirement increases by 14 or +87.5%. As mentioned previously the power and therefore energy consumption increases by the same percentage, and along with other financial adjustments associated with the change combines to increase the LCC by 85.7% or $20,555.

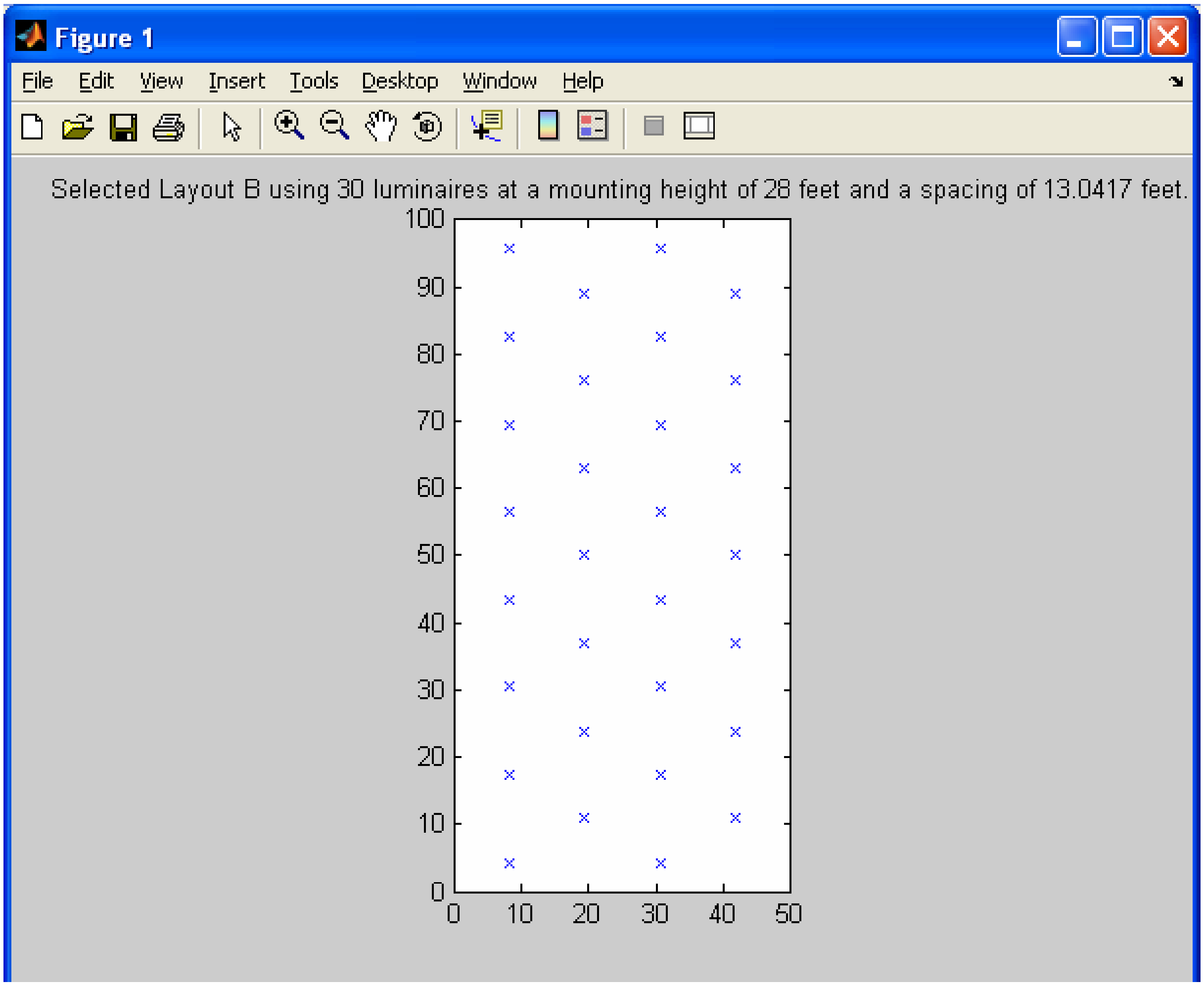


Figure 5-6: Industrial Scenario #1 with 400W Lower Output Lamp, Design A, Layout B

Table 5-3: Comparison of Preferred 400W (section 4.2) and 400W (section 5.1) Designs

MH Lamp	Luminaire Qty.	Total Power (W)	LCC	Illuminance (fc)
400W (44,000 lumens)	16	7328	$23,983	29.7
400W (36,000 lumens)	30	13,740	$44,538	31.8
Change	+87.5%	+87.5%	+85.7%	+7.1%

5.2 Impact of Ballast Selection

As stated in section 3.7, the choice of ballast has an impact upon the overall LLF which affects the number of luminaires that are needed to satisfy a lighting application. Ballast line-side regulation plays an important role as expressed by Equations 2.5, 2.6 and A.4 which is located in Appendix A. Regulating ballasts (CWA and MR) have relatively high power losses, but do not allow lamp output levels to drop as greatly under low supply voltage conditions as do the more electrically efficient reactor (RX) ballasts. So, the tradeoff between RX and regulating ballasts can be summarized as high efficiency versus supply voltage variation tolerance. The other key loss factor associated with ballast selection is the rate of lamp lumen depreciation (LLD) exhibited by lamps operated by various ballast configurations. As discussed in section 3.2, data taken from the Rector Field House on the campus of Virginia Tech over the period from May 1998 until May 2002 suggests that LLD is improved in 400W MH lamps when operated using MR ballasts [2]. This improvement, which has been incorporated into the software developed to facilitate this research, is governed by Equations 3.6, 3.7 and 3.8.

To illustrate the impact of ballast selection upon lighting project efficiency and LCC, the same application (scenario #1) will be recalculated using both CWA and MR ballasts and 400W MH sources. The specifications for this application are outlined in Table 4-1 with the only difference being that both ballast types (CWA and MR) will be considered and it will be assumed that there is a $100 per unit luminaire premium for usage of the MR ballast. The design results for the luminaires equipped with CWA ballasts were previously presented in Figure 4-1, and the comparable results for luminaires equipped with MR ballasts is presented in Figure 5-7. The preferred layout based upon Design A using MR ballasts is presented in Figure 5-8.

Floor Width (feet)	50	Cost of Energy ($/kW-Hr)	0.07
Floor Depth (feet)	100	Annual Interest Rate (percent)	5
Ceiling Height (feet)	40	Annual Inflation Rate (percent)	4
Work Plane (feet)	3	Hourly Maintenance Rate ($/Hr)	50
Min. Mounting Height (feet)	28	Time Required for Service (Hr)	0.5
Max. Mounting Height (feet)	37	Hourly Installation Rate ($/Hr)	100
Design Levels	10	Time Required for Install (Hr)	1
Ceiling Reflectance (percent)	50	Additional Material Cost ($)	20
Wall Reflectance (percent)	50	Time Required for Scrap (Hr)	0.5
Floor Reflectance (percent)	20	Lighting / HVAC Ratio	3
Cleanliness of Area	3	Economic Life of Project (Yrs)	10
Illuminance Requirement (fc)	30	Relamp Cycle (Hrs)	12000
Hours per Lamp Start	10	Luminaire Cleaning Cycle (Hrs)	12000
Operating Hours per Year	2600	Cleaning Mat'l Charge ($/luminaire)	2
Rated Voltage (Vrms)	277		
Actual Voltage (Vrms)	277		
Ballast Type	MR		
Area Cleaning Interval (months)	24		

Would you like the display the 3 most energy efficient designs? [N for no]

Lamp Power	400	400	400
Lamp Type	MH	MH	MH
No. of Luminaires	14	14	14
Mounting Height	28	29	30
LLF	0.4224	0.4221	0.4217
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	6510	6510	6510
LCC	$ 22385.41	$ 22385.41	$ 22385.41
Design ID	A	B	C

Would you like the display the 3 most cost effective designs? [N for no]

Lamp Power	400	400	400
Lamp Type	MH	MH	MH
No. of Luminaires	14	14	14
Mounting Height	28	29	30
LLF	0.4224	0.4221	0.4217
Coef. of Util.	0.5951	0.5864	0.5778
Total Power (W)	6510	6510	6510
LCC	$ 22385.41	$ 22385.41	$ 22385.41
Design ID	D	E	F

Figure 5-7: Results Generated for Industrial Scenario #1 with MR Ballast

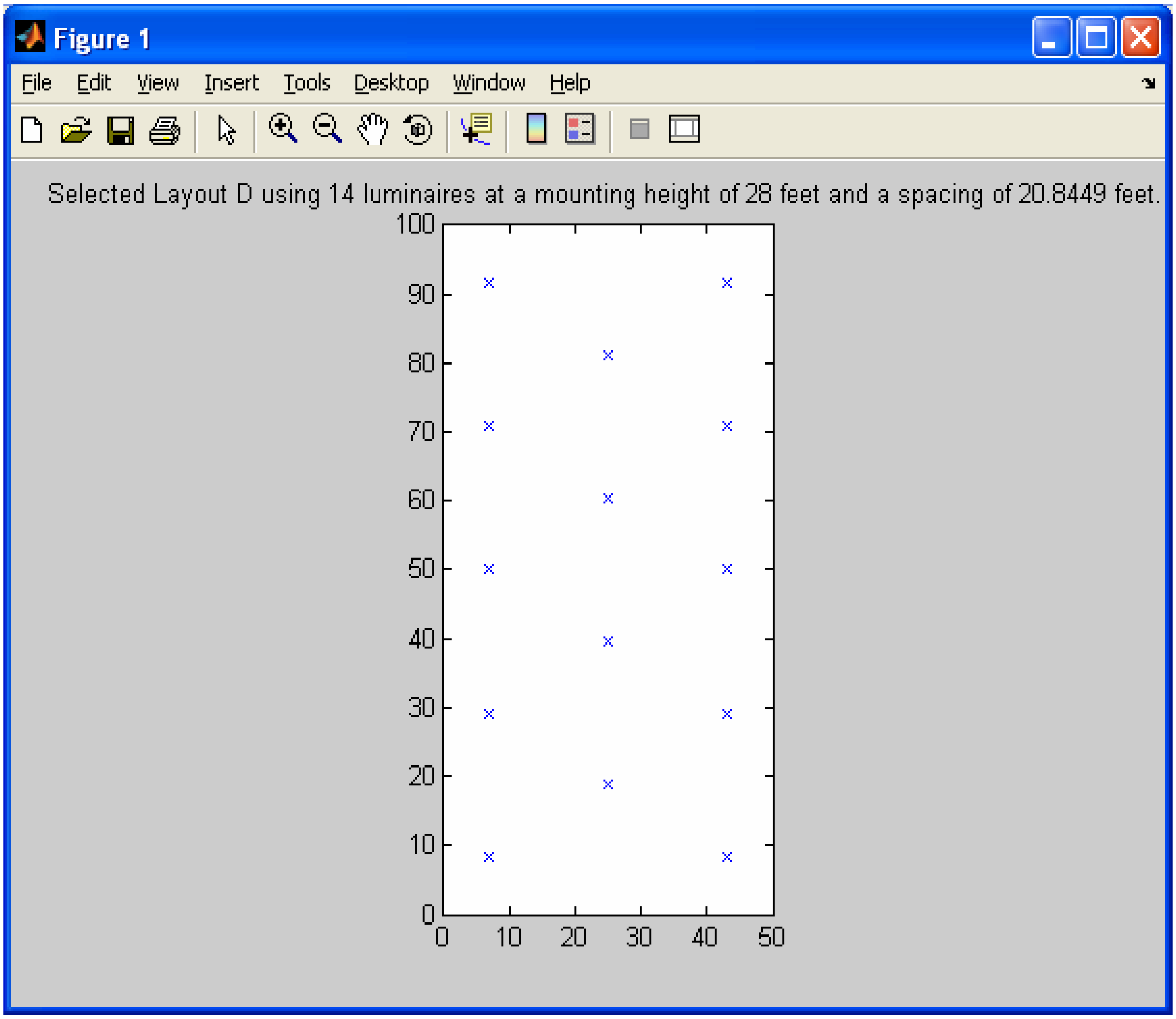


Figure 5-8: Industrial Scenario #1 with 400W MR Ballast, Design A, Layout D

Luminaires that utilize MR ballasts typically exhibit a cost which is greater than those equipped with CWA ballasts. MR ballasts are larger and heavier than CWA and RX ballasts at equivalent lamp power levels. This drives up overall product costs, which in addition to the improved line-side regulation and perceived improvements in LLD has resulted in the elevation of luminaires equipped with MR ballasts to a premium status level. The major difficulty that luminaires equipped with MR ballasts have had to overcome in the marketplace is one of increased acquisition cost over those luminaires equipped with other line frequency ballast types, specifically CWA. The results presented in Figure 5-7 indicate that if the lighting project were to utilize MR ballasts, the number of luminaires could be reduced and the LCC would actually be less than if standard ballasts were used.

Table 5-4 summarizes the results of this analysis comparing designs using the two ballasts types. The higher (improved) projected LLF of the MR equipped units resulted in a net reduction in the number of luminaires needed to meet the illuminance requirements based upon the same maintenance schedule. Luminaire quantity was reduced by 12.5% resulting in an energy demand reduction of 11.2%. Note that the power requirements of the two ballasts types differ by 7 watts (CWA – 458W, MR – 465W) [39]. Even considering the incremental acquisition cost associated with MR luminaires, the projected LCC calculations favor the design utilizing the more expensive lighting products projecting a LCC savings of 6.7%. In addition, under the same operating and maintenance conditions, the installation of a fewer number of luminaires in the case of those equipped with MR ballasts, results in an average maintained illuminance level increase of 4.7% over the case where more luminaires equipped with CWA ballasts are employed.

Table 5-4: Comparison between 400W CWA and MR Designs

MH Lamp/Blst	Luminaire Qty.	Total Power (W)	LCC	Illuminance (fc)
400W CWA	16	7328	$23,983	29.7
400W MR	14	6510	$22,385	31.1
Change	-12.5%	-11.2%	-6.7%	+4.7%

5.3 The Impact of Lighting Maintenance

As discussed previously, the design of a lighting system, particularly for general lighting applications, is dependent upon the performance of lamps and luminaires over time. Conventional practice is to perform lighting designs based upon the group replacement of lamps and the cleaning of luminaire optical assemblies on a pre-determined schedule. In the cases where luminaires are difficult to reach, which is commonplace in industrial installations, the cleaning typically only occurs when lamps are replaced.

5.3.1 Lighting System Design and Maintenance

As an example of how lighting maintenance, which in this case refers to lamp replacement and luminaire cleaning, affects the design of a lighting system, the industrial lighting scenario #1 (section 4.2) will again be used. This particular scenario is based upon a 400W MH lighting system in a moderately dirty industrial environment. It is a single-shift, year round application requiring illumination 10 hours per day, 5 days per week. The luminaires are scheduled to be cleaned and re-lamped every 12,000 hours (55 months) whereas the actual work area is cleaned on a 24 month basis. This data results in an LLF of 0.3599 which is illustrated in Figure 5-9. In contrast, the plot of Figure 5-10 illustrates the same conditions as that of Figure 4 with the exception that the luminaires are cleaned and re-lamped every 24 months. This change in maintenance schedule results in a projected LLF of 0.5976, meaning that the number of luminaires may be reduced and still meet the illumination requirements. The impact upon the LCC of the project is substantial in that there is a projected savings of $7,788.45 which translates to an LCC reduction of 32.5% relative to the original (12,000 hour re-lamp/cleaning) maintenance schedule.

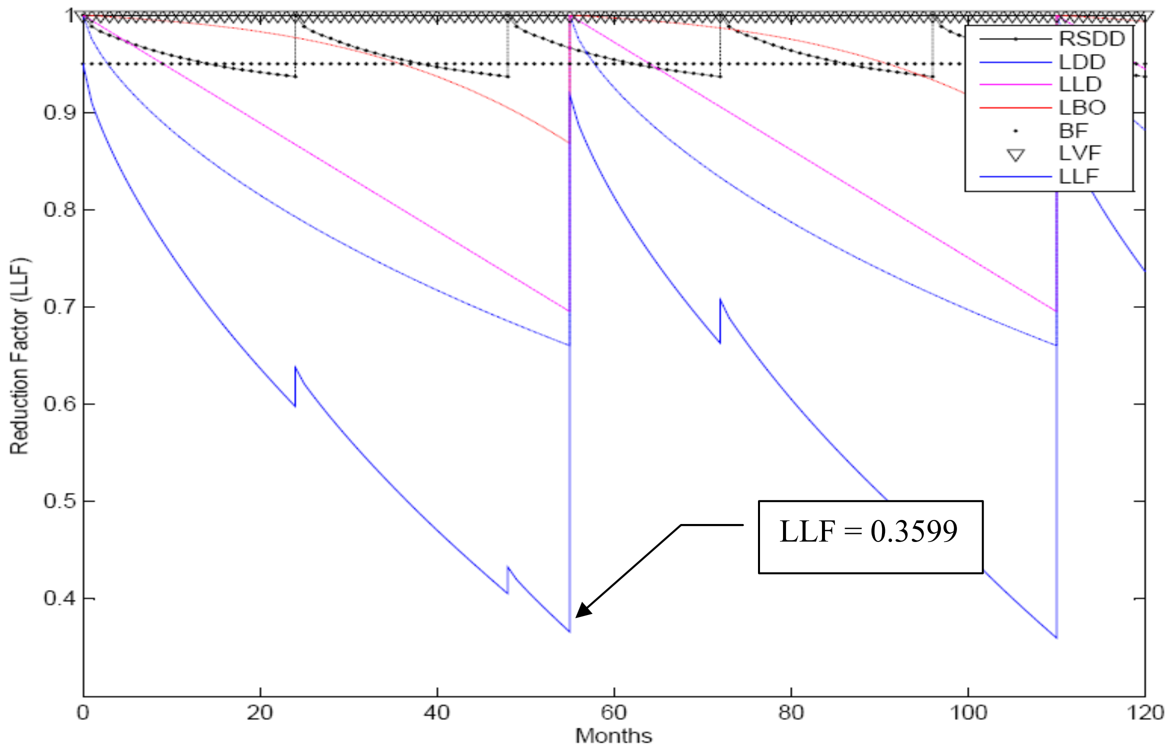


Figure 5-9: Light Output Depreciation for Scenario #1, 55 Month Luminaire Maintenance

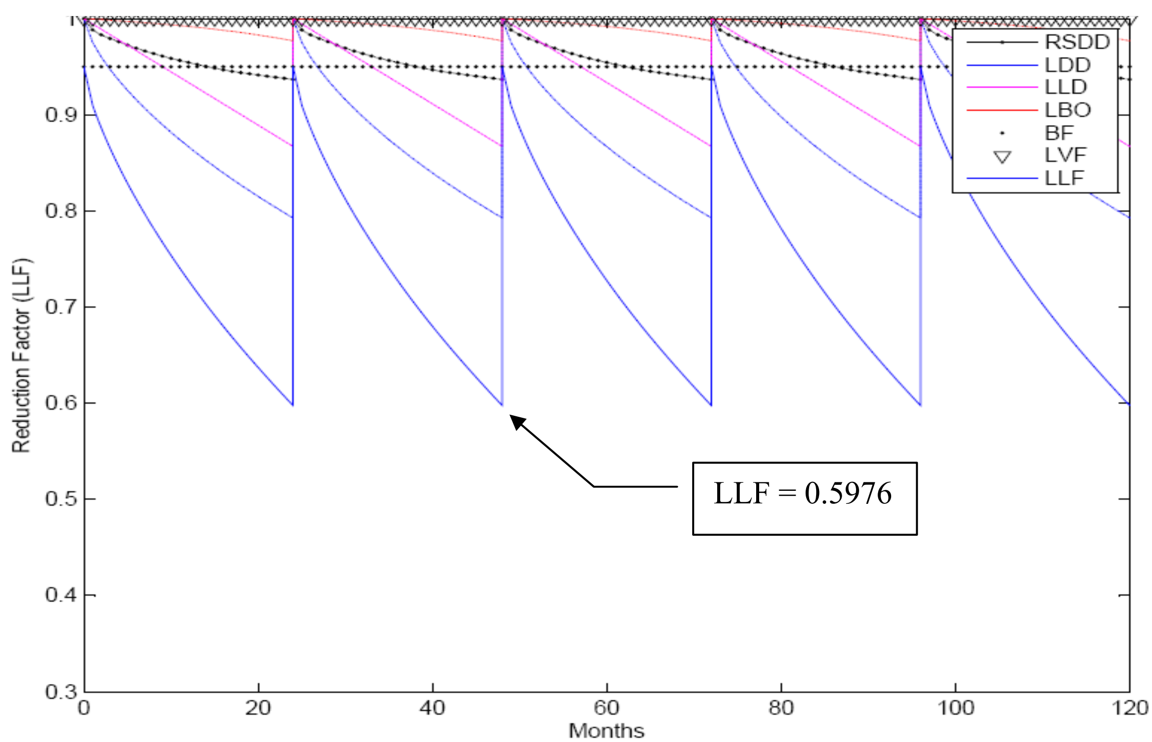


Figure 5-10: Light Output Depreciation for Scenario #1, 24 Month Luminaire Maintenance

Since the number of luminaires required for a lighting application is inversely proportional to the LLF as shown in Equations 2.10 and 2.11, the determination of a relationship between the improvement (increase) of LLF and the potential decrease in the number of luminaires that are required for a particular lighting project may be derived. As illustrated in Table 5-5, the reduction in luminaires is directly related to the amount of energy that can be saved.

Table 5-5: Energy Profiles and LCC based upon Different Maintenance Schedules – Scenario #1

Maintenance Schedule (re-lamp/clean luminaire)	55 months	24 months	Difference
Light Loss Factor (LLF)	0.3599	0.5976	0.2377
Luminaires Required	16	10	6
Luminaire Input Power (W)	458	458	---
Total Lighting System Power (W)	7,328	4,580	2,748
Operating-Hours per Year	2600	2600	---
Annual Energy Consumed by Lighting (kW-Hrs)	19,053	11,908	7,145
Annual Lighting Energy Cost @ $0.07 / kW-Hr	$1,333.71	$833.56	$500.15
Life-Cycle Cost ($)	$23,983.32	$16,194.87	$7,788.45

An equation approximating the relationship between change in luminaire quantity and change in LLF is shown as Equation 5.1.

$$\frac{NL_2}{NL_1} \cong \frac{LLF_1}{LLF_2} \qquad (3.57)$$

The value of the original (lower) loss factor is LLF_1 and the improved loss factor is LLF_2. Likewise, the number of luminaires required in the first case is NL_1 and the reduced number of luminaires is identified as NL_2. To illustrate the relationship, take a maintenance schedule and set of operating conditions that results in a minimum light loss factor of 0.6 ($LLF_1 = 0.6$). In this example the number of luminaires required based upon a maintained illumination level which is dictated by LLF_1 is arbitrarily defined as 100 ($NL_1 = 100$). If the recoverable loss factors are now altered due to more frequent lamp replacement and luminaire cleaning, the total minimum light loss factor will be increased, which for this example is arbitrarily chosen to be 0.7 (LLF_2 = 0.7). Substituting these values into Equation 5.1 and solving for the new luminaire quantity (NL_2) we see that this reduced quantity is 86 luminaires (NL_2 = 86) noting that the revised number of luminaires needs to be rounded up to the next higher integer value. For this example an increase of LLF of 0.1 yields a 14% reduction of required number of luminaires and therefore a 14% reduction in the amount of energy usage. Figure 5-11 presents data generated using the relationship of Equation 5.1 based upon various values of initial light loss factors.

