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ECONOMIC ANALYSIS OF LIGHTING SYSTEMS FOR OPEN PLAN OFFICE SPACE

By

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ABSTRACT

ECONOMIC ANALYSIS OF LIGHTING SYSTEMS FOR AN OPEN PLAN OFFICE

By

Sutarto Hartono

Energy conservation is important because of the increasing demands for energy consumption in the form of electricity, petroleum, coal and natural gas. One approach to energy conservation is to build energy consumption systems which are more efficient.

Computer software that can analyze a proposed lighting system design from a lighting quality point of view and an economic point of view does not exist. The objective of this study was to develop and validate the computer software that would provide information about the quality and quantity of light in an open plan office space and analyze the system using a simple payback analysis and a life cycle cost analysis. The computer software was developed and compared with hand calculations for two existing open plan office spaces. The software is valid and can be used to evaluate alternative designs.

Approved ______________________ Approved ______________________

Larry J Segerlind, PhD — Major Professor

Robert D.Von Bernuth, PhD — Department Chairman

DEDICATION

This thesis is dedicated to
the Lord of Jesus Christ.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area , ft^2
AAC	Average annual cost
bf	Ballast factor
CC	Ceiling cavity
cd	Candela
CIE	Commission internationale de l'exlairage (International lighting standard commission)
CRI	Color rendering index
CU	Coefficient of utilization
CW	Cool white
DHSS	Department of health and social security
DIC	Direct illuminance component / angular coordinate
E	Illuminance
ER	Energy escalation rate
FC	Floor cavity
FRS	Flat rectangular source
fc	Footcandle
GE	General electric
GSA/PBS	General services administration/public building services
h_{cc}	Height of ceiling cavity

HID	High intensity discharge
I	Discount rate
IC	Initial cost
IES	Illuminating Engineers Society
ISM	Inverse square method
L	Number of lumens produced per lamp
LCC	Life Cycle Cost
LLF	Light loss factor
LDD	Lamp dirt deprectiation
LLD	Lamp lumen depreciation
LPW	Lumen per watt
lx	Lux
n	Number of year life
N	Number of luminaire
NEPA	National energy policy act
nm	Namometer
pf	Power factor
PVEC	Present value of energy cost
PVMC	Present value of maintenance cost
PVOR	Present value of repair cost
PVRC	Present value of repair cost
PVSC	Present value of survaillance cost
RC	Repair cost

ρ	Reflectance
RR	Replacement escalation rate
S/MH	Spacing to mounting height ratio
SPD	Spectral Power Distribution
VCP	Visual Comfort Probability
VDT	Visual display terminal
W	White
WM	Warm White
YS	Years between occasional replacement

1. INTRODUCTION

1.1. Background and Problem Setting

Energy conservation is a key issue because of the increasing demand for energy consumption. Our society is becoming more technological, requiring greater use of computers, equipment and information systems that require electricity. On the contrary, the supply of energy is becoming more limited requiring energy conservation. Some alternative energy sources have the potential for commercial development. Some have already been developed. Nuclear power plants are operational, but the future of nuclear energy is uncertain since it is difficult to answer questions related to the environmental (Thorndike,1976). Solar energy technology has reached the marketplace and meets technical, economic, and environmental criteria; there are, however, political issues to be resolved. Research and development are on going in the areas of geothermal energy and synthetic fuels; while a few commercial plants have been constructed, there are serious limitations to large-scale operations (Thorndike, 1976).

The energy crisis cannot be abated in the next 10 years because conversion to renewable energy sources is a slow process (Reis et al., 1985; Thumann, 1983). Improvements can be realized by immediate adoption of conservation measures, such as reduced consumption, energy storage and recycling, and improved efficiency of current systems. These approaches are practical and could have eased the strain during the energy transition period of the 1980s.