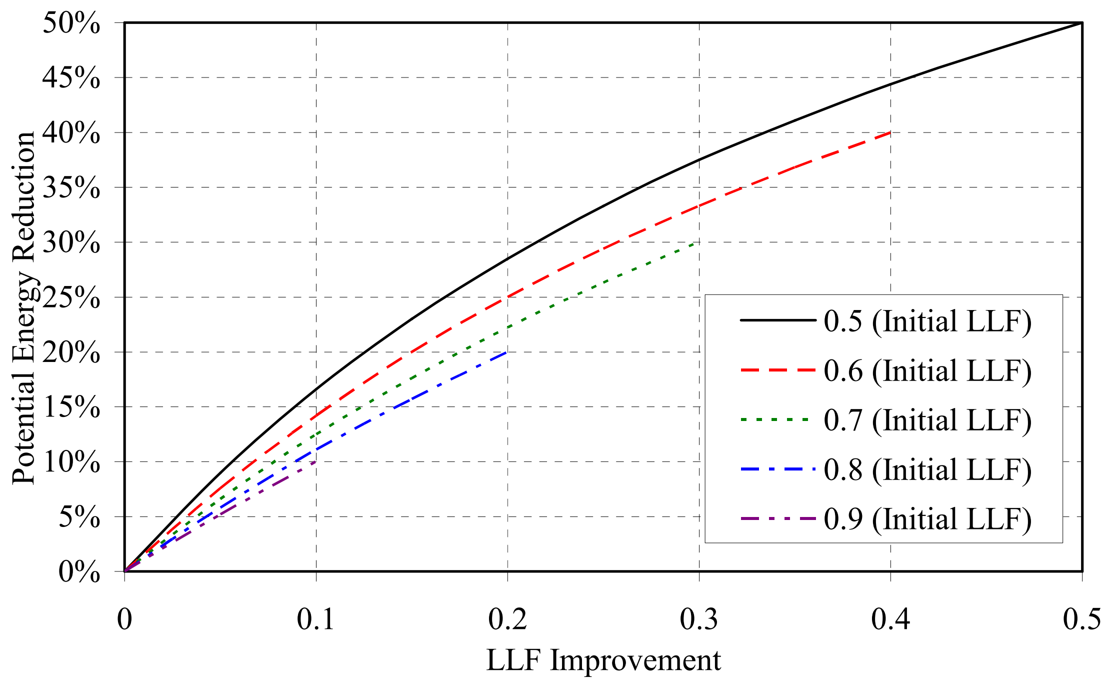


Figure 5-11: Potential Energy Savings (reduction) vs. LLF Improvement Based upon Reduced Luminaire Quantity

The results presented in Figure 5-11 may be used in the lighting design process to determine the number of luminaires needed for a given project based upon maintenance schedule. Using the same lighting project that was used as the basis of the results shown in Table 5-5 (Scenario #1), the design process is repeated and the maintenance schedule varied so that a relationship between the number of luminaires that are required and the service intervals may be obtained. The results of this analysis are presented in Figure 5-12. The stair step appearance of the curve is a result of the requirement for an integer number of luminaires.

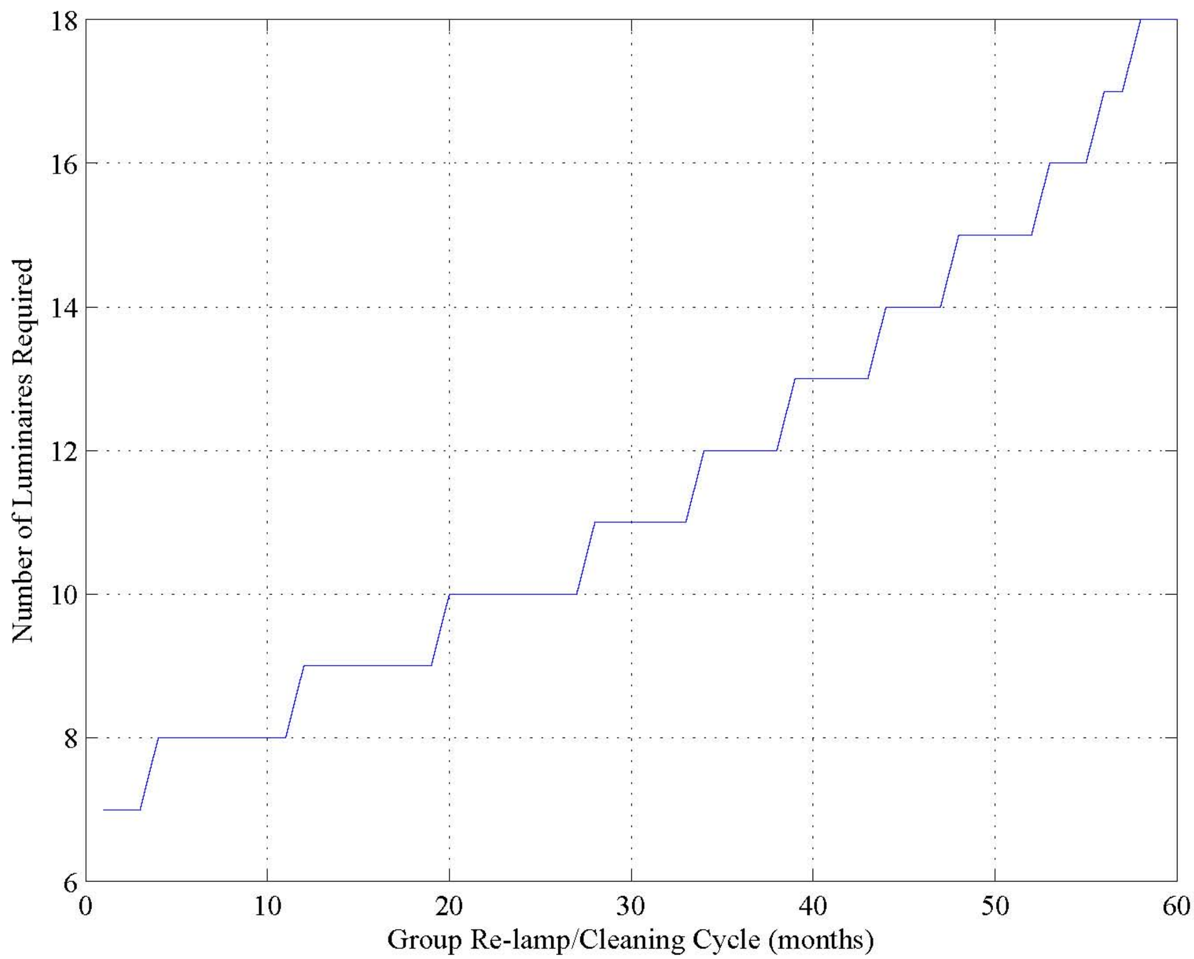


Figure 5-12: Luminaires Required vs. Re-lamp and Luminaire Cleaning Cycle (Scenario #1)

The total cost of the energy associated with the lighting project as a function of the group re-lamping and cleaning cycle displays the same characteristic shape as the relationship of Figure 5-12. This cost, which is based upon an energy rate of $0.07 per kilowatt-hour, is shown in Figure 5-13. The cost of maintenance over the life of the project versus the variable luminaire servicing (re-lamp/cleaning) cycle is shown in Figure 5-14.

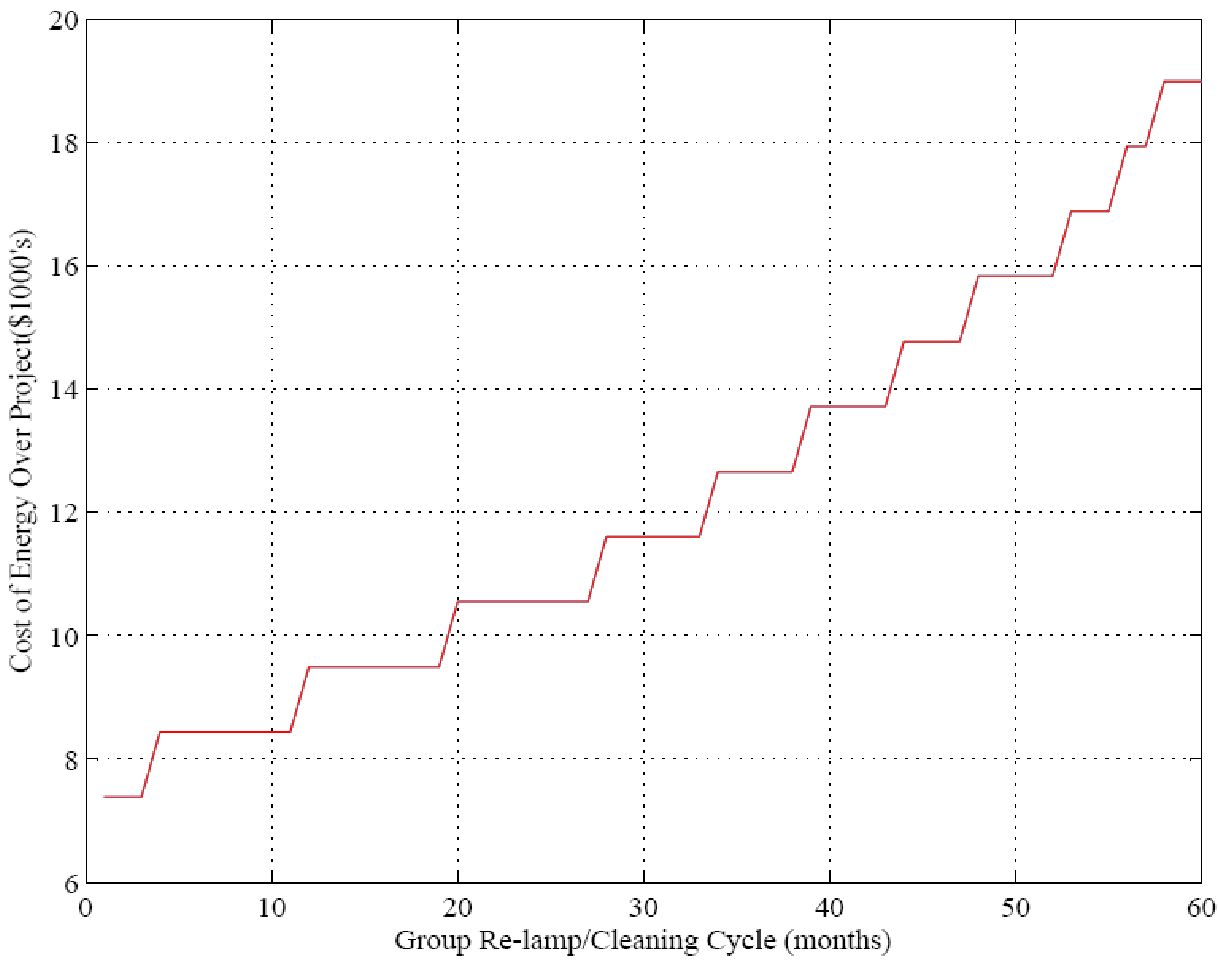


Figure 5-13: Lighting Project Energy Cost vs. Re-lamp/Luminaire Cleaning Cycle (Scenario #1)

By combining all of the financial data with the ability to reduce the luminaire count a plot of the LCC versus maintenance interval may be obtained, which for this scenario is shown in Figure 5-15. The result of this analysis is that the minimum LCC is attained when the design is based upon all lamps being replaced and luminaires cleaned every 19 months, which in this particular case is an LCC of $15,114.67. This result is significant because group re-lamping in this case would be performed after only 4,117 operating hours which is only 20.6% of rated lamp life, and conventional practice is to performing lighting designs based upon lamps being replaced much less frequently - 50% to 70% of rated lamp life [7],[40].

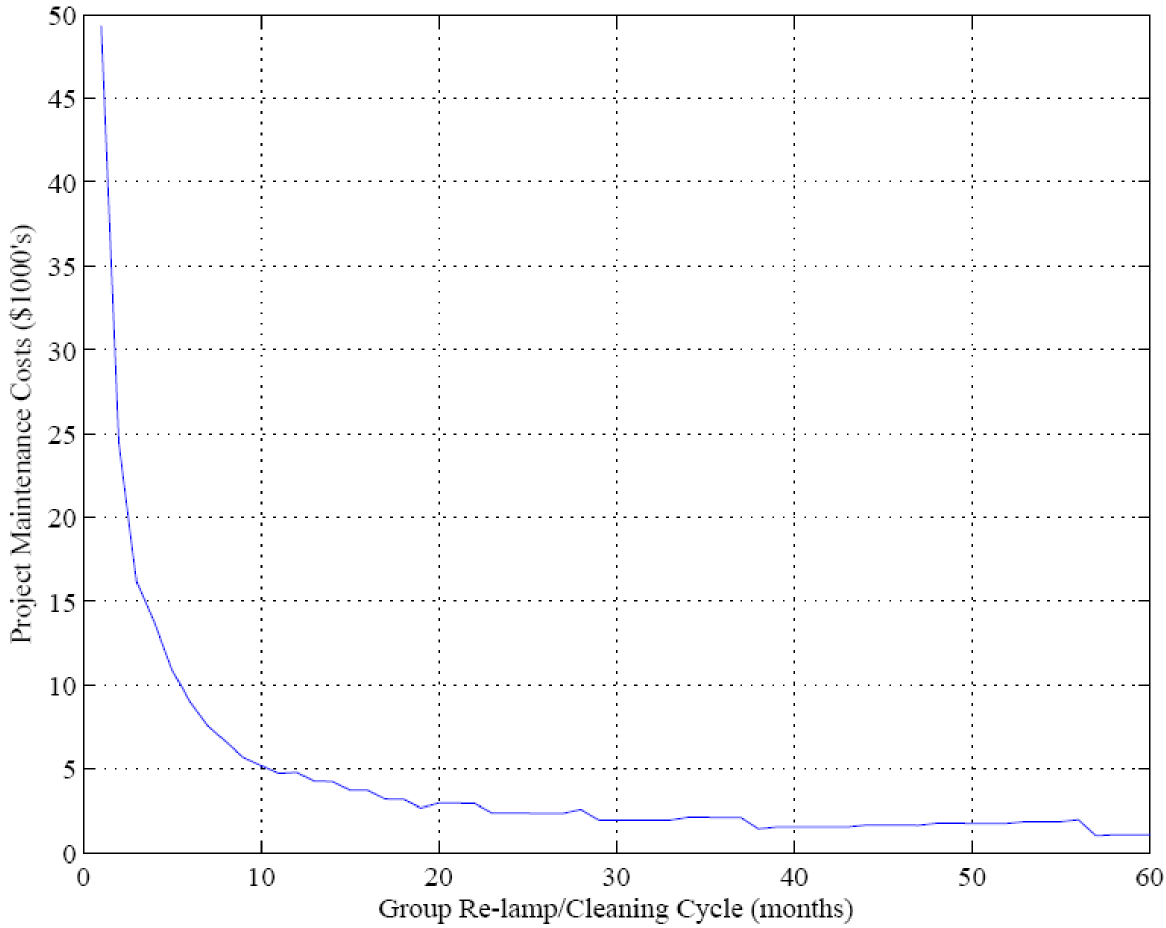


Figure 5-14: Cost of Maintenance vs. Re-lamp and Luminaire Cleaning Cycle (Scenario #1)

The data presented in Figure 5-12 through Figure 5-15 was created by way of a new program that replaces the master design program presented in Appendix A. In this case, the new program (MHANLZG2) repeatedly calls on the programs that were originally called by the master design program, incrementing through the luminaire servicing intervals. Luminaire layouts are not performed since this would significantly slow execution, however possible layouts may be verified as feasible for a given number of luminaires after the maintenance interval is selected. As design tools, the analysis programs MHANLZG2 and the HPS counterpart HPSANLZG2, may be used to determine an optimal project service cycle which not only will minimize project costs, but also reduce energy consumption.

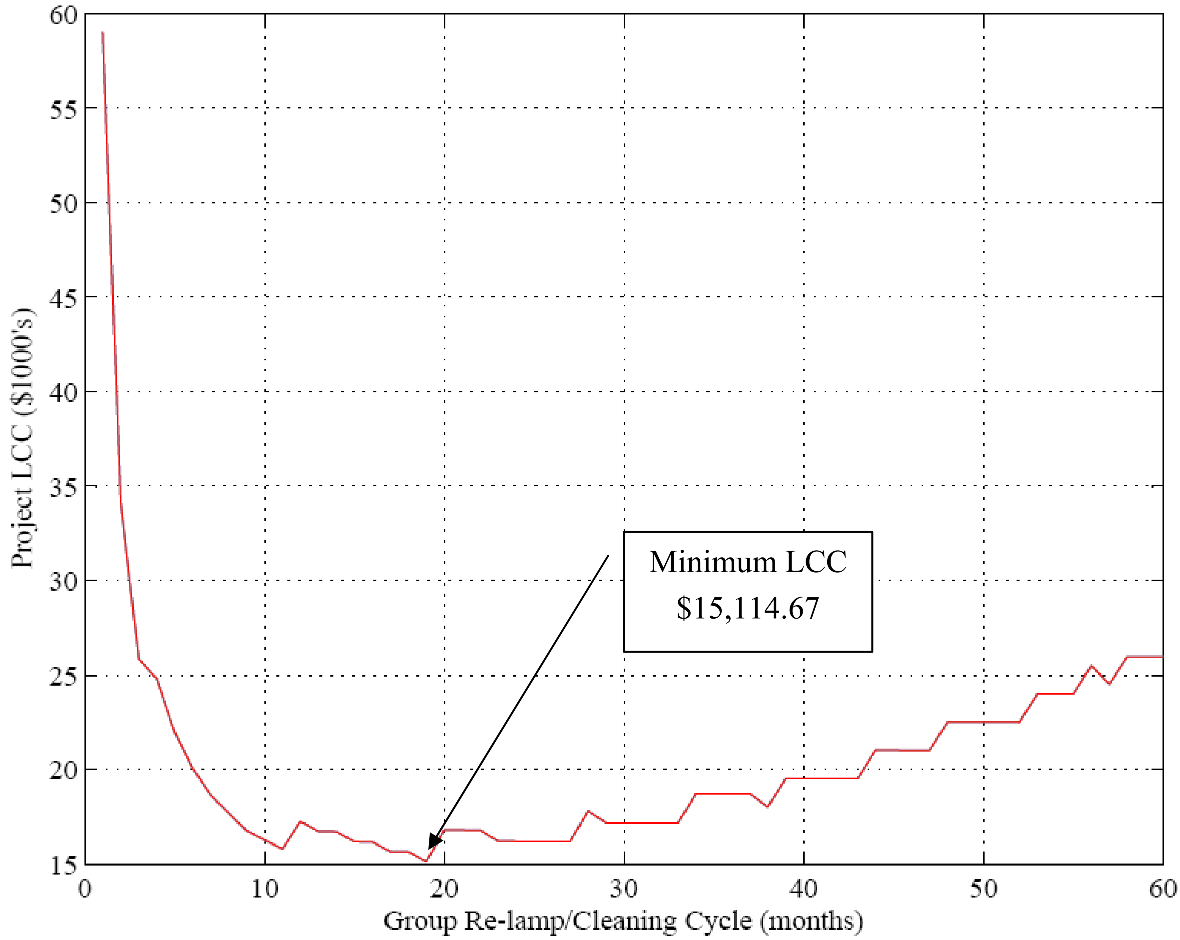


Figure 5-15: Lighting Project LCC vs. Re-lamp/Luminaire Cleaning Cycle (Scenario #1)

5.3.2 Lighting System Design and Lamp Family

Using the design requirements of Scenario #3 (large area), which are outlined in Table 4-4, a similar analysis to that presented in section 5.3.1 is performed comparing the use of MR ballasted 400W HPS and MH sources with respect to lighting system maintenance. Figure 5-16 illustrates the number of luminaires that would be required to satisfy this lighting application as a function of re-lamping and luminaire cleaning intervals for designs using 400W MH and HPS sources.

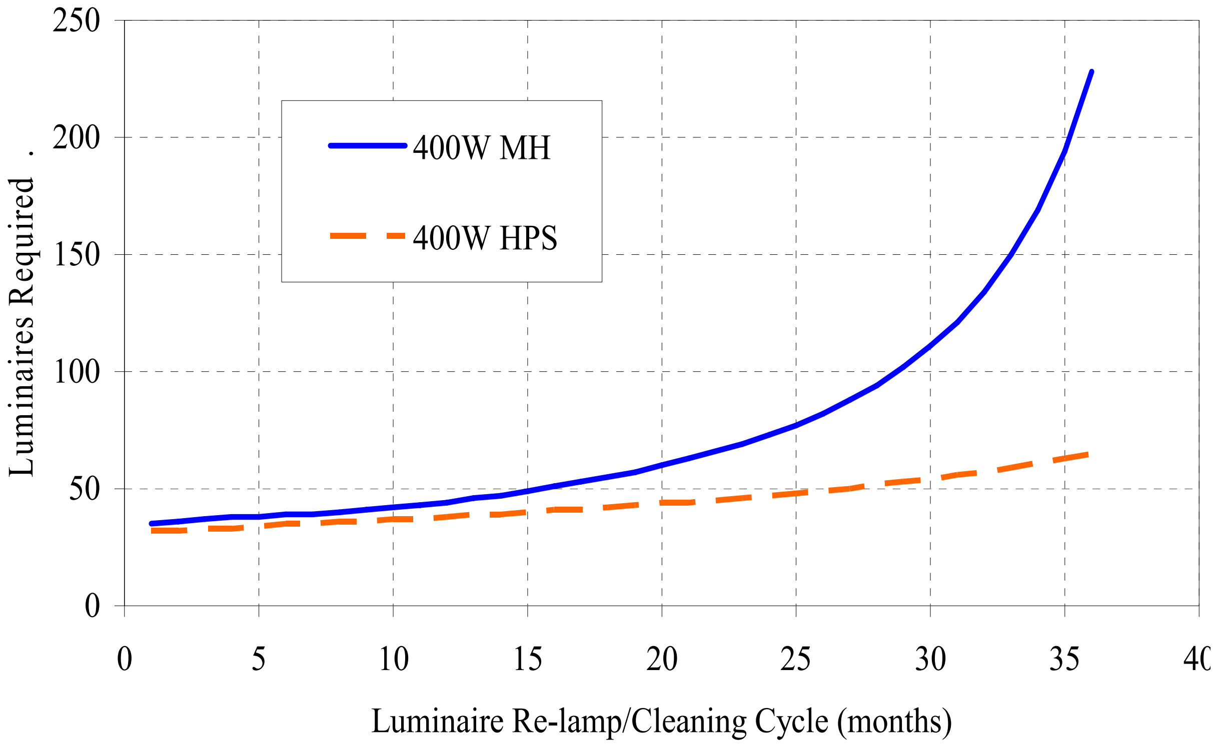


Figure 5-16: Luminaires Required vs. Re-lamp/Cleaning Cycle (Scenario #3)

The fundamental observation when studying the plot of Figure 5-16 is that the quantity of MH luminaires required is consistently greater than the quantity of HPS luminaires that would be required for a specific maintenance interval. One reason for this is that the 400W MH lamp generates 13.7% fewer rated (initial) lumens than does the 400W HPS lamp. Another reason is that the LLF associated with the MH luminaire decreases at a greater rate which leads to a greater rate of increase of the number of luminaires that are required. Since the amount of energy needed to achieve the desired lighting results is directly related the number of luminaires installed, the MH luminaires become less and less attractive economically as the maintenance interval is increased when compared to the HPS alternative.

This strategy may also be applied to a LCC analysis as the maintenance interval may be varied resulting in a varying luminaire requirement which provides a changing LCC profile. Figure 5-17 illustrates the impact of maintenance schedule upon the lighting project LCC. The use of the 400W MH luminaires will result in higher project costs due to increased luminaire quantities and energy usage. What is most interesting however, are the points at which minimum LCC occurs in both cases. For this lighting application, when using the MH luminaires the lower LCC results occur when the luminaires are serviced every 5 to 15 months. In the case of the HPS designs, maintenance intervals between 5 and 20 months provide relatively low LCC values. The maintenance intervals at which the minimum points of the two curves occur are presented in Table 5-6.

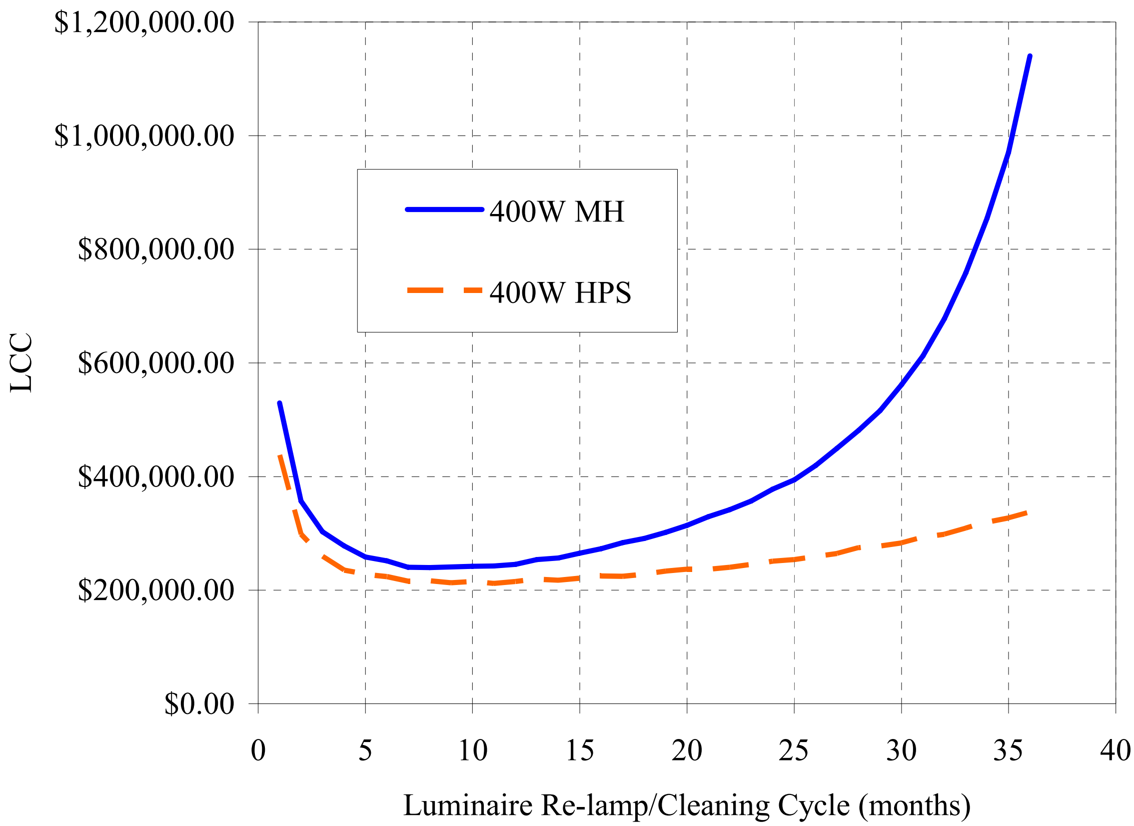


Figure 5-17: LCC vs. Maintenance Interval (Scenario #3)

Table 5-6: Maintenance Interval Yielding Minimum LCC (Scenario #3)

Luminaire / Source	Metal-Halide	HPS
Maintenance Interval (months) (re-lamp / clean luminaire)	8	11
Luminaires Required	40	37
Minimum LCC ($)	$239,485.07	$211,853.96

As stated previously, it is customary to schedule group re-lamping and luminaire cleaning based upon economic lamp life - typically between 50% and 70% of rated lamp life. The 400W MH lamp has a rated life of 20,000 hours, and if a re-lamp point of 70% of rated life was chosen, which was the case in section 4.4, the results in the re-lamping and cleaning of luminaires every 14,000 hours. Based upon the operating schedule in the above example (scenario #3), at 7,280 operating hours per year, luminaire service would be performed every 23 months. Using this maintenance scenario if the MH alternative was selected, 69 luminaires would be required and the LCC of the lighting project would be $357,055.68, which are confirmed by the values presented in Figure 4-27.

If the HPS alternative were selected and the same maintenance cycle were employed, the result is that lamp replacements would be performed at 58.3% of rated lamp life since the 400W HPS lamp has a rated life of 24,000 hours. As pointed out in section 4.4 this results in a LCC of $245,449.16. However, if the maintenance schedule were adjusted in the case of the HPS option to 70% of rated life, these luminaires would be serviced every 28 months, resulting in an even greater LCC of $274,873.69 since the required luminaire count would increase from 46 to 52. From the data used to generate the plot of Figure 5-17, the minimum LCC for both lamp types may be extracted as shown in Table 5-6.

Figure 5-18 shows the energy consumption that can be directly attributed to the lighting system (not including HVAC) in the case where the MH luminaires are used. The energy consumption quantities for both the minimum LCC and standard maintenance practice are indicated as is the amount of energy that could be saved over the life of the lighting project by performing the lighting design based upon an eight month maintenance interval. In this example the potential energy savings is 1472.56 megawatt-hours, or approximately 42%.

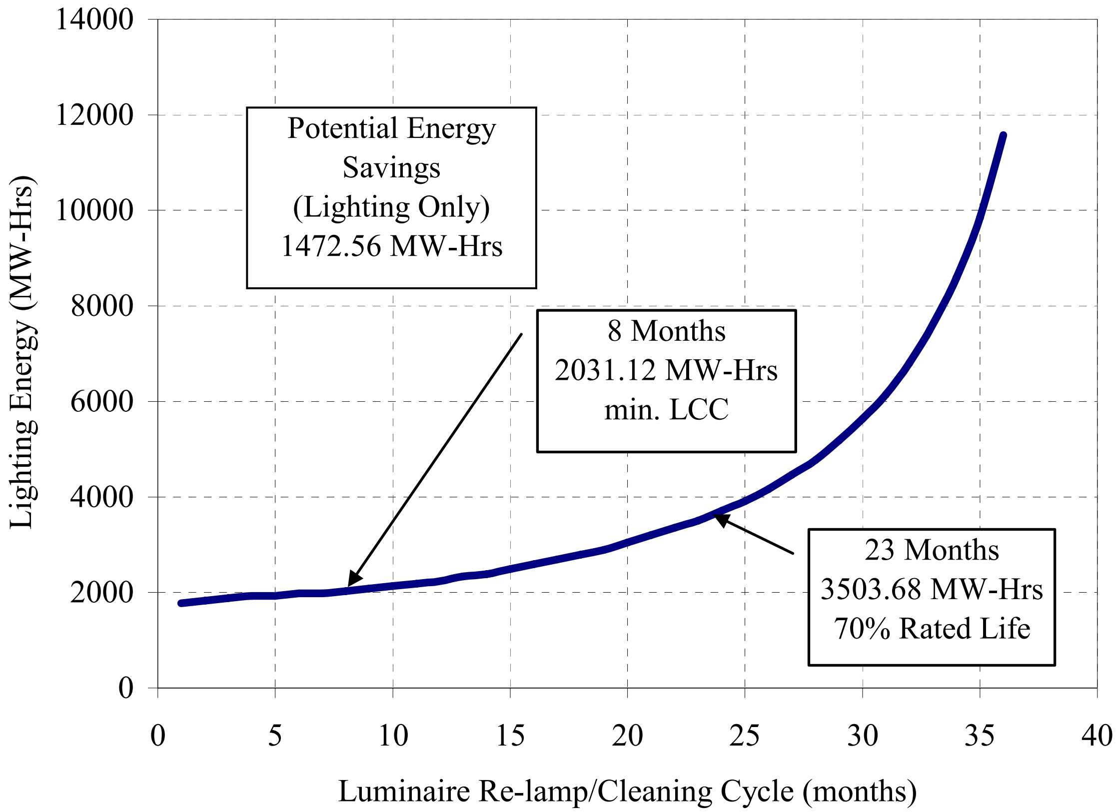


Figure 5-18: Lighting Energy Consumption vs. Maintenance Interval for MH Luminaires (Scenario #3)

Figure 5-19 presents a similar argument based upon the selection of HPS as the lighting source. In this case the reduction in energy consumption that may be realized is 481.57 megawatt-hours, which is approximately 20%.

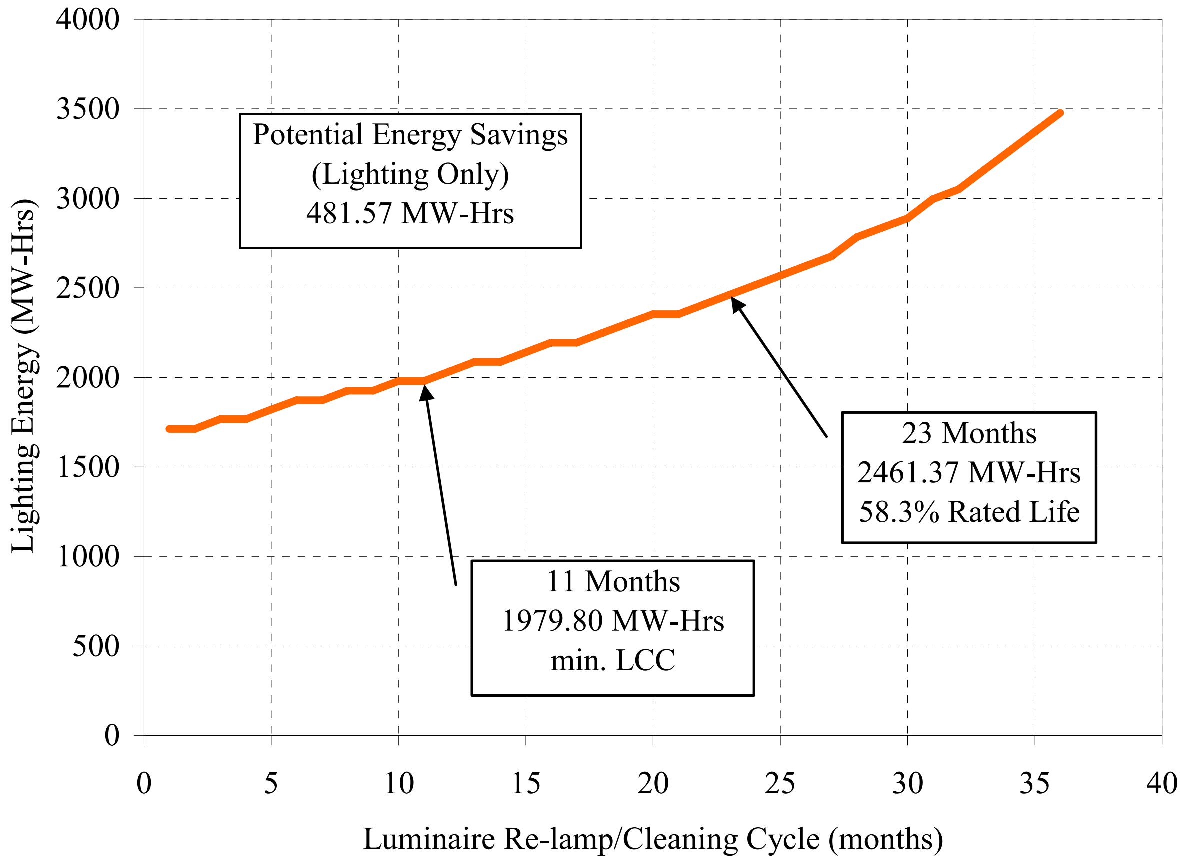


Figure 5-19: Lighting Energy Consumption vs. Maintenance Interval for HPS Luminaires (Scenario #3)

To approximate the reduction of energy consumption by the HVAC system an additional one-third of the projected energy savings in Figures 5-18 and 5-19 could be realized using the guideline of one watt of HVAC to three watts of lighting power, however this figure will fluctuate based upon environmental conditions. If conditions warrant the use of air-conditioning there will be an HVAC energy savings due to the reduction in heat resulting from a reduced number of luminaires. If however it is heating season, the reduced lighting load will result in greater demand upon the heating system to replace the reduced heating contribution from the lighting system.

5.4 Impact upon the Environment

The most significant environmental implications of this research may be placed in one of two categories: the reduction of greenhouse gas levels, specifically CO_2, due to decreased energy demand, and the potential increase of available mercury due to more frequent lamp replacement.

5.4.1 Carbon-Dioxide (Greenhouse Gas) Impact

The reduction of CO_2 emissions has been a topic of discussion since the latter part of the 20th Century [41]. General consensus is that a reduction in the generation of electricity by way of fossil fuel combustion is the method that will result in the most immediate slowing of the build-up of greenhouse gasses. Until alternative energy sources are developed to a scale sufficient to significantly displace fossil fuels, the obvious course of action is to reduce energy consumption thus reducing demand and consequently CO_2 emissions.

To illustrate the impact of improved lighting project design based upon more frequent servicing consider again industrial Scenario #3. In the case where the MH products are used, if group relamping is performed when the lamps functionally reach 70% of rated lamp life (14,000 burn-hours), then group luminaire servicing will occur every 23 months. In the case of HPS usage, selecting a re-lamping interval of 23 months translates to lamps achieving 58.3% of their rated life before replacement. However, if the re-lamp interval for the HPS case were adjusted so that operating lamps were allowed to remain in service for 70% of their rated life, the result would be lamp replacement every 28 months which would demand even more energy to satisfy the lighting application. Figures 5-18 and 5-19 in section 5.3 illustrate the amounts of lighting energy that is required over the life of the project based upon luminaire servicing interval for the two lamp types. Figure 5-20 presents the projected amount of generated CO_2 which could be avoided based upon energy savings achieved by the methods resulting from this research.

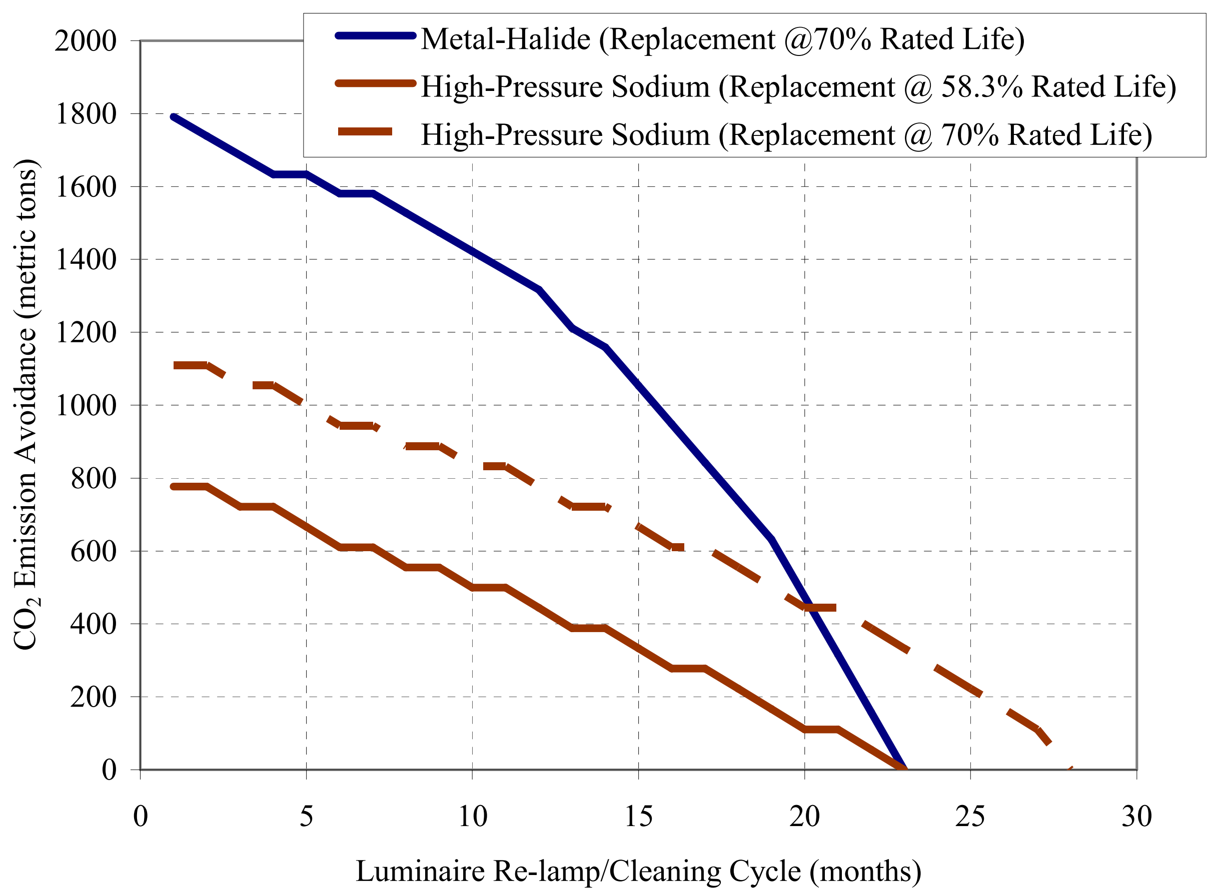


Figure 5-20: CO_2 Emission Avoidance vs. Re-lamp/Cleaning Cycle (Scenario #3)

Each of the curves in Figure 5-20 represent the amount of CO_2 generation that would be avoided if the number of luminaires were reduced relative to the number needed based upon reference re-lamp intervals. For example the MH curve, which is based upon a re-lamp interval of 23 months, indicates that by re-lamping/cleaning every 15 months and taking advantage of the improved LLF and associated reduction of luminaire quantity, the generation of almost 1,100 metric tons of CO_2 may be avoided over the life of the lighting project.

A similar analysis may be performed using the 400 HPS curves presented in Figure 5-20. The solid HPS curve is based upon the same application requirements as those investigated in sections 4.4 and 5.3, a re-lamp/cleaning cycle of 23 months, which is the replacement of lamps and associated luminaire cleaning based upon the 70% life point of the 400W MH lamp, or 58.3% of the rated lamp life of the 400W HPS lamp. The dashed HPS curve is based however upon replacing the HPS lamps at a point corresponding to 70% of the rated life of the HPS lamp which is 28 months under the described operating requirements. The reason for including both HPS curves was to offer a direct comparison to the analyses of sections 4.4 and 5.3 between the MH and HPS alternatives, which in this case are represented by the solid curves, as well as to project the CO_2 avoidance as if HPS lamp life were the basis of the lighting design. As is the case with the MH curve, as re-lamping/cleaning is performed more frequently the amount of required lighting energy declines as a result of the need for fewer luminaires. However, in the case of HPS the depreciation of lamp lumen output (LLD) is not as rapid as that of MH sources resulting in less energy savings as servicing intervals are reduced. Using the 23 month lamp replacement point as nadir for the solid HPS curve, the amount of CO_2 generation that can be avoided by more frequent luminaire servicing may be easily obtained. The CO_2 avoidance of the dashed HPS curve is based upon a reference of re-lamping occurring every 28 months, resulting in a greater quantity of greenhouse gas reduction relative to the solid HPS curve.

5.4.2 Mercury Impact

The practice of re-lamping and cleaning on a more frequent basis may have a positive impact upon energy usage, CO_2 emissions, and overall lighting project cost (LCC); however it is natural to ask if there are downsides to what appears to be a "win-win" lighting design strategy. The most direct byproduct of more frequent lamp replacement would be the release of available mercury into the environment. Available mercury in this case refers to that mercury which is redistributed throughout the environment as a consequence of human action. It follows that more lamps would need to be manufactured and disposed of to support more frequent group relamping, leading to greater risks of lamp breakage which would liberate more available mercury. Offsetting this apparently damaging argument against more frequent re-lamping would be the reduction of mercury vapor resulting from the combustion of fossil fuels to provide the needed electrical energy.

Figure 5-21 illustrates the mercury burden associated with a standard 400W MH lamp. This data is based upon published lamp data from a leading lamp manufacturer as well as that presented in a article published in 1993 in the Journal of the Illuminating Engineering Society [30] [43]. Through an analysis of varying forms of fossil fuels it was estimated that 54 nanograms of mercury is released in vapor form for every watt-hour of electrical energy that is generated [30]. It should be noted that the lamp content amount is the liquid mercury that the lamp contains upon original manufacture. During normal operation a portion of this mercury reacts with other lamp materials and becomes unavailable for release or recycling. The longer a lamp is operated before it is removed from service, the lower will be the amount of available mercury. That being said, the worst case scenario would be the disposal of a lamp containing the entirety of the original mercury dose and therefore that amount will be used for future calculations and comparisons.

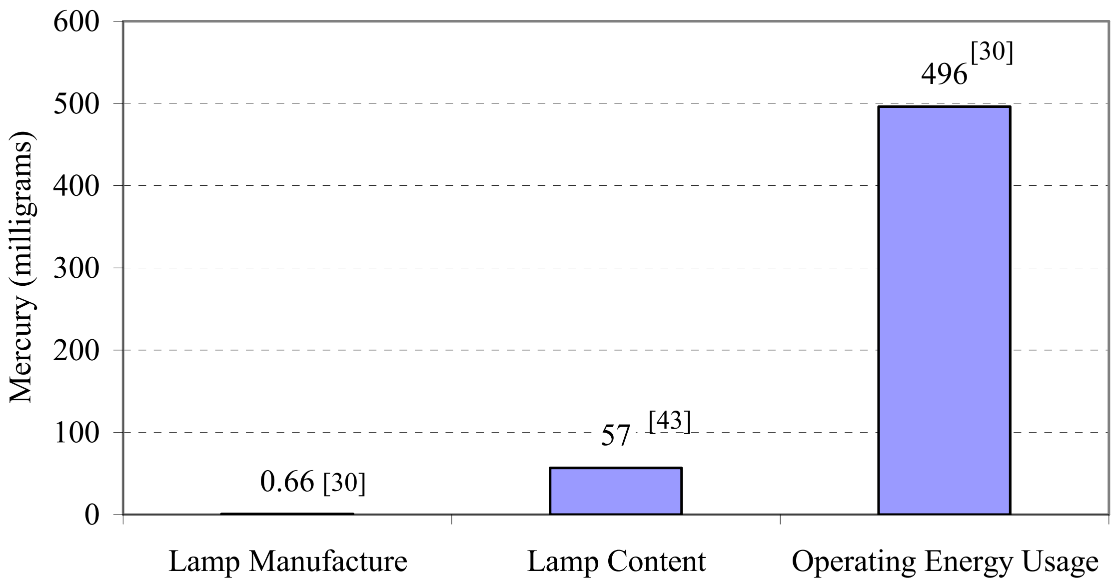


Figure 5-21: Mercury Burden of a 400W MH Lamp (20,000 hour life)

The mercury which is unaccounted for in the process of lamp manufacture is an approximate estimate being determined by mercury purchase data for the lamp industry over the period 1978 to 1987 [30]. It is noted in the source material that the correlation of the data to other markers yielded an order of magnitude difference between the calculated per-lamp mercury loss quantity and the anticipated value. However, since this manufacturing loss quantity is two orders of magnitude less than the lamp content quantity it will be used with minimal impact upon the final results.

Figure 5-22 presents the total mercury burden associated with the example lighting application (Scenario #3) as a function of luminaire maintenance cycle when 400W MH luminaires are employed. The data presented illustrates that as the re-lamp/cleaning interval is reduced the amount of electrical energy required falls which proportionally affects the mercury that is vaporized as part of the fossil fuel based generation process.