There are two basic ways to improve energy efficiency. The first involves changes in the way that existing systems are operated, such as reduction in lighting levels in industrial and commercial buildings, and higher thermostat settings on room air conditioners (Stein and Reynold, 1992). These changes are characterized by their low (or zero) capital cost, the speed with which they can be implemented, and the fact that all require operational (human) changes. The second type of change involves improvement in the technical efficiency of the energy systems (space heating and cooling equipment, appliances, building structures, industrial process equipment). Examples include the installation of more efficient fluorescent lamps in industrial and commercial buildings, or the replacement of existing lighting systems with energy efficient equipment. Both of these examples reduce energy consumption.

Lighting has been one of the prime targets of mandatory standards to reduce energy consumption because of the apparent depletion of nonrenewable energy resources (Helms and Belcher, 1991). Most energy conservation programs in office buildings are directed toward electrical consumption and lighting use. Even though only 7% of the total, lighting is a primary target for energy conservation (Helms and Belcher, 1991; Philips-Office Lighting, 1993). Decreasing energy consumption in lighting includes:

1. Lighting is "visible". People don't think as much about other energy use, such as a manufacturing processes, Lighting is continually before us continually (Murdoch, 1985).
2. Lighting represents 30% to 50% of the operating cost of the building, which shows up as a monthly business expense (Sorcar,1982; Helms and Belcher,1991; Lindsey,1991).
3. There are ways to conserve energy in lighting without giving up the quantity and quality of light recommended. Therefore, the lighting system is an important concern in the economics of energy efficiency (Sorcar, 1982; Helms and Belcher, 1991; Lindsey, 1991; Murdoch, 1985).

The office environment has become complex and highly specialized because of technological advancements including computers, cellular telephones, fax machine, control systems, and electronic mail, In today's automated office, a systems approach is necessary to increase productivity and maintain consistency of quality. Philips Lighting's Office Building states that a lighting system is one of the most important tools in optimizing office worker performance, since its impact is measurable on the bottom line.

Office space can be divided by function into five categories: (1)Open plan [general staff office space], (2)Private offices, (3)Executive offices, (4)Drafting rooms, and (5)Conference rooms (Stallard et al., 1984). In terms of office management, every part of the office building should be connected to performance, comfort, ambiance (mood) and cost effectiveness.

The problem of increasing the energy efficiency of the lighting system while maintaining the purpose of office management needs to be studied. Lindsey (1991) stated efficiency cannot be based on simple metrics such as lumens per watt or fixture efficiency since they ignore the basic purpose of a lighting system: to allow people to see in order to perform a visual task.

1.2. Objective of this Study

There are two interrelated reasons for pursuing this study. The first is that federal and state governments have passed lows related to the energy efficiency of the lighting system and its impact on cost reduction. The second is the management concern and interest over the problems posed by performing visual tasks while maintaining an acceptable level of performance, comfort, ambiance, and cost effectiveness.

1.2.1. Government's concern

The first document that was a direct outcome of the "energy crisis", caused by the OPEC oil embargo of 1973, regarding the visibility of lighting, was a General Services Administration/Public Building Services (GSA/PBS) publication, entitled "Energy Conservation Guidelines for Existing Office Buildings". It was published in 1974. The newest law is public law 102-846-Oct 24, 1992, that Congress passed with the title " An Act to Provide for Improved Energy Efficiency". It deals with energy conservation for buildings and includes performance standards to maximize practicable energy efficiency, as well as encouragement for states and local governments to adopt and enforce the standards. Regarding lighting, this energy law commands minimum efficiency standards for selected electric lamps. Eighteen to thirty-six months after enactment, lamp manufacturers will no longer be allowed to produce many popular fluorescent, High Intensity Discharge (HID), and incandescent lamp types which do not meet the new efficiency standard.

One example is the traditional T-12 Med Bipin F40CW, the most widely used fluorescent lamp prior to the law's passage. Specifiers will obtain direct energy savings by selecting from several alternative lamp types such as the F40SPEC30/RS/EW-II, F40SPEC35/RS/EW-II, or F40SPEC41/RS/EW-II, Philips Lighting, (1991). Inefficient lamps are no longer a choice. The energy efficiency of the lighting system is now mandatory.

1.2.2. The office management concern

From the office management point of view, a good lighting design would be one that addresses the range of age among workers and the tasks performed in each category of office space, meets the IES (Illuminating Engineers Society) recommendations for quantity of light, and provides for quality in terms of visual comfort, ambiance, color rendition and cost efficiency.

The energy efficiency of a lighting system for an office building cannot be based only on dollars as a function of lumens per watt, but must also account for the basic purpose of the lighting system which is to allow people to see well in order to perform a visual task accurately and comfortably. The lighting system should provide illumination of sufficient quantity and quality for the task being performed, at the lowest cost. The components of quantity, quality, and cost are :

- Cost refers to luminaire, installation, operation, and maintenance costs of the system.
- Quantity is measured as lumens per unit area, footcandles or lux.
- Quality is related to the human as a user, concerning glare control and color. The elements of glare control and the color include Visual Comfort Probability (VCP) and Color Rendering Index (CRI).

Lindsey (1991) stated a few dollars saved on power cost may be lost many times over if lighting levels are reduced below the requirement of effective seeing.

Regarding cost, quantity, and quality, how much light should be provided for today's office tasks? The IES recommendations encompass a broad range of illuminance levels for a variety of seeing tasks. They are a function of (1) The age of the worker (an aging eye requires more light for the same visual acuity), (2)The importance of the task (how critical are speed and accuracy), and (3)The difficulty of the task which depends on the size and contrast of the details GE-Office Lighting (1991).

There are a wide array of existing cost-effective, energy efficient measures which represent an enormous and largely untapped energy resource. Adoption of these measures can substantially reduce growth in energy use, and save money for the consumer while having only a slight life-style effect on the user. In addition, an energy efficient lighting system can reduce the adverse environmental effects of energy production and conversion, and provide additional time to develop new energy resources.

The objective of this study was to assess the energy efficiency of a lighting system for open plan office spaces that meets IES recommendation and provided quality lighting in the work environment, especially from the management point of view.

1.3. Scope of the study

This study addresses three components: (1)A lighting system for open-plan office space, (2)Economics, and (3)Management of the lighting system (see conceptual model-Appendix A)

There are many questions to be considered. How is energy efficiency calculated? What is a practical design method appropriate for the design of energy efficient lighting systems? What are the fundamental concepts of lighting systems for an office building? What are the components of the lighting system? What are the factors which significantly determine efficiency and quality of the lighting system? How should the lighting system be managed?

A computer program has been developed for integrating the three components given above, to create an integrated program for the economic cost analysis, to design the lighting system and provide some graphics for the management issues.

The results of this study are expected to provide a positive contribution to design decisions made in the selection of efficient lighting systems for open office spaces.

2. REVIEW OF LITERATURE

2.1. Lighting Systems

Clearly, vision depends on light. A lighting system is provided to an environment in which people, through the sense of vision, can function effectively, efficiently and comfortably. Lighting systems produce an artificial visible light (Nuckolls, 1983). "Artificial" means that the light is produced by electrical power. Light can be artificially generated two ways. One is by sending electrical current through an element which may be surrounded by gases, such as in incandescent lamps. The other is by emitting radiant energy though the movement of atoms, such as light produced by fluorescent and high intensity discharge (HID) lamps.

Fluorescent and HID lamps are controlled by ballasts that allow a surge of current to start the lamp and then regulate the electrical current during operation. This combination of lamp, ballast, fixture and other equipment designed to distribute the light is called the luminaire. Fluorescent light is the most commonly light source used in office buildings.

The study of lighting systems involves the quantity and quality of light. Quantity of light in an area is the relationship between the amount of light leaving the lamp called light output (lumens) and the amount of light that actually reaches the surface area where people need it called light level (footcandles, lux). Quality of light describes how light leaving the lamp, interacts with the work environment such as room surfaces, desk tops, computer screens and the like; and directly with human eyes. Just as people need the right amount of light to perform tasks productively so do they need good lighting quality to perform tasks comfortably. Ensuring proper lighting quality primarily involves controlling glare and color rendition.