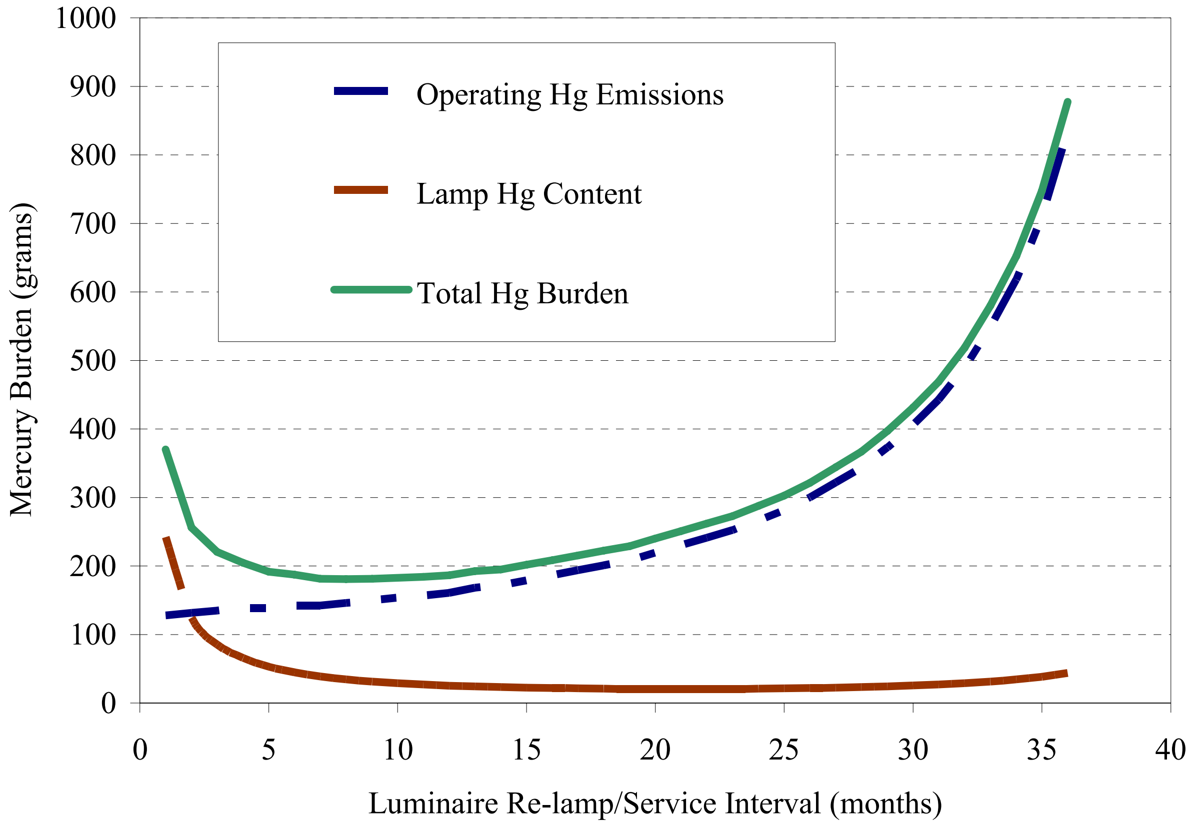


Figure 5-22: Mercury Burden vs. Re-lamp/Cleaning Interval over Project Life using 400W MH Luminaires (Scenario #3)

In Figure 5-22 as this maintenance interval decreases the amount of mercury directly associated with the lamps increases since the lamps, of which there are fewer, are disposed of on a more frequent basis. The total mercury burden is the summation of these two curves and indicates that the overall burden is lowest for this lighting application when the luminaires are serviced every 7 to 10 months. The minimum total burden, which is 180.84 grams of mercury, occurs when the project is designed based upon a re-lamp cycle of 8 months. If the re-lamp cycle were 23 months, which would be the 70% rated lamp life interval, the total burden would be 273.02 grams of mercury. Thus by reducing the luminaire service interval from 23 to 8 months a mercury load reduction of 42% could be achieved. These figures are summarized in Table 5-7.

Table 5-7: Mercury Burden over Life of Lighting Project using MH Luminaires (Scenario #3)

			Reduction
Maintenance Interval (months) (re-lamp/clean luminaire)	23	8	65.2%
Luminaires Required	69	40	42.0%
Total Mercury Burden (grams)	273.02	180.84	33.8%

A like analysis is performed as if 400W HPS luminaires were used for the example lighting application. Figure 5-23 shows the mercury allocation for a 400 W HPS lamp.

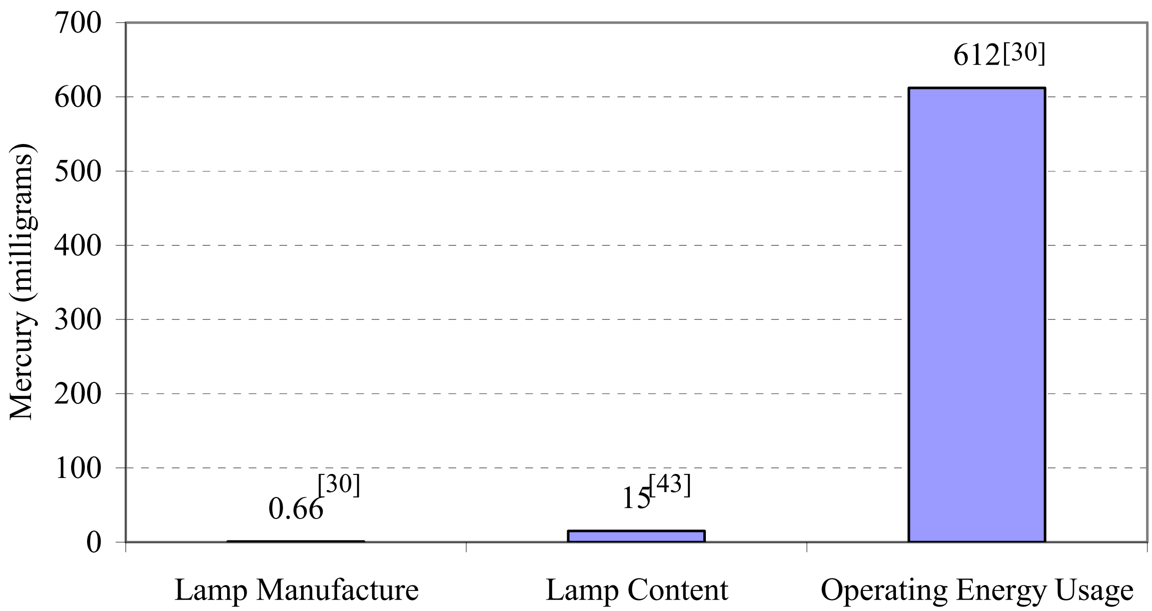


Figure 5-23: Mercury Burden of 400W HPS Lamp (24,000 hour life)

When comparing this plot to that of Figure 5-21 it should be noted that HPS lamps have less mercury than do equivalently sized (power level) MH sources, however in this example the power demand of a 400W HPS luminaire is slightly greater than that of the 400W MH luminaire. Add to this the fact that the HPS has a greater projected lamp life than the MH lamp (24,000 hours vs. 20,000 hours), the result is a greater mercury operating fossil fuel based energy emission burden over the life of the lamp. Figure 5-24 illustrates that as the re-lamp/service interval is shortened the amount of electrical energy required reduces as does the mercury which is vaporized resulting from electrical energy generation.

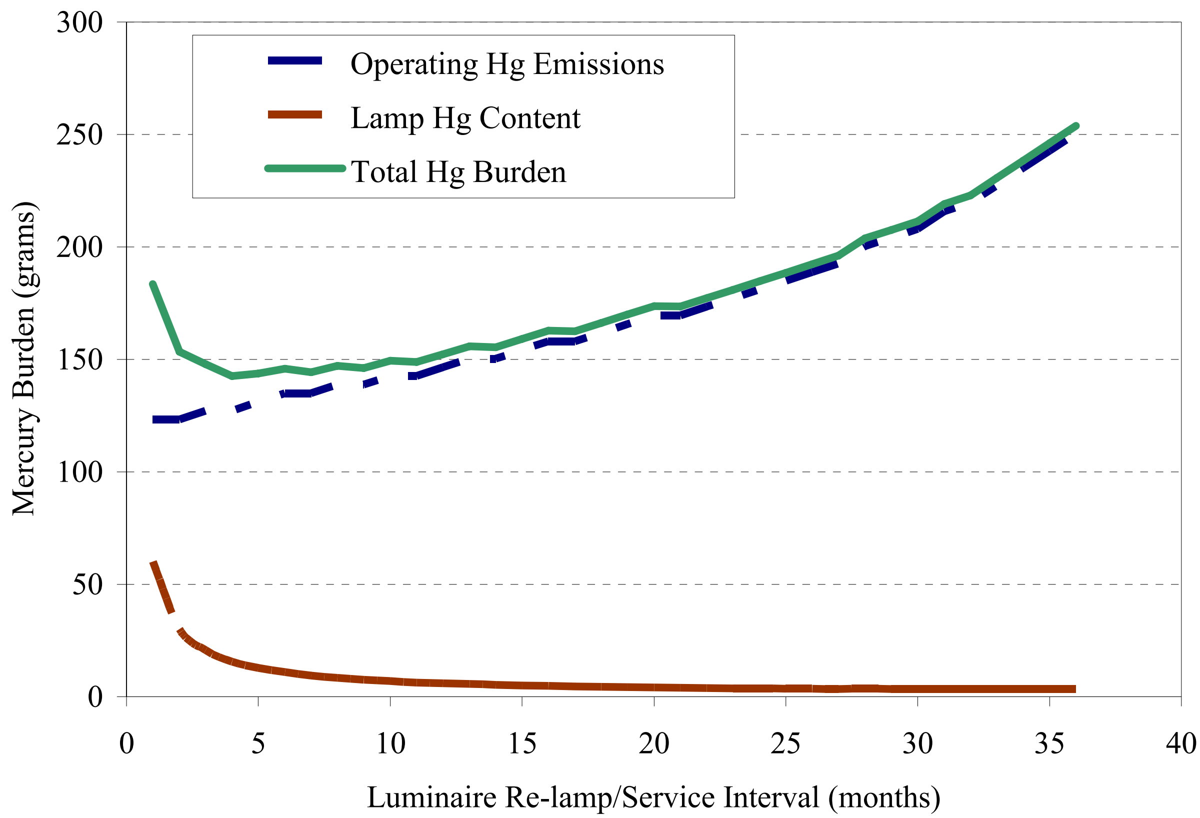


Figure 5-24: Mercury Burden vs. Re-lamp/Cleaning Interval over Project Life using 400W HPS Luminaires (Scenario #3)

As was the case with the MH system, as this interval decreases the amount of mercury directly associated with the lamps increases since the lamps, of which there are fewer, are disposed of on a more frequent basis. The total mercury burden curve indicates that the minimum overall burden for this application occurs when the luminaires are re-lamped and cleaned somewhere in the range of every 4 to 5 months. The minimum total burden, which is 142.64 grams of mercury, occurs when the project is designed based upon a re-lamp cycle of 4 months. If the re-lamp cycle were 28 months, which would correspond to 70% of rated 400W HPS lamp life, the total burden would be 203.826 grams of mercury. Therefore, by reducing the luminaire service interval from 28 to 4 months a mercury load reduction of 30% could be realized, a summary of which is given in Table 5-8.

Table 5-8: Mercury Burden over Life of Lighting Project using HPS Luminaires (Scenario #3)

			Reduction
Maintenance Interval (months) (re-lamp/clean luminaire)	28	4	85.7%
Luminaires Required	52	33	36.5%
Total Mercury Burden (grams)	203.83	142.64	30.0%

6 Conclusions and Recommendations for Future Research

6.1 Summary and Conclusions

The goal of this research was to investigate methods for the saving of energy and, consequently, the reduction of negatively impacting environmental effects resulting from the generation of electrical power. As it pertains to general area industrial lighting applications, the results of this research indicate that significant reductions in the consumption of electrical energy and the associated generation of carbon dioxide may be reduced by way of more efficient lighting designs. These more efficient industrial lighting designs are projected through reductions in luminaire quantities resulting from life-cycle projections of both economic and photometric performance. These analyses were facilitated by the creation of lighting design software which provides multiple designs based upon variations of lamp type, lamp power level, ballast type, luminaire type, luminaire mounting height and frequency of group luminaire maintenance. The realization of these more energy efficient lighting designs is achieved through the application of two original non-conventional layout algorithms. Methods presented for the reduction of luminaire quantities, as supported by this research, fall into three categories:

1. This initial category focuses upon increased flexibility in lighting design through the use of variable industrial luminaire mounting heights. Simulations performed using the developed software suggest that for a specific lamp (type and power level), ballast (type), and optical assembly combination (luminaire) - the lower the mounting height, the fewer luminaires are needed to provide equivalent levels of horizontal illumination upon the work plane. This statement is qualified by the constraint that the spacing criteria is not

violated and that a vertical illumination requirement is not tied to the performance specification.

2. The second category is the investigation of different lamp and ballast types in the design process. Often, based upon a specific color preference, mounting height requirement, or simply lighting product availability, possible lighting solutions are ignored which could significantly reduce overall lighting project costs and energy consumption levels. Results of the research indicate that it is not always the highest output lamp which offers the greatest value, just as it is not the least expensive ballast that offers the lowest overall lighting project costs. Results from testing performed at the Rector Field House on the campus of Virginia Tech indicate that significant reductions in LLD may be realized through the use of MR ballasts [2]. Using these results as a part of the software model it is demonstrated that the improved LLD due to the use of MR ballasts provides for significant improvement in LLF, which subsequently allows for lighting designs which are more cost effective and electrically efficient.

3. The final category, which delivers projections that are significant in terms of the reduction of energy consumption and LCC, is simply an increase in the frequency of lighting system maintenance including group re-lamping and luminaire cleaning. Industry practice with regard to luminaire maintenance in discharge lighting systems revolves around either spot maintenance, which is not addressed by this research, or group luminaire re-lamping/cleaning, which is the basis for LLF calculations used in the design process presented in this dissertation. Those loss factors contributing to the

overall LLF that may be recovered as a result of improved maintenance offer the opportunity of significant economic and environmental savings. The concept of recovering a portion of a luminaire's output is common knowledge throughout the industrial lighting industry, however the economic and environmental significance of these improvements has either never been researched to the extent presented herein, or the results of such analyses have never been made public. Even with the recycling of a greater number of mercury-containing discharge lamps resulting from more frequent lamp replacements, when compared to the emissions of the metal as a result of fossil fuel power generation, the environmental benefits in the majority of cases will outweigh any perceived detriments.

Worth noting is that the industrial lighting system model developed for this research does not include certain aspects of illumination design which are becoming more frequently incorporated into indoor lighting applications. For example, the use of natural light (daylighting) to supplement artificial lighting has been popular for many years. However, with regard to industrial lighting applications the standing IES recommendation is that designs should not rely upon daylighting where task illuminance is required [5]. The obvious reasons for this statement are that natural lighting is unpredictable during daylight hours, and non-existent between sunset and sunrise. Since industrial facilities are generally required to be flexible with regard to hours of operation, the reliability and availability of natural light to provide a portion of needed illumination is a problem.

On the other hand, an opportunity is afforded by the use of lighting controls and dimmable luminaires through which significant amounts of energy can be saved during those periods when daylight can be harvested.

Another energy saving strategy employed in industrial lighting applications is the dimming of HID luminaires through the use of occupancy sensors. HID systems that utilize CWA ballasts equipped with switchable, dual-value capacitors provide the ability to significantly reduce lamp power levels through the alteration of ballast impedance when full illumination levels are not required. This would be the case when areas of a facility are uninhabited for extended periods of time.

The results of this research indicate that in contrast to standing industry recommendations for re-lamping, more frequent HID lamp replacement coupled with a reduction in the number of installed luminaires will retard the degradation of the environment, both from a greenhouse gas perspective as well as that of overall mercury load (emissions and disposal). The reduction in the generation of CO_2 due to a reduction in industrial lighting energy consumption is a straightforward calculation. As pointed out in the emission analysis of the third lighting application scenario presented in section 5.4.1, in the case where 400W MH luminaires are used between 1300 and 1400 metric tons of CO_2 generation could be avoided over the life of the project by reducing the quantity of luminaires through the performing of maintenance on an annual basis (12 months vs. 23 months). The period of 23 months being the 70% of rated lamp life recommended re-lamp interval.

One question arises concerning the more frequent disposal of lamps containing mercury, which is currently a topic of significant social interest. Again referring to the analysis of the data presented in section 5.4.1, in all maintenance scenarios other than those involving group lamp disposal being performed every 4 months or less, any increase in mercury released into the environment by way of more frequent lamp disposal is more than offset by the reduction of fossil fuel born mercury emissions resulting from the usage of fewer luminaires. The amount of mercury released into the environment through lamp disposal should continue to be reduced through the increase of lamp recycling activity throughout the country. In fact, among environmentally conscious groups, a goal is that there will come a time when all lamps containing mercury will be recycled rather than disposed of, allowing for the near 100% reclamation of the pollutant. This change in the way discharge lamps are handled upon replacement should further support the practice of re-lamping on a more frequent basis.

The software developed for this research has in all cases proven to be accurate as supported by direct comparisons with designs rendered by a commercially available lighting design program. In certain instances the designs generated by the software created for this research outperformed the designs offered by the commercial design program from both photometric and energy efficiency perspectives. The proposed layout algorithms, which allow for the realization of luminaire layouts using reduced luminaire quantities, will hopefully provide lighting industry with a basis for reevaluating the way in which indoor lighting layouts are determined.

The ongoing evolution of light sources including solid-state technologies (LED), reduced diameter fluorescents, and MH lamps utilizing ceramic arc tubes offer various improvements in the areas of lumen depreciation, life, and efficacy, all which have found or are finding their way into the marketplace. The concepts presented in this body of work should translate, either directly or with revision, to these new technologies as they are applied to industrial lighting applications since many of the factors affecting lighting system performance (life, LLD, dirt) are universal.

Regardless of the endeavor, the justification for recommending changes to what is considered to be conventional practice is generally the disclosure of what will be improved as a result of these changes. In the case of this dissertation the projected benefits realized through the reduction in the number of luminaires installed in an industrial facility are the reduction in the consumption of energy, project LCC, and certain environmental hazards. However, seemingly positive changes in policy and procedure are often accompanied by the increase or creation of other negative issues. With regard to the recommendations presented in this document, two issues come to mind. First is that the reduction in the number of luminaires results in greater impact upon maintained illumination levels resulting from premature lamp or ballast failure. If fewer luminaires are installed the failure of a single luminaire will have a greater impact upon the reduction of both overall and close proximity illumination levels. This problem can be amplified if there are significant mechanical obstructions in the vicinity. Second, the relatively long service life of HID lamps and associated maintenance intervals has been a key marketing point since their introduction. Many end-users may not choose to take advantage of the benefits of more frequent maintenance for various reasons which may include the availability of maintenance personnel, or the maintenance challenges encountered within industrial facilities which operate on a 24 hours per day, 365 day per year schedule.

There will always be applications that will not allow certain lamps due to color requirements, or that will not accept certain ballasts due to electrical service conditions such as line voltage dips and brown-out events. There will be projects that only permit certain luminaire mounting configurations making a layout using a reduced quantity of luminaires difficult if not impossible. However, there are many industrial lighting applications that will tolerate some or all of the changes suggested by this research, and these changes should lead to significant cost reductions for the end-user in addition to reduced stress upon our planet's environment and energy reserves.

6.2 Recommendations for Future Research

This research focuses upon the specific but regularly encountered general area HID indoor lighting application – the industrial facility. Future research should be performed by way of expanding these concepts to outdoor lighting applications. Outdoor lighting design is quite different from indoor design for a number of reasons, one of which being that the zonal cavity method does not apply. However, the economic model to determine LCC could be used as a template to develop similar tools for studying various outdoor lighting applications.

Another area that invites similar study is the indoor lighting application employing fluorescent luminaires. Many industrial as well as virtually all commercial lighting projects utilize these lighting products, and although there are similarities between the fluorescent and HID cases, there are also a number of differences requiring modifications to the lighting system model presented in this dissertation. Design by way of the zonal cavity method is common in fluorescent lighting applications, however the differences in the photometric distributions of HID and fluorescent luminaires are, in general, prohibitive for the utilization of the layout algorithms presented herein. New layout algorithms could be developed to possibly allow for the realization of reduced luminaire quantities and associated reductions in financial and environmental factors.

The effect of artificial lighting upon HVAC costs was treated throughout this research by way of an incremental energy cost based upon a simple ratio. This is a worst case scenario in that under certain circumstances the effect of electric indoor lighting upon HVAC costs may be positive. When heating is required in a facility the lighting raises the ambient temperature, thus reducing the amount of additional energy needed to heat the space. Enhancements to the model presented would be the incorporation of a more realistic method for projecting HVAC energy costs or savings as a function of environmental conditions.

The lighting system model presented does not account for obstructions in the industrial area being illuminated. This is an aspect of lighting design which can greatly affect the quantity and placement of luminaires that are needed because obstructions can substantially affect the ability of a lighting design to provide adequate illumination. Future models should be developed incorporating design techniques which will account for obstructions and other site-specific design considerations. Also, the use of grid-type ceilings is not addressed by this research since this scenario may significantly limit flexibility of design layouts which will consequently place constraints upon the number of luminaires that can be removed. This situation restricts a direct utilization of the presented layout concepts in certain commercial and institutional applications. Modifications to the layout algorithms could provide a more appropriately structured model for translation into these lighting application environments.

Appendix A – Software Implementation

What follows is the disclosure of the function of the programs written using the MATLAB® software package in support of this research. These programs, or M-files as they are commonly referred to, were created to determine the quantity and positioning (layout) of luminaires to satisfy an industrial lighting requirement using a pool of lamp, ballast, and photometric options. This software will also facilitate the determination of the most energy efficient and cost effective designs for an industrial lighting application based upon various luminaire options and maintenance scenarios. Rather than enclosing the actual programs as part of this manuscript, the detailed description of each program is presented to facilitate future software development sparked by the results of this research. Figure A-1 provides and overview of the interaction between the various programs with the lettered markers indicating the sequence of execution.

Master Design Program

IMASTERG2 is the master design program which is the centerpiece of the lighting design software developed in support of this research. Through the calling of other programs it calculates the number and physical configuration of both MH and HPS industrial High-Bay and Low-Bay luminaires needed to meet specific industrial lighting design requirements. At the beginning of a new project, a data entry and storage program (LIGHTDATA) is called by the master program allowing for the entry of the lighting application specifications listed in Table A-1. Depending upon the lamp family being used in the design process, the master program routs all of the necessary design information to one or both of the industrial design programs (INDUSTRIALMHG2 and INDUSTRIALHPSG2).

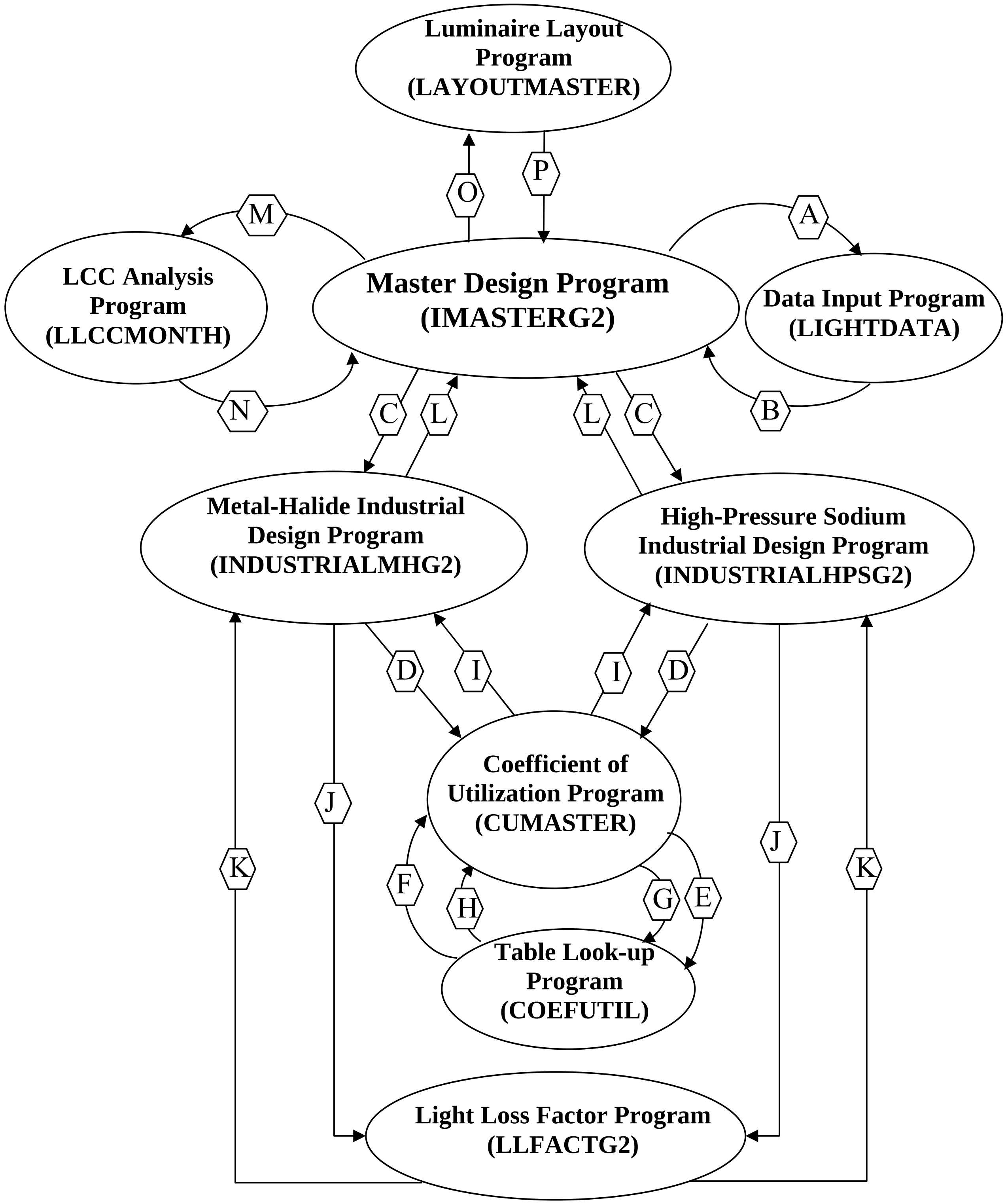


Figure A-1: Software Interaction Diagram

Table A-1: Input Data and Variable Identification used by IMASTERG2

Input Variable Identification	Variable Name
Floor width (feet)	*aw*
Floor depth (feet)	*ad*
Desired work plane illuminance (footcandles)	*mill*
Height of work plane (feet)	*wph*
Height of ceiling (feet)	*rh*
Maximum allowable mounting height (feet)	*mhx*
Minimum allowable mounting height (feet)	*mhm*
Ceiling Reflectance (percent)	*reflc*
Wall Reflectance (percent)	*reflw*
Floor Reflectance (percent)	*reflf*
Cleanliness Factor (unitless)	*clnfct*
Rated Luminaire Supply Voltage (V_{RMS})	*rvolt*
Actual Luminaire Supply Voltage (V_{RMS})	*avolt*
Ballast Type [CWA, Reactor, Magnetic Regulator]	*blstyp*
Operating Hours per Start	*hrsprstrt*
Operating Hours per Year	*hrspryr*
Time Between Group Relamping (months)	*relamp*
Time Between Work Area Cleanings (months)	*rmcln*
Time Between Luminaire Cleanings (months)	*lumcln*
Planned Life of Project (years)	*prjlife*
Mounting Heights to Evaluate (positive integer)	*mntlvls*

The results of the execution of these industrial design programs are returned to the master design program in the form of arrays (*mhdsgns* or *hpsdsgns*), either of which contains the data consisting of luminaire quantities and project power levels over the range of mounting heights requested.