The sense of vision is based on the eye's ability to absorb and process selectively a portion of the electromagnetic spectrum. The visible portion of the electromagnetic spectrum extends from about 380 (deep blue) to 770 nm (deep red). The eye is most responsive in the yellow-green region (550-560 nm); sensitivity decreases toward deep blue at one end and deep red at the other (IES Lighting Handbook, 1984). Thus, color and brightness are the important factors of visual sensation.

As an applied art and science, the discussion of conceptual lighting systems should include psychology. A detailed discussion of psychological factors in the lighting system was provided by Nuckolls (1983).

A discussion of lighting systems in this study involved seven components: (1)Fluorescent lamp, (2)Ballast, (3)Diffusing and shielding media, (4)Fluorescent luminaire (5)Electrical Control, (6)Quantity of light, and (7)Quality of light (see Conceptual Model-Appendix A).

2.1.1. Fluorescent Lamp

Sorcar (1982) explained that fluorescent lamps produce light by creating an arc between two electrodes in an atmosphere of very low-pressure mercury vapor and some inert gas in a glass tube. The inside of the glass tube is coated with phosphor. The mercury vapor produces 253.7 nanometer (nm) ultraviolet energy that strikes the crystals of phosphor and excites them to produce light.

Fluorescent lamps have hot cathodes in order to strike an electric charge in the lamps. Four types of hot cathode fluorescent lamps are now in use: (1)Preheat, (2)Instant start and slimline, (3)Rapid start, and (4)Trigger start (Sorcar, 1982). This study focused on the rapid start lamps since they are the most appropriate for office spaces (Sorcar, 1982; Steffy, 1990). All fluorescent lamps need ballasts to limit the current and to provide the necessary starting voltages.

Fluorescent lamps are commonly manufactured in seven basic styles such as (1)Standard T12 ("T12" means a tubular shape with a diameter of 12/8 " or 1.5 inches), (2)Improved efficiency T12, (3)Improved efficiency T10, (4)Improved efficiency T8, (5)High output HO, (6)Large compact, and (7)Small compact (Steffy, 1990). High output lamps (HO) are designed to operate as high as 1.0 ampere (operate on a rapid start type circuit). For indoor application, they are usually operated at 0.8 amperes and for outdoor applications at 1.0 amperes (Philips Lighting, 1991). General applications of these seven styles of fluorescent lamps are given in Table 1.

Table 1. Fluorescent Lamp Types and Typical Application Characteristic

Application Characteristics	Standard T12	Improved efficiency T12	Improved efficiency T10	Improved efficiency T8	High output	large compact	Small compact
Low General direct lighting							v
Moderate general direct lighting	v	v	v	v		v	
High general direct lighting	v	v	v	v	v	v	
Low to moderate general indirect lighting	v	v	v	v		v	
Moderate to hight general indirect lighting	v	v	v	v	v	v	
Portable task lighting						v	
Soft accent							v
Grazing wall washing (wall ≤ 10')		v	v	v	v	v	
Frontal wall washing (walls < 10 ')	v	v	v	v	v	v	v
Ballast required	v	v	v	v	v	v	v
Easily dimmable	v	v		v			
Relative lamp cost (low, moderate, high)	Lo	Mo	Hi	Mo	Mo	Hi	Mo
Relative lamp/ballast/luminare efficiency)	Lo	Mo	Mo	Hi	Lo	Hi	Mo

Source: Steffy, 1990

Note: V means applicable
Lo : Low ; Mo: Moderate; Hi : High

Lamp ordering codes for fluorescent lamps are based on ANSI standards that are a combination of letters and numbers representing different characteristics of the lamp. Figure 1 given an example using a Philips product. Each code carries a manufacturer's specifications. For example:

TL 80 System - Lamp Specification:

"Lamps shall be Philips TL 80 series lamps having:

- Color rendering index of 85
- T-8 diameter bulb
- Medium bi-pin bases

- Color temperature of _ K (3000,3500 or 4100)
- Initial lumens of ____ (1400, 2500, 3050, or 3800)
- Nominal wattage of ___ (17,25,32,40)
- Powered by electronic ballasts designed for 265 ma T8 lamps
- An Electrode guard

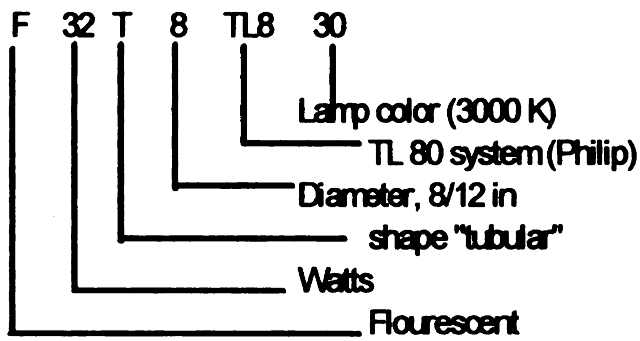


Figure 1. Fluorescent Ordering Code

color or Spectral Power Distribution (SPD) curves for different types of fluorescent lamps depend on the phosphor coating on the bulb wall. Fluorescent lamps are commonly marketed in 4100^{o} K (Cool White), 3500^{o} K (White), and 3000^{o} K (Warm White).

Every typical fluorescent lamp has specific characteristics such as: (1)Color impressions, (2)Color rendering index or CRI, (3)Efficacy, and (4)Life time.

The range of color impressions of fluorescent lamps varies from white, blue, green, gold, pink and red; and usually is represented as color temperature.

Color temperature is not a measure of actual temperature. It defines color only, and can be applied only to sources closely resembling a blackbody in color. The color temperature ratings sometimes given as a matter of convenience to the several types of "white" fluorescent lamps can be regarded only as approximations.

Color Rendering is an evaluation of how natural colors appear under a given light source. For example, a red shirt can be rendered more pink, more yellow, lighter, or darker depending on the characteristics of the lamps. The standard measurement of color rendering called Color Rendering Index (CRI) was developed by the CIE (Commission Internationale De l'Eclairage) the International Lighting Standard Commission, Philip lighting (1991). Efforts to qualify lamps based on CRI have had limited success, however, this is the system being used today to describe color rendering.

Fluorescent lamps are influenced by ambient temperature (IES Lighting Handbook, 1984; Sorcar, 1982; Helm et al., 1991; Steffy, 1990; Craig, 1994). The pressure of mercury gas inside fluorescent lamps is based on the coolest point in the lamp. A low temperature decreases the pressure inside the lamp, and it generates smaller ultraviolet energy, thus decreasing the lumen output. This condition also occurs at high temperatures and lumen output decreases for high temperatures above 30^{o}C. Figure 2 shows that the wattage consumption is significantly affected by temperature variation. At higher temperatures, the lumen output and power consumption decrease more or less in the same proportion. Fluorescent lamps operate most efficiently at ambient temperatures between 25 to 35°C

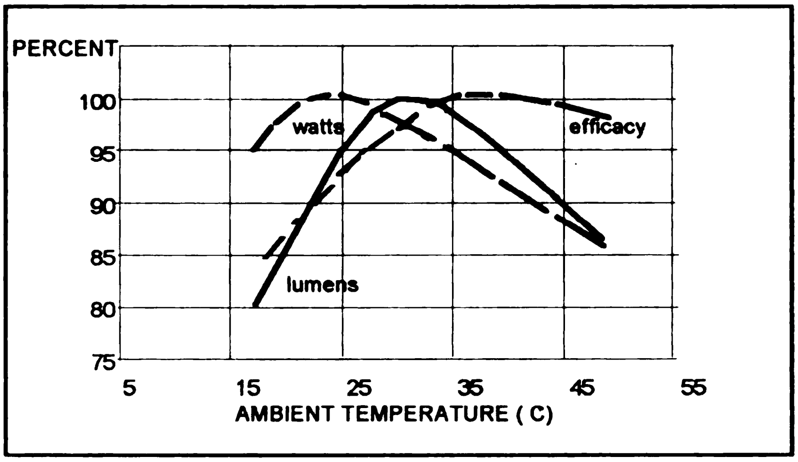


Figure 2. System Characteristic VS Ambient Temperature
TL 80 Lamp on Electronic Ballast

Source: Philips lighting (1991)

Lamp manufacturers publish rated life for their lamps in their brochures. Rated lamp life is an average because the life of each individual lamp cannot be predicted. Some individual lamps have a life time rating longer then average but others burn out before the average life. Most T12 and T8 fluorescent lamps have a lamp life rating of 20,000 hours, GE Lighting, (1991). Regarding the life-rating, the burnout rates of fluorescent lamps rise sharply past 70% of rated life. Table 2 shows the percentage of burnouts.