Life-cycle costing is then performed using the information gathered by the data input program and assigned to variables residing in the master design program. The input parameters and associated variables are shown in Table A-2. These variable values are then sent to the LCC calculation program (LLCCMONTH), along with the design data generated by the industrial design program(s), and LCC calculations are performed for each design that has been generated.

Table A-2: Input Data and Variable Identification used by IMASTERG2 for LCC Analysis

Input Variable Identification	Variable Name
Cost of Electrical Energy ($/kw-Hr)	*nrgcost*
Annual Interest Rate (percent)	*intrate*
Annual Rate of Inflation (percent)	*infrate*
Hourly Rate for Maintenance ($/hour)	*mntcost*
Time Required to Re-lamp/Clean Single Luminaire (hours)	*mnttime*
Hourly Rate for Installation ($/hour)	*instcost*
Time Required to Install Single Luminaire (hours)	*insttime*
Additional Material Cost for Single Luminaire Installation ($)	*admat*
Time Required to Scrap Single Luminaire (hours)	*scrptime*
Lighting to HVAC Energy Cost Ratio	*hvacfctr*
Cleaning Material Charge for Single Luminaire ($)	*clnmatl*

The present worth of the LCC, the elements of which were presented in detail in section 3.3, are returned to the master design program for each design and added to the design arrays which have already been established. All of the details of the lighting designs for the various mounting heights are now located in design arrays (*mhdsgns* and *hpsdsgns*), allowing for the ranking of each design based upon energy consumption and LCC. The user is offered a choice of whether or not to display the three most energy efficient designs and the three most cost effective designs. Unless at least three of these six designs are displayed and one of the designs is selected, the design process stops since the luminaire layout is executed based upon the selection of one of the six designs.

The master design program passes the details of the preferred design to the luminaire layout program (LAYOUTMASTER), the elements of which were presented in section 3.4. The luminaire layout program then returns the results of one of four layout configurations interactively selected by the user. A summary of the selected design along with key design parameters and a summary of all designs are then presented by the master program, an example of which is shown in Figure A-2.

Design Summary

Lamp Power	400
Lamp Type	MH
Luminaire	BL400HXBIMED
No. of Luminaires	116
Mounting Height	28
Re-Lamp (months)	24
Luminaire Cleaning (mos.)	24
Area Cleaning (yrs.)	1
Coef. of Util.	0.8195
LLF	0.5260
Total Power (W)	53128
LCC	$156906.86

Do you wish to see the rankings of all designs based upon efficiency and LCC? [return to accept, enter N to skip]

PWR LVL(W)	LAMP	QTY	MTG. HGHT	LLF	LCC
400	1	116	27	0.52604	1.5691e+005
400	1	116	28	0.52604	1.5691e+005
400	1	117	29	0.52604	1.5826e+005
400	1	117	30	0.52604	1.5826e+005
400	1	118	31	0.52604	1.5961e+005
400	1	118	32	0.52604	1.5961e+005
400	1	119	33	0.52604	1.6096e+005
400	1	119	34	0.52604	1.6096e+005
400	1	120	35	0.52604	1.6232e+005
400	1	120	36	0.52604	1.6232e+005

PWR LVL(W)	LAMP	QTY	MTG. HGHT	LLF	TOTAL POWER (W)
400	1	116	27	0.52604	53128
400	1	116	28	0.52604	53128
400	1	117	29	0.52604	53586
400	1	117	30	0.52604	53586
400	1	118	31	0.52604	54044
400	1	118	32	0.52604	54044
400	1	119	33	0.52604	54502
400	1	119	34	0.52604	54502
400	1	120	35	0.52604	54960
400	1	120	36	0.52604	54960

Figure A-2: Example Output Summary (IMASTERG2)

DATA INPUT PROGRAM

The program LIGHTDATA allows the user to enter all of the pertinent information for the lighting project by the use of MATLAB command window prompts, and stores this information in a data array (*LDATA*). The sole purpose for maintaining a central array containing the lighting project specifications is to provide for the consistent retrieval of data by other programs used in this research. The data input program also provides the user the ability to specify the lamp family (MH and/or HPS) and the luminaire data file to be used with the desired lamp power level in each lamp family. It is important to note that lamp power levels are selected by the user. For example, if it were only desired to perform designs based upon 360W and 400W MH lamps then the user would only accept those options when queried by the software. When these power levels are selected the user would specify which corresponding luminaire (luminaire data file) should be used for each design or accept the default, which was selected to be a standard high-bay industrial luminaire with a medium photometric distribution. The data included in the data array corresponds to the variables listed in Tables A-1 and A-2, and the luminaire data files are assigned to the variables listed in Table A-3.

Table A-3: Lamp Power Levels Available for use including Luminaire Data File Assignments

Lamp Family	Power Level (W)	Luminaire Data File
Metal-Halide	200	*mhlumfile200*
	250	*mhlumfile250*
	320	*mhlumfile320*
	350	*mhlumfile350*
	360	*mhlumfile360*
	400	*mhlumfile400*
	450	*mhlumfile450*
	750	*mhlumfile750*
High-Pressure Sodium	200	*hpslumfile200*
	250	*hpslumfile250*
	310	*hpslumfile310*
	400	*hpslumfile400*
	600	*hpslumfile600*

The entries in Table A-3 list the currently available lamp options in both the MH and HPS lamp families for power levels above 175 watts and below 1000 watts, and also summarizing the HID lamp options available for use by the software. Upon entering choices for the desired lamp family and power levels, a series of queries are posed to the user regarding the following: unit cost of the luminaire, lamp unit cost, lamp disposal cost, initial lamp lumen rating, mean lumen rating, and the rated lamp life. This offers the user the flexibility of using lamps that vary in certain aspects of their performance. These quantities are stored in data arrays (*mharray* and *hpsarray*) which are passed to other programs as required.

Two fundamental data components required for design and layout of an industrial lighting project are the CU tables and spacing criterion for the luminaires that are being employed. As presented previously, a representative CU table is shown in Table 2-1, however this table does not include the spacing criterion. In that the developed software requires CU data as well as the spacing criterion, it is logical to develop a file format that is readily imported into the MATLAB program. To this end, a straightforward text file format is presented that contains all of the information necessary to perform a lighting design utilizing a specific luminaire based upon the zonal-cavity method. The format chosen is termed a *design table*, an example of which is shown in Figure A-3.

```
                                         BL400HXBIWID
LIGHTING DESIGN TABLE FOR 400W MH INDUSTRIAL LUMINAIRE, COL 1 (ROW4-14) RCR AND (ROW15) SPACING
CRITERIA (WIDE)
ROW1 EFF.FLOOR CAVITY RELECTANCE, ROW2 CEILING CAVITY REFLECTANCE, ROW3 WALL REFLECTANCE (IES#
HP03801.IES)
 0   20   20   20   20   20   20   20   20   20   20   20   20   20   20   20   20   20   20
 0   80   80   80   80   70   70   70   70   50   50   50   30   30   30   10   10   10    0
 0   70   50   30   10   70   50   30   10   50   30   10   50   30   10   50   30   10    0
 0  .99  .99  .99  .99  .97  .97  .97  .97  .92  .92  .92  .88  .88  .88  .84  .84  .84  .82
 1  .91  .87  .83  .80  .88  .85  .82  .79  .81  .79  .76  .78  .76  .74  .74  .73  .71  .69
 2  .82  .75  .70  .65  .80  .74  .68  .64  .71  .66  .62  .68  .64  .61  .65  .62  .59  .57
 3  .75  .66  .59  .53  .72  .64  .58  .53  .62  .56  .51  .59  .54  .50  .57  .53  .49  .47
 4  .68  .57  .50  .44  .66  .56  .49  .44  .54  .48  .43  .52  .47  .42  .50  .45  .42  .40
 5  .62  .51  .43  .37  .60  .50  .42  .37  .48  .41  .36  .46  .40  .36  .44  .39  .35  .33
 6  .57  .45  .37  .32  .55  .44  .37  .31  .42  .36  .31  .41  .35  .31  .39  .34  .30  .28
 7  .52  .40  .33  .27  .50  .39  .32  .27  .38  .32  .27  .37  .31  .26  .35  .30  .26  .24
 8  .48  .36  .29  .24  .47  .36  .29  .24  .34  .28  .23  .33  .27  .23  .32  .27  .23  .21
 9  .45  .33  .26  .21  .43  .32  .25  .21  .31  .25  .21  .30  .24  .20  .29  .24  .20  .19
 10 .41  .30  .23  .18  .40  .29  .23  .18  .29  .22  .18  .28  .22  .18  .27  .22  .18  .16
2.1
```

Figure A-3: Example Luminaire Design Table (400WHXBIWID.txt) [43]

The structure of this file serves two needs. First, the spacing criterion is presented as the bottom entry in the lower left corner of the table (in Figure A-3 a value of 2.1), and second the reflectances across the top of the table are presented in a discernable form for use by software search algorithms. Referring to Figure A-3, a two line text header identifies the luminaire photometric test and describes the structure of the design table with the effective cavity floor reflectance (ρ_{fce}) and the effective ceiling cavity reflectance (ρ_{cce}) values presented in the first two numerical rows below the header. The third row of design table values are the wall reflectances (ρ_W) corresponding to each column of CU values. The format of Figure A-3 distributes all values to their appropriate columns, which is necessary when being successfully searched by a software algorithm that will be subsequently described.

It is necessary that design tables are available for access by the software for each luminaire that is employed in the design process, however that does not imply that all of the tables are unique. For example the design table of Figure A-3 not only applies when a 400W MH luminaire is selected, but also when a 360W MH luminaire is selected since the same luminaire photometric characteristics apply. This is due to the commonality of lamp sizes and arc-tube (light center) locations. The only items that change relative to the 400W product from a photometric standpoint are the initial and mean lumen ratings of the 360W lamp, which are not presented as part of the design table content. The design table filename without extension, which for the sake of clarity was chosen to be the luminaire product name, is required to be entered and assigned to the corresponding luminaire data file variable name as listed in Table A-3. It should be noted that there is only one luminaire used for a given lamp power level during one design cycle.

Industrial Design Programs

INDUSTRIALMHG2 and INDUSTRIALHPSG2 are the industrial design programs used to determine the number of luminaires required to illuminate the work plane of a rectangular work area to a desired level. They produce designs for multiple mounting heights, multiple optical assemblies (luminaire optics), and multiple lamp power levels. Both of these programs are invoked by the master design program (IMASTERG2) are nearly identical in structure, therefore unless stated otherwise descriptions made on behalf of one program will apply to both. The variables that are required to be passed to these programs are summarized in Table A-4. It should be noted that these are the same quantities presented in Table A-1, the only difference being the variable names. The purpose for employing different variable names for the same quantities throughout the various programs was to isolate operations between them, which significantly aided in the troubleshooting of the software. Also passed to the industrial design programs are the data arrays (*mharray* and *hpsarray*) which contain the all of the applicable lamp performance information as well as lamp and luminaire cost information.

Based upon the physical parameters of the room (*hc*, *hminm*, *hmaxm*, *hfc*) and the number of mounting height levels (*lvls*) that are to be investigated, the minimum and maximum ceiling cavity heights are calculated (*hrcmin* and *hrcmax* respectively). Recall from chapter 2 that the cavity heights are required for the determination of the cavity ratios, which in turn are required for determining the CU. A new variable is introduced, the floor factor, which is simply a dimensional constant used repeatedly in future calculations. Referring to Equation A.1, the ratio of the sum of the floor dimensions to the product of those dimensions can be consolidated into the floor factor (*ff*).

$$ff = \frac{f_w + f_d}{f_w f_d} \tag{A.1}$$

Table A-4: Input Parameters used by Functions INDUSTRIALMHG2 and INDUSTRIALHPSG2

Input Variable (units)	Variable Name
Floor width (feet)	*fw*
Floor depth (feet)	*fd*
Desired work plane illuminance (footcandles)	*efc*
Height of work plane (feet)	*hfc*
Height of ceiling (feet)	*hc*
Maximum allowable mounting height (feet)	*hmaxm*
Minimum allowable mounting height (feet)	*hminm*
Ceiling Reflectance (percent)	*rc*
Wall Reflectance (percent)	*rw*
Floor Reflectance (percent)	*rf*
Cleanliness Factor (unitless)	*cleanf*
Lamp Lumen Depreciation (per unit)	*lld*
Rated Luminaire Supply Voltage (V_{RMS})	*vrated*
Actual Luminaire Supply Voltage (V_{RMS})	*vact*
Ballast Type [CWA, Reactor, Magnetic Regulator]	*btype*
Operating Hours per Start	*hrsperst*
Operating Hours per Year	*yrbhr*
Time Between Group Relamping (months)	*relmp*
Time Between Work Area Cleanings (months)	*rclean*
Time Between Luminaire Cleanings (months)	*tclean*
Mounting Heights to Evaluate (positive integer)	*lvls*

The values for the maximum and minimum cavity ratios are then calculated using Equation 7.2.

$$CR_{XX} = \frac{5h_{XX}(f_w + f_d)}{(f_w f_d)} = 5 \times h_{xx} \times ff \tag{A.2}$$

These quantities, along with the number of mounting levels will allow for the calculation of lighting designs at the various mounting heights. Table A-5 lists the cavity ratios and their abbreviations as employed by the industrial design programs.

Table A-5: Room Cavity Ratios and Abbreviations

Floor Cavity Ratio (CR_{FC})	*fcr*
Minimum Room Cavity Ratio (CR_{RC})	*rcrmin*
Maximum Room Cavity Ratio (CR_{RC})	*rcrmax*
Minimum Ceiling Cavity Ratio (CR_{CC})	*ccrmin*
Maximum Ceiling Cavity Ratio (CR_{CC})	*ccrmax*

The luminaire power consumption databases (*mhblstlarge.txt* and *hpsblstlarge.txt*) are loaded by the software and used to assign luminaire power consumption levels based upon the selected lamp power level and ballast type. These databases may be modified using a simple text editing program to accommodate variations in ballast input power consumption ratings. This may be necessary in certain situations since individual ballast manufacturers produce similar units that sometimes differ with regard to published electrical performance.

At this point in the execution of the industrial design programs the design tables are loaded for each power level of interest, after which the CU tables are extracted from the design tables and placed under the CU array name *CUTxx*, where '*xx*' corresponds to the first two digits of the rated lamp power level. These arrays will be passed on to the coefficient of utilization program (CUMASTER) which serves to extract the correct CU value from the tabulated CU data residing in array *CUTxx*. Additionally the spacing criterion for the luminaire in question is retrieved and assigned to the scalar variable *spcxx*, where again '*xx*' corresponds to the first two digits of the rated lamp power level.

The software is designed to calculate multiple lighting designs based upon varying luminaire mounting heights, which is realized by determining the CU value in each case. To determine these values the following information is needed: room cavity ratio (*rcr*), ceiling reflectance (*rc*), wall reflectance (*rw*), floor cavity or work plane height (*hfc*), floor reflectance (*rf*), ceiling height (*hc*) and the floor factor (*ff*). The design calculations are accomplished by utilizing the minimum and maximum room cavity ratios as determined by Equation A.2, where the variable names and associated quantities are those listed in Table A-5. In determining of CU values for the various mounting heights, the only design variable which changes is the room cavity ratio, which is altered by an incremental variable *rcrdel* that is defined in Equation A.3.

$$rcrdel = \frac{(rcrmax - rcrmin)}{(lvls\text{-}1)} \tag{A.3}$$

All of these quantities will be passed to the coefficient of utilization program, which is discussed in more detail in a subsequent section. At the completion of each iteration to determine the CU, the room cavity ratio is updated by incrementing the value of *rcr* by *rcrdel* beginning with *rcrmin*. The industrial design programs then pass the room cavity ratio, cleanliness factors, lamp information, ballast information, cleaning intervals, and operating information to the light loss factor program (LLFACTG2) which calculates the light loss factors used in the determination of the required number of luminaires for the individual designs. All of the design results are then placed in design arrays (*MHCHOICES* and *HPSCHOICES*) that are subsequently passed back to the master design program.

Coefficient of Utilization Program

CUMASTER, the coefficient of utilization program, is used to determine the CU based upon a set of input variables which are passed to it by the industrial design programs. Within this program the following quantities are employed: room cavity ratio (*rcr*), ceiling reflectance (*rc*), wall reflectance (*rw*), floor cavity or work plane height (*hfc*), floor reflectance (*rf*), ceiling height (*hc*) and the floor factor (*ff*). Extracted from the design table, the CU table is passed from the individual industrial design program using the same identification format, *CUTxx*, where '*xx*' corresponds to the first two digits of the rated lamp power level. The first step performed is the calculation of the effective ceiling cavity reflectance (*rcce*) using Equation 2.2. The height of the room cavity (*hrc*) is calculated directly the room cavity ratio (*rcr*), and a variable is introduced (*wcratio*) that is the result of the evaluation of Equation 2.3, which is the ratio of the wall area within the ceiling cavity to the ceiling area.

The effective ceiling cavity reflectance (*rcce*) will most frequently differ from the integer reflectance values presented in the CU table. This situation creates a need for the program to extrapolate the correct CU value from the table based upon the upper and lower bounds of *rcce* that are provided. Using the variable names *rccu* (upper published bound of ρ_{cce}) and *rccl* (lower published bound of ρ_{cce}) the relationship is defined as $rccl < rcce < rccu$. The lower and upper bounds are determined by way of a search algorithm across the row containing the integer values of ρ_{cce}. The same situation arises concerning the wall reflectance. For the purpose of simplifying the determination of the CU it is common to select a standard value of wall reflectance which is in close proximity to the actual value. In the same manner as previously discussed, the upper and lower limits are determined and labeled *rwu* and *rwl* respectively. Referring to Figure A-4, for hypothetical values of *rcce* and *rw* equal to 74.6 and 28 respectively, the locations of values *rccu*, *rccl*, *rwu* and *rwl* are identified .

rccu *rwu* *rccl* *rwl*

ρcc ...	80				70			
ρw ...	70	50	30	10	70	50	30	10
RCR								
0	0.97	0.97	0.97	0.97	0.94	0.94	0.94	0.94
1	0.91	0.88	0.85	0.83	0.88	0.86	0.84	0.81
2	0.85	0.79	0.75	0.72	0.82	0.78	0.74	0.7
3	0.79	0.72	0.66	0.62	0.76	0.7	0.65	0.61
4	0.73	0.65	0.59	0.54	0.71	0.64	0.58	0.54
5	0.68	0.59	0.53	0.48	0.66	0.58	0.52	0.48
6	0.63	0.53	0.47	0.43	0.61	0.52	0.47	0.42

Figure A-4: Values of Reflectance Bounds for *rcce* = 74.6 *and rw* = 28

Once the reflectance boundary values of Figure A-4 have been identified they are passed, along with the CU table and the room cavity ratio, to a table look-up program (COEFUTIL) that will be described later in this appendix. Returned by the table look-up program are the four table entries corresponding to the four corner values that will be used to determine the desired CU value. These intermediate CU values returned to coefficient of utilization program are listed in Table A-6 along with their assigned variable names, pointing out that these CU values are based upon the actual room cavity ratio which will in the majority of cases not be one of the integer values presented in the published CU table.

Table A-6: Intermediate CU Quantities Returned to CUMASTER from COEFUTIL

CU value corresponding to:	Variable Name
rccu and *rwu*	*uu*
rccu and *rwl*	*ul*
rccl and *rwu*	*lu*
rccl and *rwl*	*ll*

Three linear regressions are then performed to determine another set of intermediate CU values using the effective ceiling cavity reflectance (*rcce*) and actual wall reflectance (*rw*). This procedure is illustrated in Figure A-5.

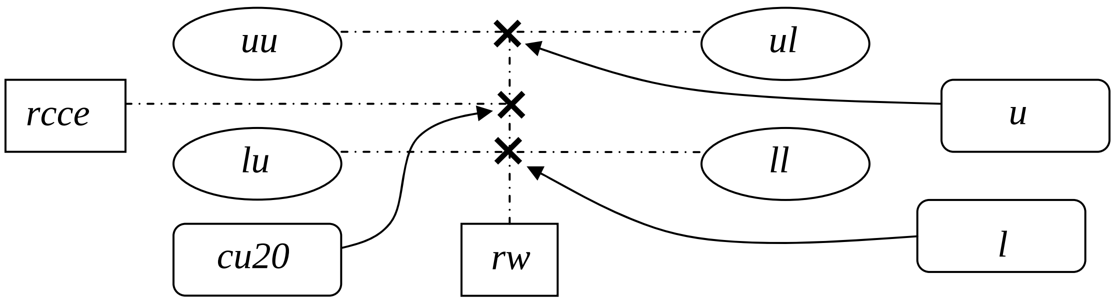


Figure A-5: Intermediate CU Values *u*, *l* and *cu20*

Once the new intermediate CU values (*u* and *l*) are determined, another regression is performed to determine the intermediate CU value (*cu20*) corresponding to the effective ceiling cavity reflectance (*rcce*) and the actual wall reflectance (*rw*). This CU value (*cu20*) remains an intermediate value since the CU tables are based upon a floor cavity reflectance of 20%.

To arrive at the final CU value it is necessary to employ another set of tables that are appropriately referred to as *Multiplying Factors for Other than 20% Effective Floor Cavity Reflectance* [4]. These tables have already been presented as Table 2-2, Table 2-3 and Table 2-4, and they are represented in the software as text files *FCFT30.txt*, *FCFT10.txt* and *FCFT00.txt* corresponding to effective floor cavity reflectances of 30%, 10% and 0%. In addition, a dummy table (*FCFT20.txt*), in which all entries have a value of 1.0, is needed which corresponds to a floor cavity reflectance of 20%. Based upon the value of effective floor reflectance (*rfce*), which is calculated by using Equation 2.2, two tables are loaded so that the multiplying factor may be determined. If the value of the effective floor cavity reflectance is greater than 30%, then the multiplying factor published in the 30% table (*FCFT30.txt*) is employed. Notice that these tables are structured (headings) in the same manner as the CU table presented in Table 2-1. The multiplying factors are categorized by the effective ceiling cavity reflectance (*rcce*), the wall reflectance (*rw*), and the room cavity ratio (*rcr*), therefore the table look-up program (COEFUTIL) may again be employed to determine the intermediate and ultimately the final floor reflectance correction factor (*rccf*).

The two multiplying factor tables are loaded which bound the effective floor cavity reflectance value and are labeled *uptable* and *lotable*. The boundary values of the effective floor cavity reflectance represented by these two tables are labeled *urfc* and *lrfc* corresponding to upper and lower floor cavity reflectances. In the event that the value of *rfce* equals 30, 20, 10 or 0, the tables assigned to *uptable* and *lotable* are the same. The variables identified within each individual table are shown in Table A-7 and are determined using the table look-up program.

Table A-7: Intermediate Multiplying Factors Returned to CUMASTER from COEFUTIL

Multiplying Factor corresponding to:	Variable Name
rccu and *rwu*	*uufc*
rccu and *rwl*	*ulfc*
rccl and *rwu*	*lufc*
rccl and *rwl*	*llfc*

As before, these corner values are used to extract the exact multiplying factor needed from both tables; *rccfu* for the multiplying factor from the *uptable*, and *rccfl* for the multiplying factor from *lotable*. Unlike the CU determination (*cu20*), an additional regression is required to determine the value of the floor cavity correction factor (*rccf*). Using variables *rccfu*, *rccfl*, *urfc* and *lrfc,* the final multiplying factor can be determined, with the complete process being illustrated in Figure A-6.

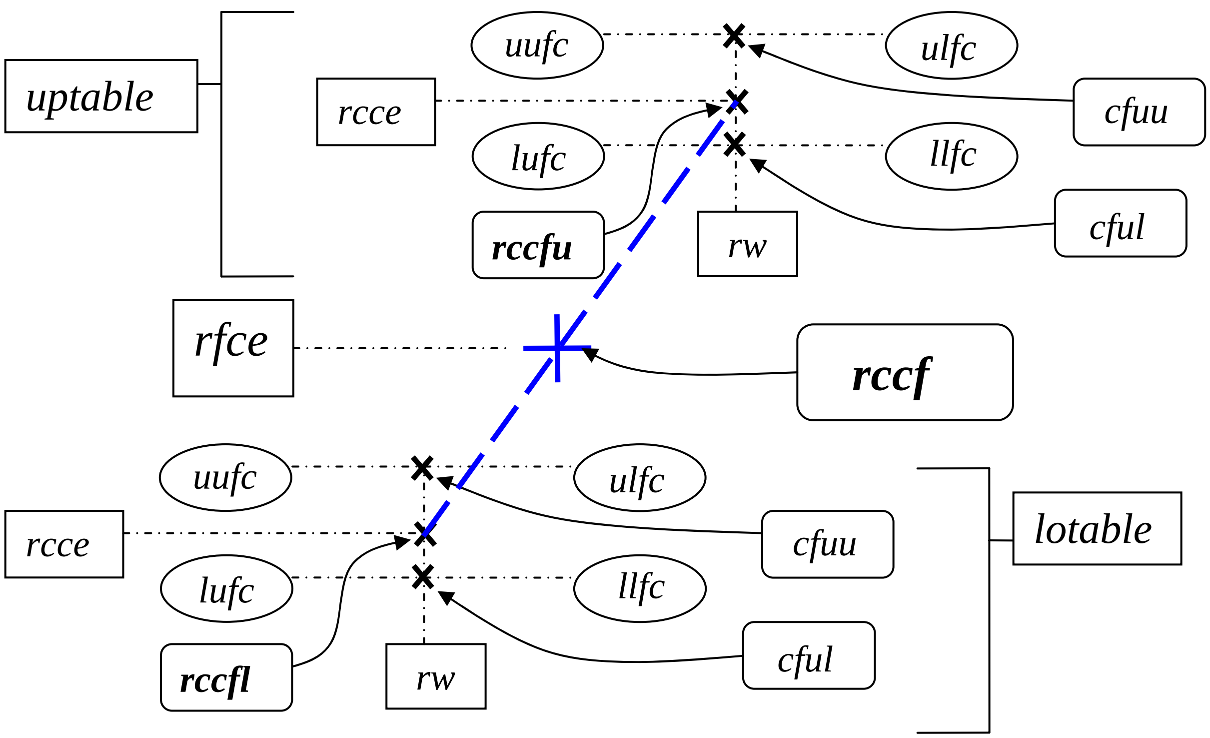


Figure A-6: Procedure for Determining Floor Cavity Reflection Correction Factor (*rccf*)

Table Look-Up Program

COEFUTIL is a program designed to extract a value from a CU table, or other table using similar formatting as shown in Figure A-7, where Figure A-7 is extracted from the design table presented in Figure A-3. As stated earlier, the top row is the effective floor cavity reflectance (20%), the second row is the effective ceiling cavity reflectance and the third is the wall reflectance. Below these rows, arranged in a column wise manner are the CU values corresponding to the specific values of reflectances listed above. This program is used to determine either the four corner values corresponding to upper and lower reflectance bounds at a specific room cavity ratio, or the corner values associated with the determination of the floor cavity correction factor (*rccf*).

0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
0	80	80	80	80	70	70	70	70	50	50	50	30	30	30	10	10	10	0
0	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
0	.99	.99	.99	.99	.97	.97	.97	.97	.92	.92	.92	.88	.88	.88	.84	.84	.84	.82
1	.91	.87	.83	.80	.88	.85	.82	.79	.81	.79	.76	.78	.76	.74	.74	.73	.71	.69
2	.82	.75	.70	.65	.80	.74	.68	.64	.71	.66	.62	.68	.64	.61	.65	.62	.59	.57
3	.75	.66	.59	.53	.72	.64	.58	.53	.62	.56	.51	.59	.54	.50	.57	.53	.49	.47
4	.68	.57	.50	.44	.66	.56	.49	.44	.54	.48	.43	.52	.47	.42	.50	.45	.42	.40
5	.62	.51	.43	.37	.60	.50	.42	.37	.48	.41	.36	.46	.40	.36	.44	.39	.35	.33
6	.57	.45	.37	.32	.55	.44	.37	.31	.42	.36	.31	.41	.35	.31	.39	.34	.30	.28
7	.52	.40	.33	.27	.50	.39	.32	.27	.38	.32	.27	.37	.31	.26	.35	.30	.26	.24
8	.48	.36	.29	.24	.47	.36	.29	.24	.34	.28	.23	.33	.27	.23	.32	.27	.23	.21
9	.45	.33	.26	.21	.43	.32	.25	.21	.31	.25	.21	.30	.24	.20	.29	.24	.20	.19
10	.41	.30	.23	.18	.40	.29	.23	.18	.29	.22	.18	.28	.22	.18	.27	.22	.18	.16

Figure A-7: Format of CU Table for use with COEFUTIL

The quantities which are passed to the table look-up program from the coefficient of utilization program are the room cavity ratio (*rcr*), the effective ceiling cavity reflectance (*rcce*), the wall reflectance (*rw*) the table being searched (*M*). The table (*M*) is either a CU table or one of the floor cavity correction factor tables. The algorithm used by this program is illustrated in Figure A-8, and is described as follows:

(i) Determine the number of rows and columns of *M*.

(ii) Initialize flags and index variables (*f, g, i, j*). The flags *f* and *g* are used to indicate when the last column and last row are searched respectively. The index values *i* is used to increment the row number and *j* is used to increment the column number.

(iii) Scan the row 2 values until a matching entry of *rcce* is found. If no entry is found then the execution is halted.

(iv) Once the column with a matching *rcce* is found the next row (row 3) entry in this column is checked to see if it matches the specific value of *rw*. If the entry does not match *rw* then the column number is incremented and the process returns to step 3.

(v) If the values of *rcce* and *rw* are matched successfully to a specific column through the execution of steps i through iv, a row search of the boundary values of the room cavity ratio. The row number is incremented and the actual value of *rcr* is compared to the column 1 entry. Once the column 1 entry exceeds the actual value of *rcr* then this row number is used as the upper bound, and the preceding row is used as the lower bound.

(vi) The value of *rcr* in the row being used as the upper bound is identified as *mrcru*, and the *rcr* of the previous row is *mrcrl*. The table entries corresponding to the upper and lower bounds in the column of interest are labeled *cuh* (for high or upper) and *cul* (for lower).

(vii) A linear regression is performed between the values of *cuh* and *cul* using the *rcr* as the evaluation point. The result is the table entry of interest (*c*), which is returned and assigned to the variable dictated by the calling program CUMASTER.

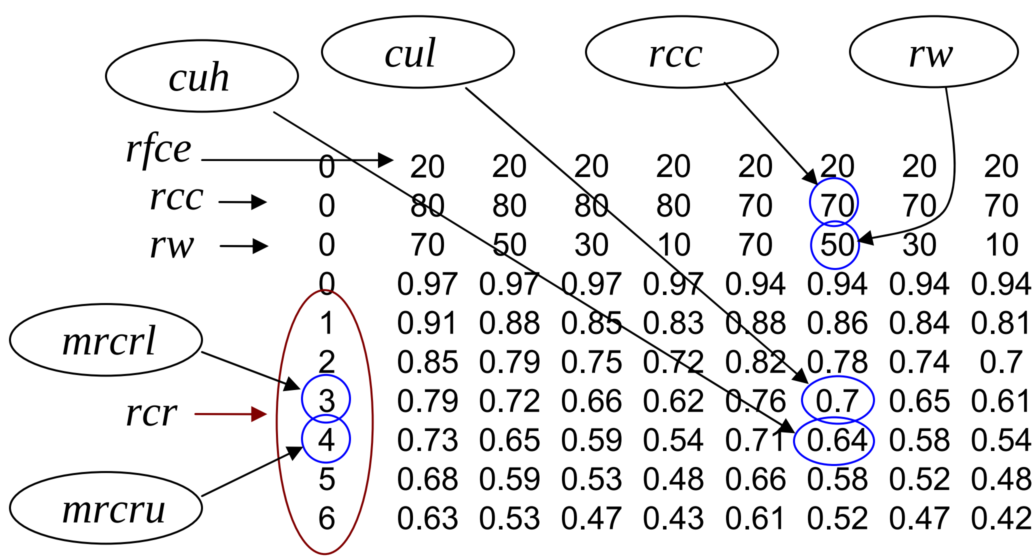


Figure A-8: Values of CU Bounds for *rcc* = 70, *rw* = 50 and 3 < *rcr* < 4

Light Loss Factor Program

The light loss factor program named LLFACTG2 determines the values of the individual loss factors, the product of which is the light loss factor used in a given lighting design. It is invoked by either of the industrial design programs (INDUSTRIALMHG2 and INDUSTRIALHPSG2) and returns the light loss factor (LLF) used in the determination of the number of luminaires required to satisfy the design requirements by way of Equation 2.10. The variables passed from the industrial design program are listed in Table A-8.

Table A-8: LLFACTG2 Input Variables

Input Variable (units)	Variable Name
room cavity ratio	*rcr*
cleanliness factor	*cleanf*
rated lamp life (hours)	*lmplife*
lamp family	*lfamly*
initial lamp lumen rating	*llum*
mean lamp lumen rating	*mean*
operating hours per year	*yrbhr*
operating hours per start	*hrsperst*
rated luminaire voltage	*vrated*
actual luminaire voltage	*vact*
ballast type	*btype*
time between group relamping	*relmp*
time between luminaire cleanings	*tclean*
time between area cleanings (months)	*rclean*
project life	*plife*
maintenance category	*cat*

The first factor to be determined is the luminaire voltage factor (LV), which is accomplished by evaluating either Equation 2.5 or 2.6, both of which are located in section 2.4.2. The equation selected is based upon whether the ballast being used is a regulating type (*btype* = 1) or a non-regulating type (*btype* = 2). In the case where a magnetically regulating (MR) ballast is used (*btype* = 3) the formula used is shown as Equation A.4, which is based upon improved line-side lamp power regulation.

$$LV = 1 - \left[\left(1 - \frac{\text{Line Voltage @ Luminaire}}{\text{Rated Luminaire Voltage}} \right) \times 1.0 \right] \qquad \text{(A.4)}$$

Next to be defined is the ballast factor (BF), which is again assigned by the type of ballast which is being employed. For reactor or magnetic regulator (MR) ballasts (*btype* = 2 or 3) the ballast factor (*BF*) is assigned to be 1.0, whereas for the constant wattage autotransformer (*btype* = 1) the ballast factor is 0.95. It is known that HID lamp life is shortened when lamp burn cycles fall below 10 hours per start [40]. An approximation of this shortened lamp life is included which will affect LBO and LLD factors. If the burn cycle falls below 5 hours per start the rated lamp life is reduced by 25%. In the cases where burn cycles fall below 2.5 and 1.25 hours per start, the rated lamp life is reduced by 45% and 60% respectively [40].

Recoverable loss factors vary over time. As described in section 2.4.2 these factors are room surface dirt depreciation (RSDD), luminaire dirt depreciation (LDD), lamp burn-outs (LBO), and lamp lumen depreciation (LLD). As a result, the values of the these loss factors used in the determination of the light loss factor will vary with lamp replacement and cleaning cycles – the more frequent the servicing, the closer these factors are to 1.0. To determine these factors, calculations are performed on a monthly basis, taking into account the months when cleaning and re-lamping are planned. The number of calculations performed for a particular recoverable factor is dictated by the time interval between project installation and the maintenance performed to recover the loss. For example, if the room is to be cleaned annually then the loop used in determining RSDD will perform 13 calculation cycles generating data for months 0 through 12.

In the case of LLD, LBO, and LDD, the loop will perform iterations based upon the planned re-lamping schedule. The benefit of using this method to determine the individual loss factors is that it allows for the generation of a light loss factor curve as illustrated in Figure 2-1, which is located in section 2.4.2. The minimum value of the LLF curve is then returned to the industrial design program and is used to evaluate Equation 2.10.

The table containing the constants required for the calculation of the room surface dirt depreciation factor is resident in the program due to its small size. As stated in section 2.4.2, the RSDD factor is always based upon the maintenance category V data. Referring to Table 2-5 and Equation 2.7, this information is defined in a 1x2 matrix (*DDCnst*), the values of which are presented in Table A-9.

Table A-9: Array Entries used to Determine Room Surface Dirt Depreciation

5 (v. clean)	4 (clean)	3 (medium)	2 (dirty)	1 (v. dirty)
0.078	0.128	0.190	0.249	0.321

The top row of Table A-9 contains the possible values of the cleanliness factor (*cleanf*), which is entered manually at the beginning of the design process. A decision-based loop within the program matches the value of *cleanf* to the proper row 1 entry and the corresponding row 2 entry is assigned to the variable *A* used in Equation 2.7 and also Equation 2.8. The dirt depreciation percentage (*PDD*) is calculated using Equation 2.7, with the value of *t* being the cleaning period in years (*tclean*) that has been passed from the industrial design program after being converted from the monthly equivalent. Using a table search algorithm similar to the one used in COEFUTIL, the table of *RSDD* values is searched to determine the precise value for the given room cavity ratio. The algorithm first determines if the value of *PDD* lies outside of the bounds of the table, which would be *PDD* > 40 or *PDD* < 10. If this is the case then execution is halted since the dirt depreciation percentage does not lie within feasible limits. Otherwise, the upper and lower boundary values of *PDD* are determined from the first row of the table and are labeled *pddu* and *pddl* for upper and lower respectively. Similarly, the first column of the table containing the room cavity ratio (*rcr*) values is searched to determine the upper and lower boundary values which are labeled *rcru* and *rcrl*. As would be the case if the *PDD* being out of range, execution of the program would halt if *rcr* > 10 or *rcr* < 1.0. These table values, which correspond to *pddu*, *pddl*, *rcru* and *rcrl*, form the corner values that are used to determine the value of room surface dirt depreciation (*RSDD*). The values described are illustrated in Figure A-9 for a *PDD* of 36 and an *rcr* of 3.4. In the same manner described previously, linear regression is used to determine the room surface dirt depreciation value for the specific values of room cavity ratio and *PDD*.

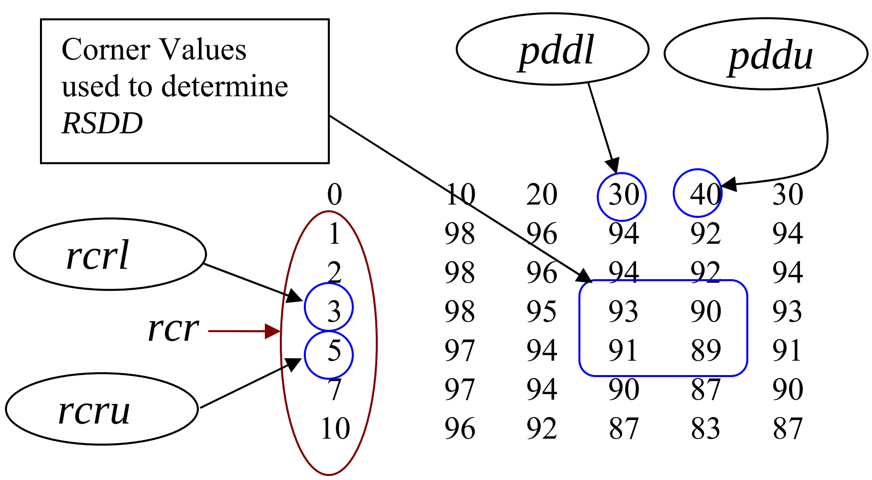


Figure A-9: Corner Values used in the determination of RSDD for *rcr* = 3.4 and *PDD* =36

Since the value of *B* required by Equation 2.8 is always 0.7 for category III luminaires, as shown in Table 2-5, Equation 2.8 can be rewritten as presented in Equation A.5.

$$LDD = e^{-At^{0.7}} \tag{A.5}$$

The luminaire dirt depreciation (LDD) is calculated using Equation A.5, again with the variable ***t*** replaced by the value assigned to variable *tclean*. The software has access to the complete table of dirt depreciation constants (categories I though VI), so a minor change in the calling program could be made so that other luminaire types may be easily accommodated. This dirt depreciation table is labeled *DDC.txt* and is loaded into a dirt depreciation array (*DDTABLE*) by the light loss factor program during execution.

The last operation performed by this program is the placing all of the individual loss factors into an array that will allow for a projection of a LLF characteristic over the life of the lighting project. The minimum point of this LLF characteristic (*llfmin*) is passed back to the calling program and will be used in the determination of the number of luminaires that are required to satisfy the project performance constraints.

Life-Cycle Cost Analysis Program

Invoked by the master design program, LLCCMONTH is a life-cycle costing program that performs present worth calculations for various design and maintenance scenarios. The variables that are required by the program are listed in Table A-10. The details of the calculations performed by this program were addressed in section 2.5 and therefore do not need repeating in this appendix. As mentioned previously, the quantities used for the variables listed in Table A-10 are entered through the execution of the data input program (LIGHTDATA).

Table A-10: LLCCMONTH Input Variables

Input Variable (units)	Variable Name
Unit luminaire cost ($)	*lumcost*
Unit lamp cost ($)	*lmpcost*
Unit lamp disposal cost ($)	*dspcost*
Cost of Electrical Energy ($/kw-Hr)	*nrgcost*
Annual Interest Rate (percent)	*intrate*
Unit Luminaire Input Power	*lumpwr*
Annual Rate of Inflation (percent)	*infrate*
Hourly Rate for Maintenance ($/hour)	*mntcost*
Time Required to Re-lamp/Clean Single Luminaire (hours)	*mnttime*
Hourly Rate for Installation ($/hour)	*instcost*
Time Required to Install Single Luminaire (hours)	*insttime*
Additional Material Cost for Single Luminaire Installation ($)	*admat*
Time Required to Scrap Single Luminaire (hours)	*scrptime*
Lighting to HVAC Energy Cost Ratio	*hvacfctr*
Number of Luminaires Installed	*nol*
Project Life (years)	*prjlife*
Operating Hours per Start	*hrspstrt*
Operating Hours per Week	*hrspwk*
Operating Hours between Group Re-lamping	*rlmpint*
Cleaning Material Charge for Single Luminaire ($)	*clnmatl*

Luminaire Layout Program

Once the number of required luminaires is determined, a series of layouts are performed using the preferred design by a program named LAYOUTMASTER. In general area lighting applications, the goal of the luminaire layout is to distribute the luminous flux as evenly as possible over the target area. As mentioned previously, general practice is to perform a symmetric layout such as the one illustrated in Figure 2-2 located in section 2.4.4, however this may require the use of more luminaires than are needed to achieve an acceptable level of uniformity. This program utilizes the two algorithms that were developed and presented in section 3.4 to perform four layouts based upon the dimensions of the space and the number luminaires required. The preferred layout is then interactively selected and the luminaire coordinates are displayed.

Appendix B – Design and Analysis Using LitePro® Software

The process of using LitePro® to validate the results of this research is illustrated in sufficient detail to facilitate similar analyses. The zonal cavity design feature provided by LitePro® is referred to as *Quick Calc*. To generate a comparable indoor lighting design using this commercially available software a series of design steps must be performed including: creation of a new project, selection of a luminaire (pulls the appropriate CU data for the luminaire of interest), selection of a lamp type and power level, entering of all physical data (reflectances, work plane height, etc.), and selection of luminaire mounting height. The software then performs an analysis which is illustrated in Figures B-1 through B-13. When creating a new design/analysis, which will subsequently referred to as a project, the basic descriptive summary is entered in the first window that appears as shown in Figure B-1. This information is used to identify the project and create a report cover page.

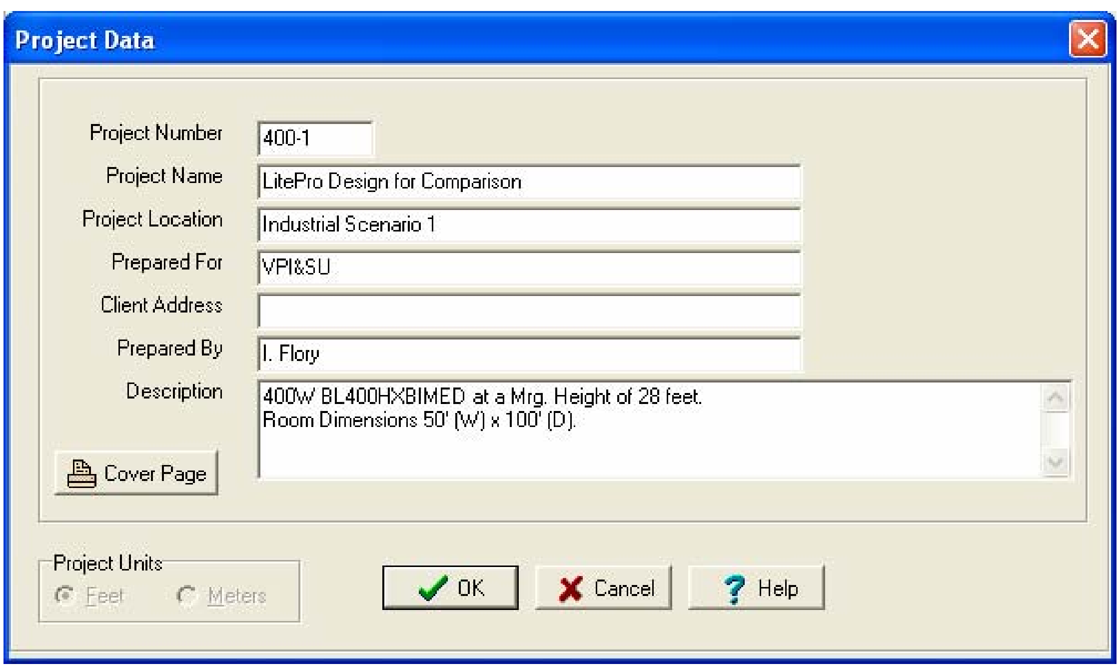


Figure B-1: New Project Data Window [35]
(Used with the permission of Hubbell Incorporated)

A submenu is opened by selecting the project name under the Project Contents heading located in left side of the main window and the command *Add Group* is selected. The name of the group, which in this example is *400W LitePro Design*, is entered as the group name along with any other descriptive information that may be needed. Once the group has been created the submenu under the group name may opened and the layout area defined. The window that appears is shown in Figure B-2, having four selection tabs which provide access for the defining of the physical space to be illuminated. The first tab labeled *Description* allows for the naming of the area, the addition of comments, and the choice of the relative cleanliness of the area as shown in Figure B-2. This window also provides the opportunity to provide the user with an additional depreciation factor in the event that one is required. For example, this may be the case if there is a significant amount of light obstruction due to equipment or other structures.