Table 2. The Burnout Rate of Fluorescent Lamps

Percent of Life time	Percent of Burnouts
0 - 60% life	3% Burnouts
60 - 70% life	6% Burnouts (9% total)
70 - 80% life	9% Burnouts (18% total)
80 - 90% life	14% Burnouts (32% total)
90 - 100% life	18% Burnouts (50% total)

(Source GE Lighting, 1991)

The National Energy Policy Act (NEPA) of 1992 was signed into law on October 24, 1992. It mandated the energy efficiency standards for lamps in terms of lamp efficacy or LPW (Lumen Per Watts) and color rendering as seen in Table 3:

2.1.2 Ballast

A ballast is a device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current and wave form) for starting and operating a fluorescent lamp. Without a ballast to limit the current, the lamp would draw so much current that it would destroy itself. The fractional flux of a lamp operated on a ballast compared to the flux when operated on the reference ballasting specified for rating lamp lumens is called the ballast factor.

The light output, life, and starting reliability of a

Table 3. Fluorescent Lamp Standards

LAMP	Nominal Wattage	Min CRI	Min Average LPW
4-Foot Medium Bi-Pin	>35 W <35 W	69 45	75 75
2-Foot U-bent	>35 W <35 W	69 45	68 64
8-Foot Slimline	>65 W <65 W	69 45	80 80
8-Foot High Output	>100 W <100 W	69 45	80 80

(source: Phillips lighting-Nepa,1992)

fluorescent lamp depends on the design of the ballast. ANSI specifies the requirements for good lamp performance. For example "class P" ballast contains a thermal protection device. If, due to abnormal conditions, the ballast begins to overheat, the thermal switch disconnects the ballast from the power source. When the ballast cools sufficiently, it is reconnected to the power source and restarts the lamp. Electronic ballasts for fluorescent lamps are commonly used for energy efficiency. One reason for using electronic ballasts is that they are designed to produce the same amount of light from standard lamps as that from electromagnetic ballasts, by using less power than magnetic ballasts (conventional ballast). Moreover, by using an electronic ballast, the lamps can be controlled with a dimmer. Electronic ballasts are soundless, unlike magnetic ballasts, because an electronic ballast does not have the laminated core and coil .

Ballasts are not interchangeable. They are designed specifically to provide the proper operating characteristics for only one type of lamp. For example a ballast for a 32-watt fluorescent cannot be used for a 40-watt fluorescent lamp.

In order to reduce energy consumption, cut operating costs, and make the overall system work more efficiently, lighting equipment manufacturers have introduced a variety of new energy saving products in recent years. Two-lamp ballasts are used frequently to reduce ballast cost and installation cost per unit. An energy-saving ballast by definition has less internal losses than the standard, or commodity type, fluorescent ballast. The present energy-saving types of ballasts are tested and certified at full light output, and they reduce ballast losses without lowering lamp lumen output. An example is the Mark III, manufactured by Advance. Interest in energy-saving ballasts increased over the last several years, while the cost of electricity continues to rise.

The capacitor corrects the power factor [input watts/(line volts x line amps in an AC circuit)]. When a fluorescent lamp is operated in conjunction with a simple inductive ballast, the overall power factor will be on the order of 50 - 60% (Thumann, 1983). The performance of this circuit is improved by adding a capacitor which compensates for the lagging current in the remainder or the circuit, improving the power factor, Philips - Fluorescent Lighting, (1991). The corrected power factor does not significantly change input watts, but decreases line current.