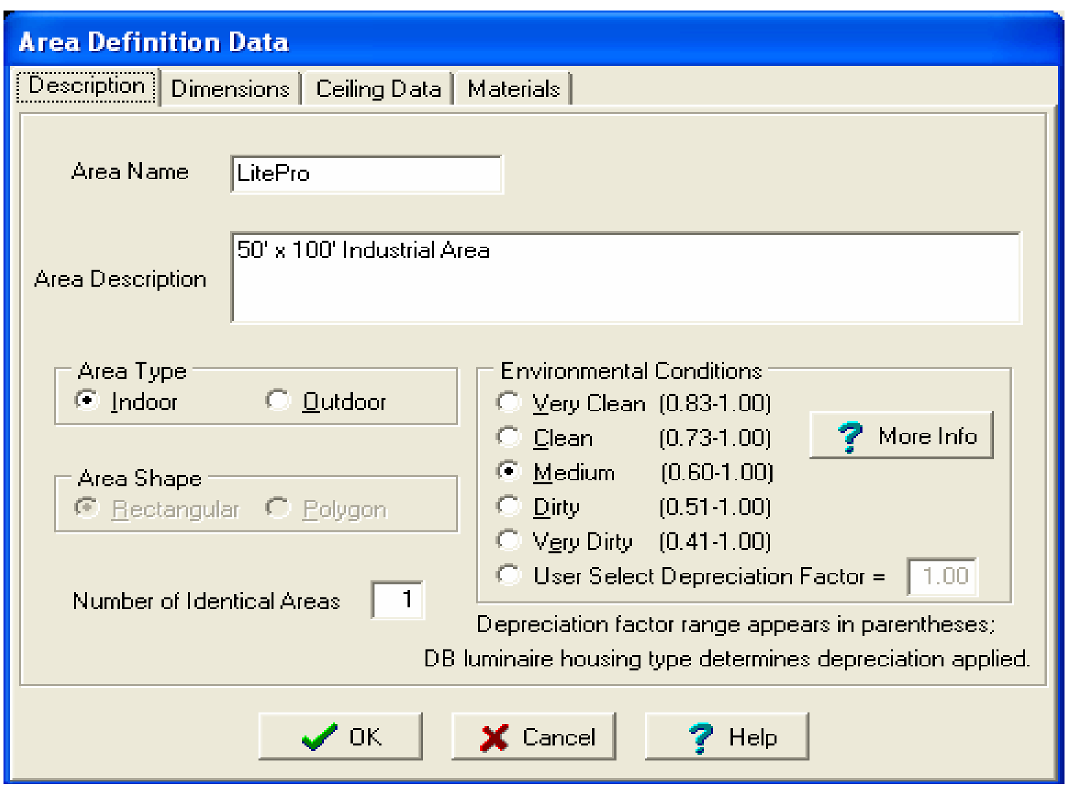


Figure B-2: New Project Area Description Window [35]
(Used with the permission of Hubbell Incorporated)

By selecting the *Dimensions* tab the geometry of the target area may be entered as shown in Figure B-3. In this example (scenario #1) the floor dimensions are 50 feet wide by 100 feet long. Other choices include the importing of offset coordinates in the event that an AutoCAD DXF file is to be imported, or if a portion of the floor space is to be omitted when the power density calculation is made.

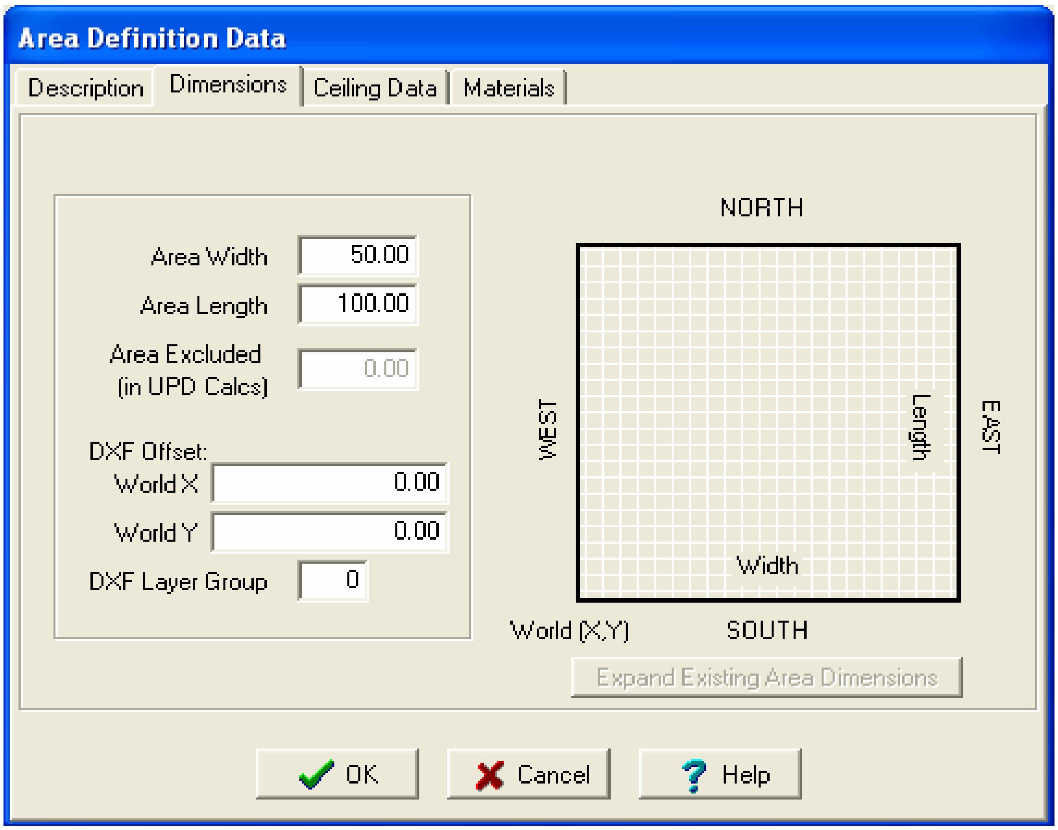


Figure B-3: New Project Area Definition Window (Area) [35]
(Used with the permission of Hubbell Incorporated)

Selection of the *Ceiling Data* tab opens a window, as shown in Figure B-4, allowing for the input of the ceiling height as well as the specification of grid parameters. The ceiling grid in this case is not what is referred to later in this appendix as a calculation grid, but is simply a representation of a physical grid (if one exists) that is associated with the lighting project, and may be omitted. A flat ceiling is selected since the developed software does not accommodate any other ceiling configuration. Figure B-5 shows the Materials window allows for the entry of ceiling, wall and floor reflectances, which in this example are 0.5, 0.5 and 0.2 respectively.

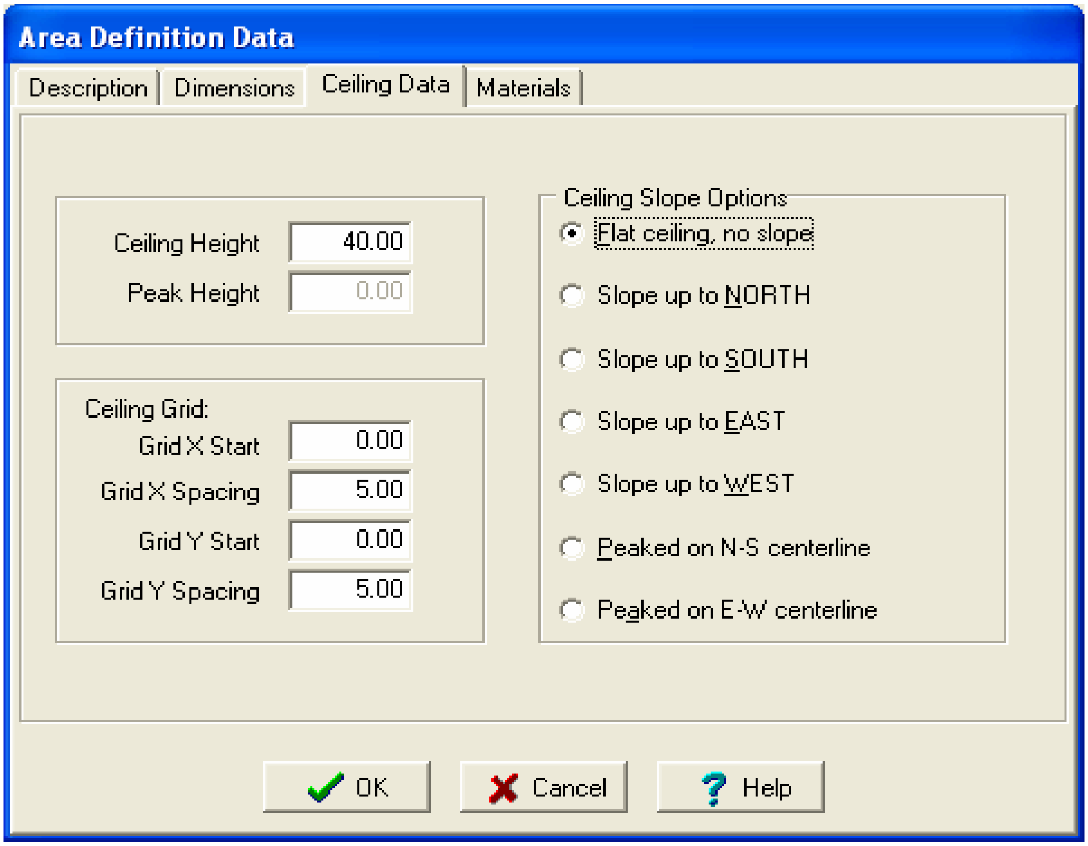


Figure B-4: New Project Area Definition Window (Ceiling) [35]
(Used with the permission of Hubbell Incorporated)

Upon completing entry of the area specifications, a calculation grid is constructed for use in the point-by-point calculation process. The illuminance at each point of the grid will be calculated to provide a projection of the design results. Figure B-6 shows the *Grid Creation* window that appears when the submenu beneath the name of the area (New Area) under the Project Contents heading in left side of the main window is activated, and the command *Add Calc Grid* is selected. As shown in the figure the grid specifies calculation points every five feet in both the *X* and *Y* directions. The calculations will be made in the horizontal plane and the resolution of the displayed illuminance results will be to the tenth of a footcandle.

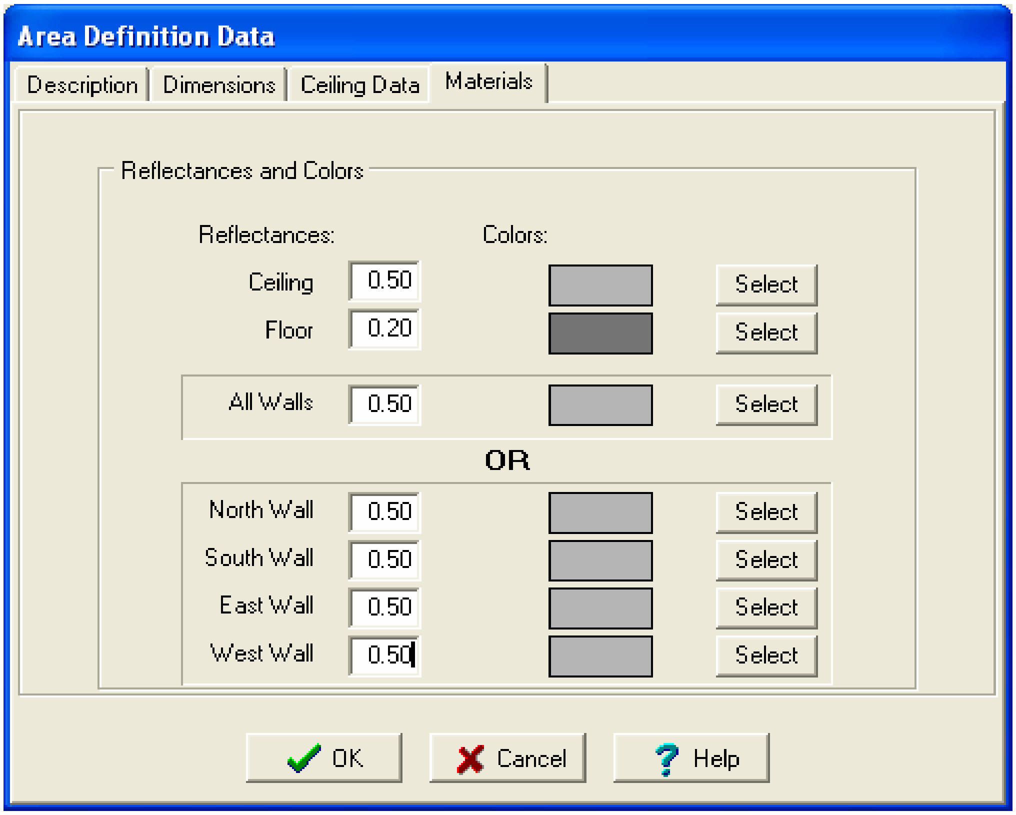


Figure B-5: New Project Area Definition Window (Reflectances) [35]
(Used with the permission of Hubbell Incorporated)

Under the Project Luminaires heading in the left side of the main window, the luminaire being used may be selected by activating the submenu and selecting one of the *Add Luminaire* commands. In this example the *Add Luminaire (Catalog #)* command was selected and a luminaire chosen as shown in Figure B-7. The associated test number (HP03802) contains the data necessary for the calculation of the required number of luminaires in addition to other photometric information of interest. It should be noted that this test number corresponds to the IES file containing, among other items, the same CU table used by the developed software to determine the required number of luminaires.

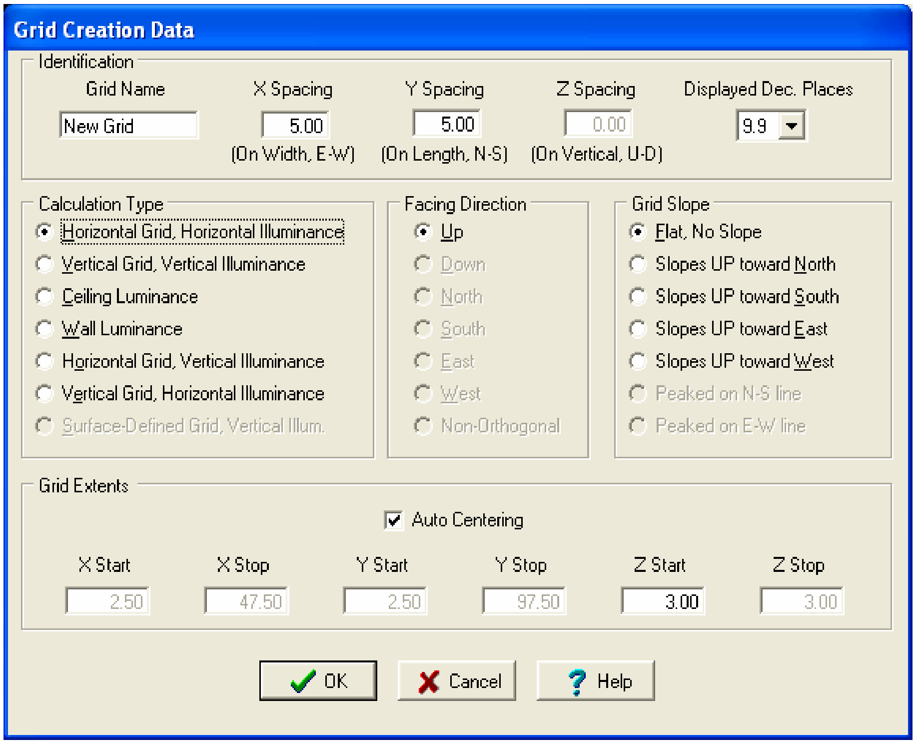


Figure B-6: New Project Calculation Grid Creation Window [35]
(Used with the permission of Hubbell Incorporated)

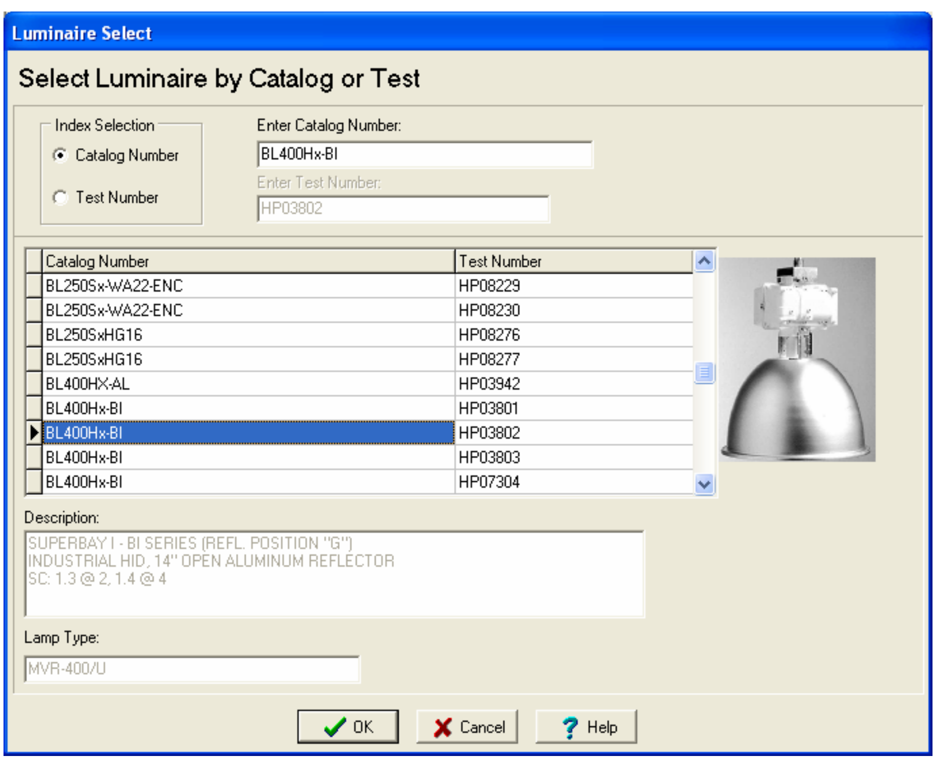


Figure B-7: Luminaire Selection Window [35]
(Used with the permission of Hubbell Incorporated)

By again activating the submenu under the *Project Luminaires* heading, the *Properties (luminaire)* command is selected, opening the window shown in Figure B-8. To graphically label the luminaires an identifier is entered in the Luminaire Type box. Many of the other fields are automatically filled, however in lower portion of the window the entry of lamp and light loss data for the project is required. Under the heading of *Performance Data* the lamp catalog number, initial lamp lumen rating, and rated individual luminaire power consumption is entered. Under the *Depreciation Factors* heading the elements making up the LLF are entered in their respective fields. These factors are specified in a somewhat different manner than is the case when using the developed software, however the important point is to ensure that the LLF, which in Figure B-8 is listed as *Total Depreciation*, is the same as the LLF used in the creation of the original design.

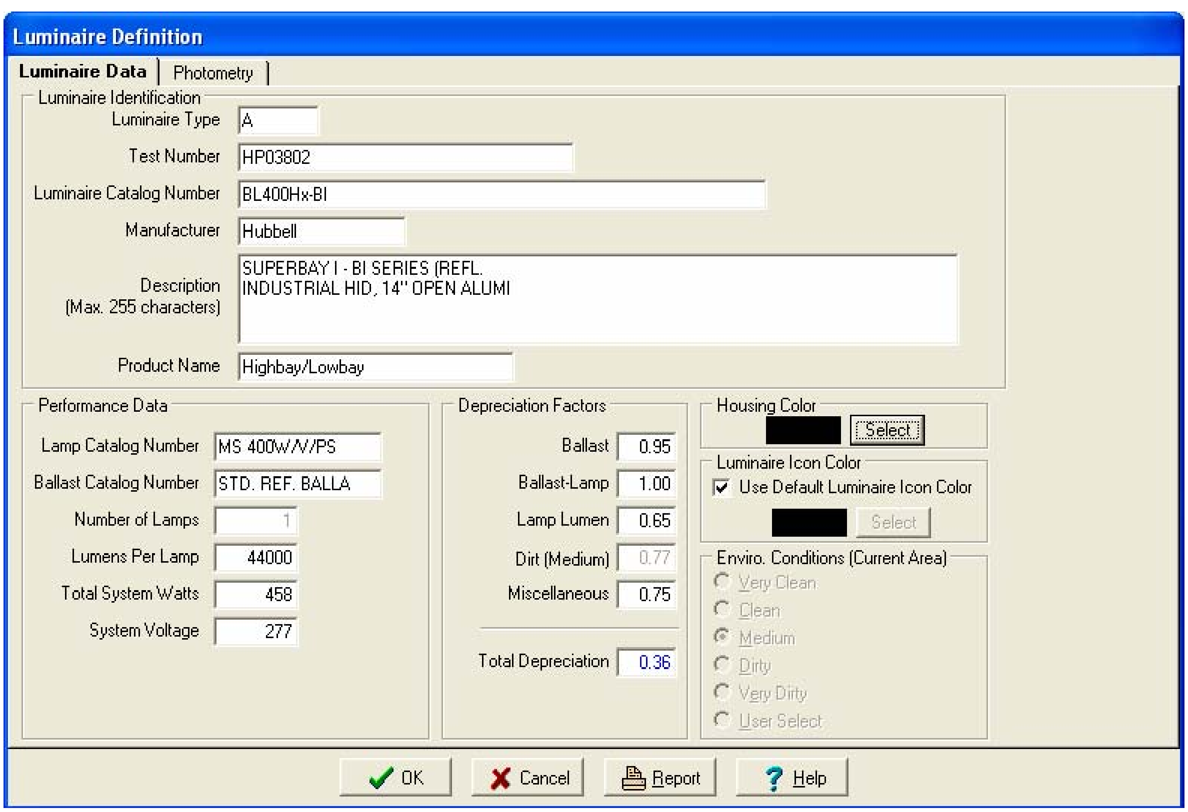


Figure B-8: Luminaire Definition Window [35]
(Used with the permission of Hubbell Incorporated)

Once the process of specifying the luminaire has been completed, the LitePro® calculation may be performed to determine the number of luminaires required to illuminate the area. By again activating the submenu under the *Project Luminaires* heading, the command Lumen Method is selected which opens the window shown in Figure B-9. It is in this window that the desired average maintained illuminance level is entered along with the height of the work plane and the mounting height of the luminaires. The *Space on 2' Increment* box should be un-checked since the luminaire locations for industrial lighting applications are not generally limited in this way. This mounting constraint is intended more for commercial and office lighting applications.

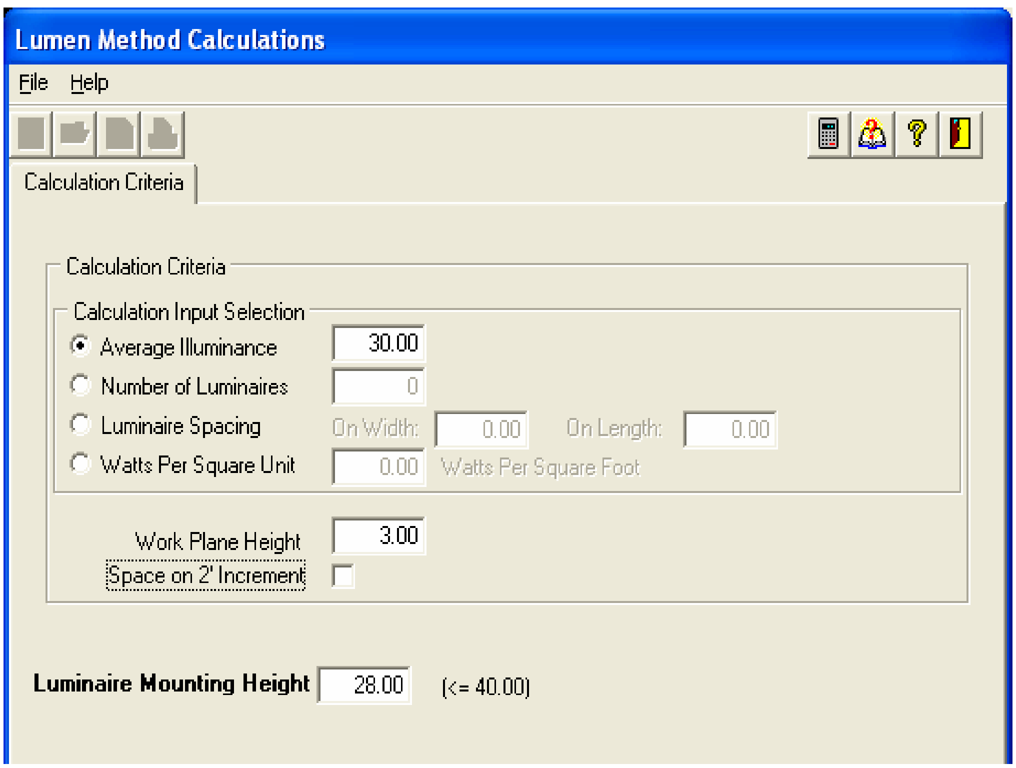


Figure B-9: Quick Calc (Lumen Method) Set-up Window [35]
(Used with the permission of Hubbell Incorporated)

Under the *File* heading on the command bar, the *Calculate* command is selected and the results of the LitePro® analysis are displayed in new window shown in Figure B-10. In this case the commercial software recommends using 18, 400W luminaires that will yield a maintained illumination level of 33.85 footcandles. Upon exiting the window shown in Figure B-10 a query is issued regarding the saving of luminaire placements. When prompted, a response of *yes* will create the window shown in Figure B-11. The plus (+) symbols indicate the locations at which the point-by-point calculations will be performed, and prior to the analysis the layout shown may be modified by adding, moving, or removing luminaires. Upon completion of the illumination analysis of the LitePro® design these editing features will be used to configure the layout to correspond with the original design generated by the developed software, as shown in Figure 4-3.

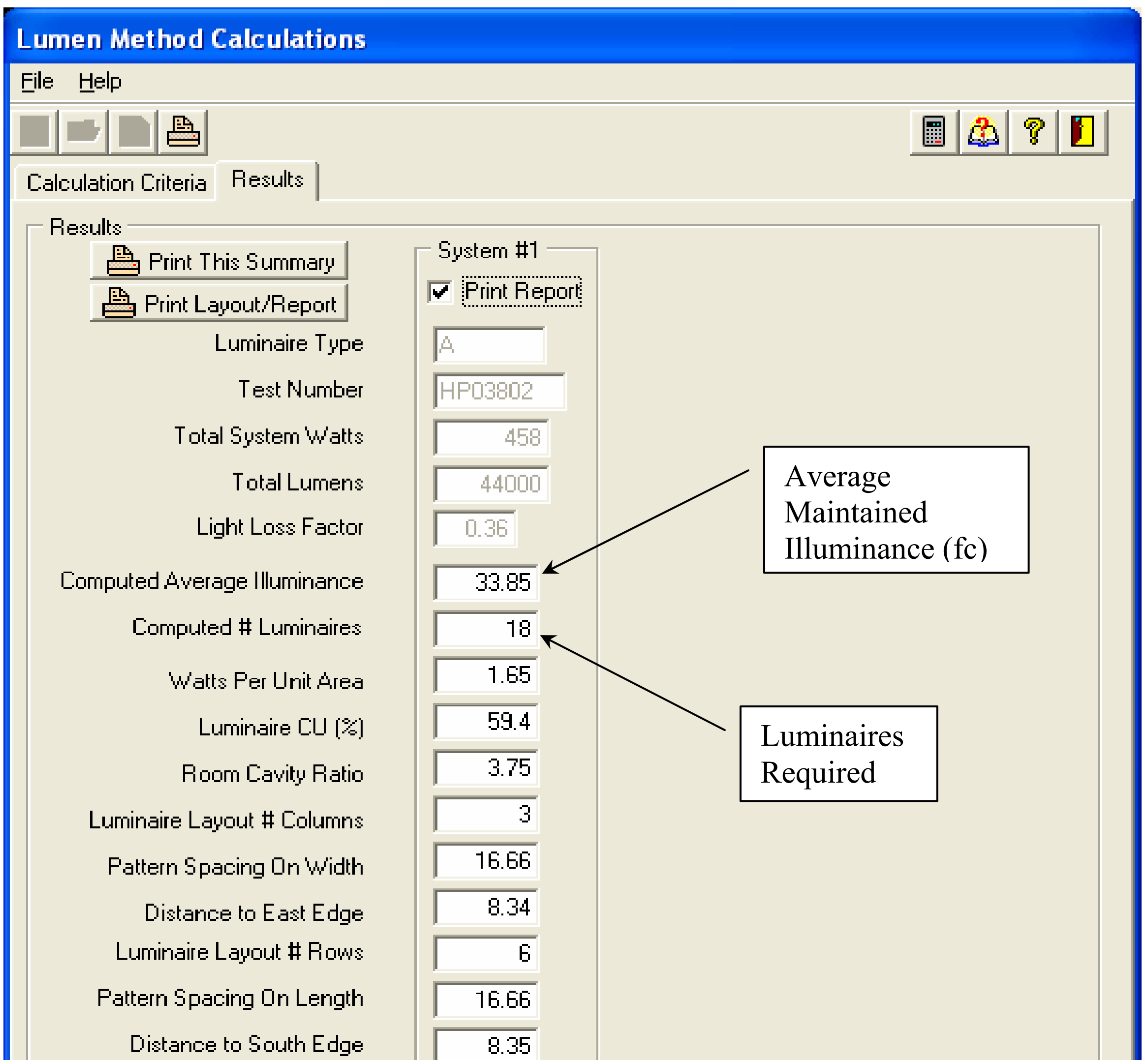


Figure B-10: Quick Calc Results Window – Industrial Scenario #1 [35]
(Used with the permission of Hubbell Incorporated)

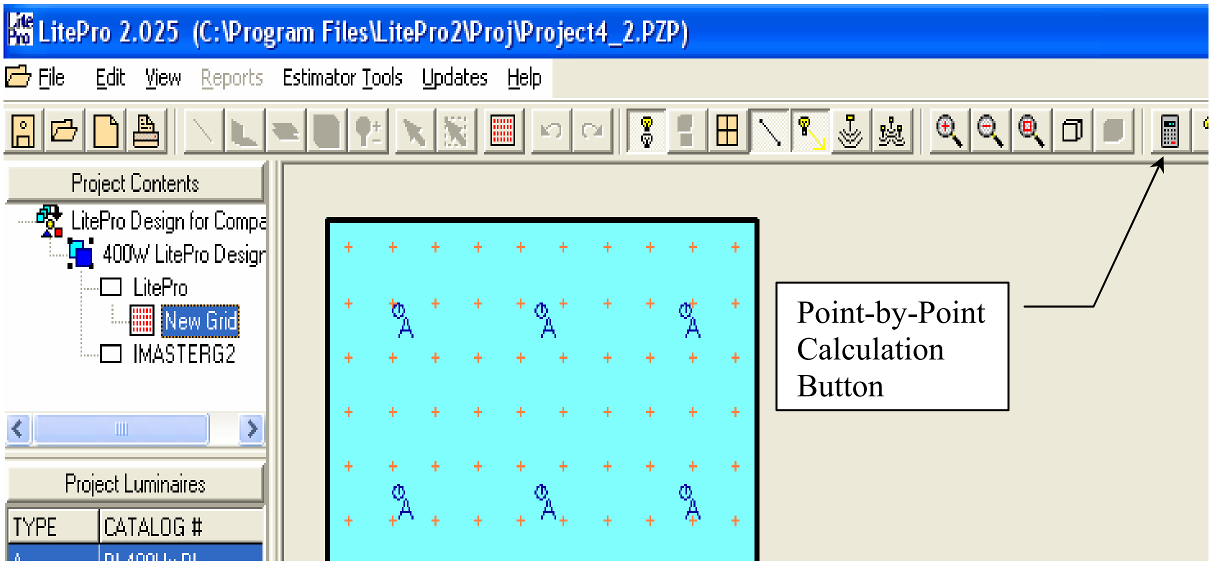
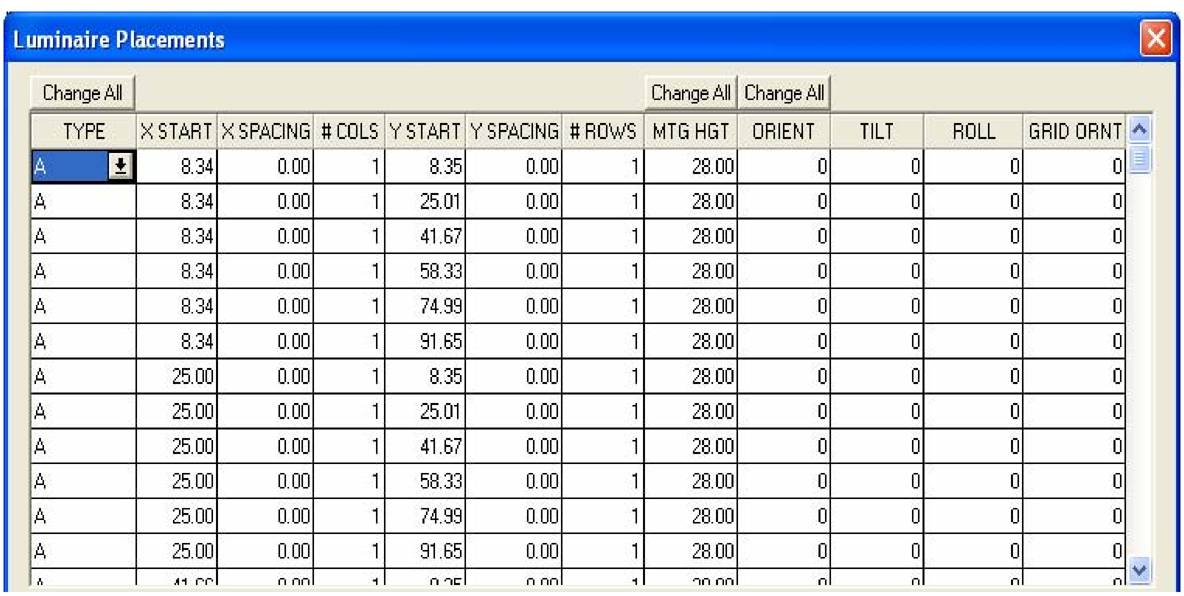


Figure B-11: Layout Determined by LitePro® Software – Industrial Scenario #1 [35]
(Used with the permission of Hubbell Incorporated)

The coordinates of the luminaires may be viewed and edited if desired by activating the area view labeled *LitePro* under the *Project Contents* heading, and then under the *Project Luminaires* heading activating the submenu and selecting *Edit Luminaire Placements*. The window shown Figure B-12 appears, which presents logistical data for each luminaire.


Luminaire Placements

TYPE	X START	X SPACING	# COLS	Y START	Y SPACING	# ROWS	MTG HGT	ORIENT	TILT	ROLL	GRID ORNT
A	8.34	0.00	1	8.35	0.00	1	28.00	0	0	0	0
A	8.34	0.00	1	25.01	0.00	1	28.00	0	0	0	0
A	8.34	0.00	1	41.67	0.00	1	28.00	0	0	0	0
A	8.34	0.00	1	58.33	0.00	1	28.00	0	0	0	0
A	8.34	0.00	1	74.99	0.00	1	28.00	0	0	0	0
A	8.34	0.00	1	91.65	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	8.35	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	25.01	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	41.67	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	58.33	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	74.99	0.00	1	28.00	0	0	0	0
A	25.00	0.00	1	91.65	0.00	1	28.00	0	0	0	0

Figure B-12: Coordinates for Luminaires of Fig. B-11 [35]
(Used with the permission of Hubbell Incorporated)

To perform the point-by-point analysis the *Calculation* button is selected as identified in Figure B-11. A calculation status window appears that affirms which calculation grid will be used in the analysis. By activating the *Calc* button the analysis begins, which upon completion the *Close* button will become selectable. When the *Close* button is selected the display shown in Figure B-11 is updated as shown in Figure B-13.

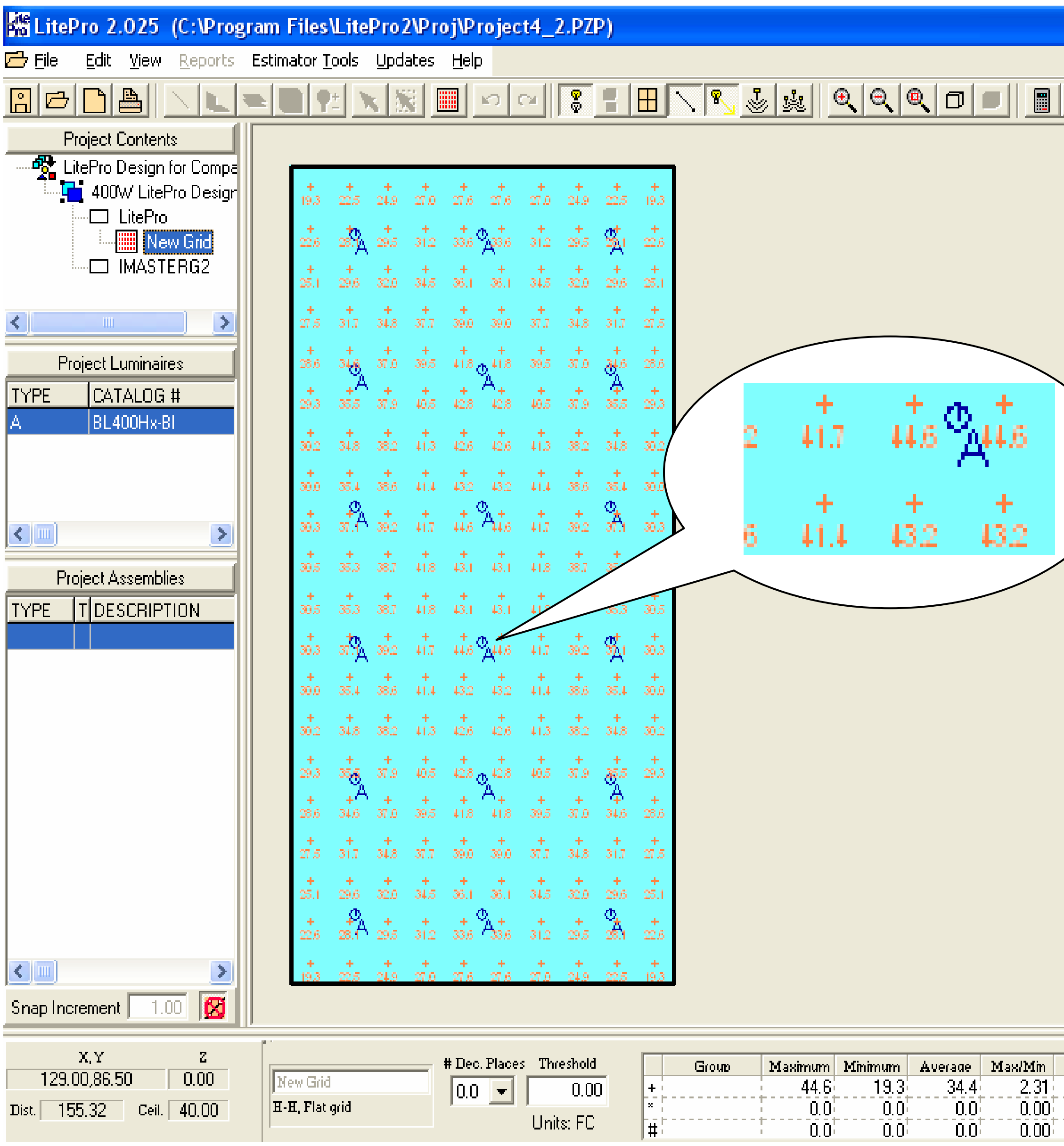


Figure B-13: Point-by-point Analysis [35]
(Used with the permission of Hubbell Incorporated)

The individually labeled points shown in the blow-up of the figure represent the calculated level of illuminance at those particular locations. Key quantities of the lighting design, appearing in the lower right corner of Figure B-13, will be used for comparison with the analysis of the design and layout offered by the software developed to support this research.

References

[1] U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate. Prepared by Navigant Consulting for the U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy Building Technologies Program. September 2002

[2] Flory, I., and S. Rahman: "Metal-Halide Lamp Life and Lumen Depreciation: A Comparison of Two 400 Watt Discharge Lamp Ballasting Systems", LEUKOS: Journal of the Illuminating Engineering Society of North America, Vol. 4, No. 3, pp. 173 – 185. January 2008.

[3] Perkowitz, S., Empire of Light – A History of Discovery in Science and Art; Henry Holt and Company. New York, New York. 1996.

[4] IES Lighting Handbook; Illuminating Engineering Society, New York. 1972.

[5] ANSI / IES RP-7-01; Recommended Practice for Industrial Lighting Facilities; The IESNA Industrial Lighting Committee – D. McSweeney, Chair. Illuminating Engineering Society of North America. New York, NY. 2001.

[6] Murdoch, Joseph B., Illumination Engineering: From Edison's Lamp to the Laser; Visions Communications. York, Pennsylvania. 1994.

[7] Lindsey, Jack L., Applied Illumination Engineering; The Fairmont Press. 2nd Edition, Lilburn, GA. 1997.

[8] Chen, K., Energy Management in Illuminating Systems; The CRC Press. New York, NY. 1999.

[9] Lamps and Lighting; Coaton, J. R., A. M. Marsden editors, John Wiley & Sons. 4th Edition, New York, NY. 1997.

[10] IEEE-Recommended Practice for Electrical Power Systems in Commercial Buildings, Std 241-1990; Power Systems Committee of the IEEE Industry Applications Society. The Institute of Electrical and Electronic Engineers. New York, NY. 1991.

[11] U.S. Lighting Market Characterization, Volume II: Energy Efficient Lighting Technology Options. Prepared by Navigant Consulting for the U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy Building Technologies Program. September 2005.

[12] Boccaletti, C., E. Stafano, E. Santini: "A Lighting System Model for Maximum Energy Efficiency and Cost Savings", Proceedings of the Fifth IASTED International Conference POWER and ENERGY SYSTEMS. Benalmadena, Spain. June 15 – 17, 2005.

[13] ANSI/ASHRAE/IESNA Standard 90.1 2007: An Overview of the Lighting and Power Requirements. Presentation by Eric Richman, LC, through the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. January 10, 2008. Available: http://www.energycodes.gov/training/pdfs/lighting07.pdf

[14] §273.9 of The Environmental Protection Agency 40 Cfr – Parts 260, 261, 264, Etc. Hazardous Waste Management System; Modification of the Hazardous Waste Program; Hazardous Waste Lamps; Final Rule. Available: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?sid=3d8933512a0acf2b02b930a0e7ca2fbf&c=ecfr&tpl=/ecfrbrowse/Title40/40cfrv25_02.tpl

[15] Jones, J. R., B. F. Jones; "Using the Zonal-Cavity System in Lighting Calculations", Illuminating Engineering, Part 1, May 1964; Part 2, June 1964; Part 3, July 1964; Part 4, August 1964.

[16] Acuity Brands- Lithonia Lighting. photometric data file - filename 96071818.IES. Available: www.lithonia.com/visual/ies/ies.asp?vfile.

[17] Lumen8 – Newsletter of Lumenation Lighting Design, "Light Loss Factors" November 2006. Available: http://www.lumenationlighting.com/pdf/Lumen8-November-2006.pdf

[18] Marsden, A.M.: "The Economics of Lighting Maintenance", Lighting Research and Technology, Vol. 25, No. 3, pp. 105-112, 1993.

[19] ANSI C82.6-2005; Ballasts for High-Intensity Discharge Lamps – Methods of Measurement. ANSI C82.2 Sub-committee – H. Wolfman, Chair. American National Standard Institute in cooperation with The National Electrical Manufacturers Association. Englewood, CO. 2005.

[20] Bedocs, L., P.N. De; "A Study of Installed Performance of Industrial Luminaires", Lighting Research and Technology. Vol. 13, No. 3, pp. 137-142. 1981.

[21] Eley, Charles, James R. Benya; Lighting and Electrical Systems. The Collaborative for High Performance Schools. Presentation copyright 2005 CHPS. Available: http://www.chps.net/events/pdfs/M&O_Lighting.pdf

[22] The NLB Guide to Industrial Lighting. National Lighting Bureau. Copyright 1992. Rosslyn, VA. 22209. Available: http://www.nlb.org/index.cfm?cdid=10352&pid=10225

[23] The NLB Guide to Energy Efficient Lighting Systems. National Lighting Bureau. Rosslyn, VA. 22209. No copyright date provided. Available: http://www.nlb.org/index.cfm?cdid=10362&pid=10225

[24] Lighting's Impact on Heating, Ventilation and Air Conditioning (HVAC) Systems, Lighting Design Lab Articles. Northwest Energy Efficiency Alliance. Available: http://www.lightingdesignlab.com/articles/lighting_hvac/lighting_hvac.htm

[25] Thuesen, H.G., W.J. Fabrycky, G.J. Thuesen, Engineering Economy; 5th Edition, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1977.

[26] Newman, D. G., J. P. Lavelle, T. G. Eschenbach, Engineering Economic Analysis, 8th Edition, Engineering Press, Austin, Texas, 2000.

[27] Rahman, S., and Arnulfo de Castro: "Environmental Impacts of Electricity Generation: A Global Perspective", IEEE Transactions on Energy Conversion, Vol. 10, No. 2, June 1995.

[28] EPA 430-R-08-005 (Final Report). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2006. United States Environmental Protection Agency. April 15, 2008. Available: http://www.epa.gov/climatechange/emissions/downloads/08_CR.pdf

[29] U.S Environmental Protection Agency – Clean Energy: Calculations and References. Available: http://www.epa.gov/cleanenergy/energy-resources/refs.html

[30] Clear, R., and S. Berman, "Environmental and Health Aspects of Lighting: Mercury", Journal of the Illuminating Engineering Society, Vol. 23, pp. 138-152. Summer 2004

[31] Osram Sylvania Inc. Product Information Bulletin. Standard METALARC® General Purpose Metal Halide Lamps. Available: http://dafnwebpd.sylvania.com/os_filenet_pages/navview.asp?docid=003673317&Title=Product%20Information%20Bulletin&NAED=64490&doctyp=Document&wdth=600&hgth=450&Desc=Standard%20METALARC

[32] Osram Sylvania Inc. Product Information Bulletin. LUMALUX and LUMALUX/ECO High Pressure Sodium Lamps. Available: http://dafnwebpd.sylvania.com/os_filenet_pages/navview.asp?docid=003673325&Title=Product%20Information%20Bulletin&NAED=67524&doctyp=Document&wdth=600&hgth=450&Desc=LUMALUX%20and%20LUMALUX/ECO

[33] Osram Sylvania Inc. Lumen Maintenance Curve – Standard, Pro-Tech, Super, Compact, and Super Saver. Product Number 64490 Available:

http://dafnwebpd.sylvania.com/os_filenet_pages/navview.asp?docid=003681197&Title=Lumen%20Maintenance%20Curve&NAED=64490&doctyp=Image&wdth=380&hgth=320&Desc=Standard%2C%20Pro-Tech%2C%20Super%2C%20Compact%2C%20and%20SuperSaver

[34] "Circle Packing": Wolfram Mathworld. Available: http://mathworld.wolfram.com/CirclePacking.html

[35] LitePro 2.025 Lighting Design Software. Columbia Lighting, Inc. a division of Hubbell Lighting Incorporated and Microwave Concepts. Version 2.025. Peyton, CO. 2005

[36] Venture Lighting International. Uni-Form Pulse Start Metal-Halide Lighting Systems – Lumen Maintenance at a Glance; Document #VLI-0767B1-0805. 2005. Available: http://www.venturelighting.com/Literature/LM_at_a_Glance_0805.pdf

[37] Bulbtronics. Available: http://www.bulbtronics.com/

[38] Venture Lighting International. Standard Probe Start Metal Halide Lamps. Available: http://www.venturelighting.com/LampsHTMLDocuments/standardmetalhalide.html#400W

[39] Advance Atlas – 2001; Advance Transformer Company, Rosemont, IL. 2001

[40] Venture Lighting Incorporated. Literature Resource Center. Lamps: Lamp Life. Available: http://www.venturelighting.com/TechCenter/LampLife.html

[41] Weart, S. R., The Discovery of Global Warming; Harvard University Press. Cambridge, Mass. September 2003.

[42] Mercury Quantity in Lamps for General Lighting Applications. November 1, 2007. Osram-Sylvania Inc. Available: http://www.sylvania.com/content/display.scfx?id=003690938

[43] Hubbell Lighting Incorporated. photometric data file - filename HP03801.IES. Available: http://www.hubbellindustrial.com/resources/photometry/