2.1.3. Diffusing and Shielding Media

The main purpose of diffusing media such as lenses and louvers is to cover the lamps from being in direct view and to spread the light intensity uniformly over a large open area, while controlling the light output in a settled manner. The shielding medium is a physical block controlling direct glare. One of the important factors involved in selecting a lens or louver is Visual Comfort Probability (VCP).

2.1.3.1. Lenses

From a photometric distribution, all lenses can be divided into two general types: diffusers and reflectors.

Diffusers are clear prismatic lenses, flat transparent sheets, or combinations of either of glass or plastic. They are used on the bottom of luminaires to redirect or block the light and to reduce the luminance glare zone. Transparent diffusers disperse the light in all downward directions uniformly. The transparency is a function of pigment density and thickness. The transparency of a 1/8 inch sheet is 45 to

70%. For the same type of material, this will drop 20 percentage points if the thickness is doubled to 1/4 inch. Diffusers generally have low absorptions; thus luminaires with diffusers have lower efficiency than open-bottom or refractor types (Murdoch, 1985). For good performance and resistance to discoloring over time, lenses should be virgin acrylic (steffy, 1990)

The fluorescent reflector is a simply bent sheet of metal finished with a highly reflective coating of an enamel paint (Nuckolls, 1983). Reflector finishes usually are based on two criteria: glare control and match to other luminaires' and/or surfaces' finishes (Steffy, 1990).

2.1.3.2. Baffles and Louvers

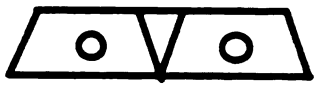
A baffle is usually V shaped, installed parallel to and between lamps in multi-lamp luminaire (Figure 3a). A louver is a group of baffles in an egg-crate arrangement, consisting of vertical fins set at right angles to form a series of repetitive cells (Figure 3b). These louvers provide shielding for the fluorescent lamp and are typically supplied in 2 by 2 or 2 by 4 foot panels of plastic or metal. A variety of cell dimensions are available. The louver may be either straight or parabolic (Figure 3c). Some egg-crate arrangements have elaborate configurations on their visible edges. The shielding angle of a baffle or louver is the angle between the vertical (Nadir) and the line of sight at which all objects above are concealed, or the shielding angle is the maximum angle, measured from Nadir, at which the lamp element can be seen. It is shown as s^o in Figure 3d (Murdoch, 1985). W is the projected width at angle s. A louver depth greater than three inches and a louver spacing of about 5 inches is suggested for good glare control. Louvers that are shallower than 3 inches in depth and greater than 6 inches in spacing should be carefully reviewed for glare (Steffy, 1991).

The selection of shielding media should consider Visual Comfort Probability (VCP), efficiency (the ratio of the total number of lumens emitted by a luminaire to the total number of lumens produced by the bare lamp), and cost. Table 4 shows the comparison of several types of shielding.

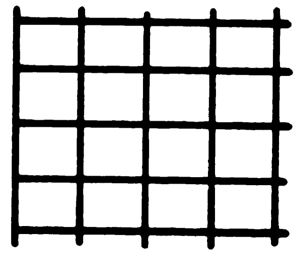
2.1.4. Fluorescent Luminaire

If the lamp is responsible for the color of light and brightness, the luminaire (the one unit system of lighting) is responsible for holding, protecting, electrifying, and controlling the output of the lamp. The luminaire influences how light is distributed on room surfaces, work surfaces, tasks, and people. Luminaires are often developed to be used or a specific category of functions, and also for appearances, since luminaires can be very noticeable and become a significant part of the overall look of a room.

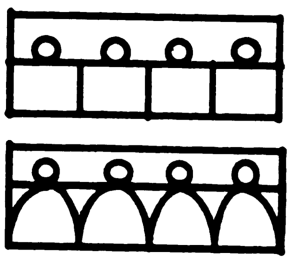
The luminaire description given on the brochure will usually consist of the nominal dimension, mounting or type, and shielding media. Luminaires for fluorescent lamps are installed as (1)ceiling-mounted : recessed, surface-mounted,



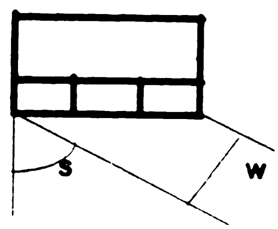
a. Baffle



b. Multi Cells of Louver



c. Straight or Parabolic Louver



d. Shielding Angle

Figure 3. Baffle and Louver Shielding Source: Murdoch, 1985

Table 4. Shielding media.

Comparison of Characteristic for Typical 2' x 4' Flourescent Troffers

Below are the three most often considered trade offs in selecting luminaire shielding. Other consideration might include fire rating, Cleanability, color stability, local code requirements, reflected glare, hiding power, module size, light distribution, etc. All Figures have been taken from data published by a number of manufacturers and should be considered approximate. Each column has been ranked in descending order for the characteristics shown.

Visual Comfort (VCP) % *		Efficiency %		Typical Cost ($) **	
Small Cell Parabolic Louver	95-99 %	Prismatic Lens	60-70%	Deep Cell Parabolic Louver	20-30
Deep Cell Parabolic Louver	60-95	Deep Cell Parabolic Louver	55-70	Small Cell Parabolic Louver	13-45
Dark Metal Cube Louver	70-90	Polarizer	55-65	Polarizer	15-25
White Metal Cube Louver	70	Translucent Diffuser	50-60	Dark Metal Louver	15-25
Polarizer	65	Translucent Plastic Louver	45-55	White Metal Louver	12-20
Prismatic Lens	55-75	White Metal Cube Louver	35-45	Translucent Plastic Louver	8-15
Transparent Plastic Louver	60	Small Cell Parabolic Louver	35-45	Translucent Diffuser	6-15
Translucent Diffuser	45	Dark Metal Cube Louver	25-40	Prismatic Lens	6-25

* IES Visual Comfort Probability estimated for large rooms (60'x60' and over). VCP will usually be higher for smaller rooms

** Net prices for 2'x4' panels only, not complete luminaires. Prices vary due to quantities purchased, geographic location.

Source: GE Lighting, 1990

or suspended, (2)Wall-mounted, and (3)Floor-mounted luminaires: light columns. Typically ceiling-mounted fixture sizes are 1 ft x 1 ft , 1 ft x 4 ft, 2 ft x 2 ft, 2 ft x 4 ft, or 4 ft x 4 ft. The character of fluorescent luminaires is affected by the shielding media. Luminaires can be designed to provide a variety of desired cut-off angles to reduce glare or to get better VCP by using a proper shielding media and design.

The photometry or optical performance of a luminaire is important to the success of a lighting system. Photometric information from manufacturers' data is useful in the development of the lighting design for a project. In general, each type of luminaire has a specific photometry. The same fluorescent lamps placed in a variety of luminaires (fixtures) will give different light distributions. On the other hand, the same type of luminaire will give a different candlepower distribution when fitted with a different type of fluorescent lamp. A detail discussion of candlepower distribution was provided by Sorcar (1982).

The luminous intensity is plotted at each angle on the polar coordinate. This represents the candlepower curve. In plotting the candlepower distribution, the luminaire is assumed to be placed at the center of the imaginary sphere in polar coordinate (Helms et al., 1991).

Spacing to Mounting Height ratios (S/MH) are also important data and are frequently used features of the photometric report. As the luminaire spacing increases, the uniformity of light level in a space will drop. Uniformity of a lighting level depends on the luminaire spacings and the distance from the walls. The maximum allowable distance will vary with mounting height variance above the work plane. Each luminaire, depending on its type of beam spread, has a maximum S/MH ratio, which, when multiplied by the mounting height from work level (room cavity), determines the spacing limitation between luminaires. A detail discussion of spacing to mounting height ratio was provided by Helms and Belcher (1991).

2.1.5. Electrical Control

Selective dimming and switching systems can help minimize energy consumption in unused spaces or in spaces where the intensity or pattern of use varies. Several methods of electrical control can be applied: (1)The connection of small groups of individual luminaires to manual switches allows unused luminaries to be de-energized at the occupant's discretion, (2)Timed controls can be used to adjust the lighting of spaces with predictable traffic patterns, or (3)Motion-detection switching can be used to activate lighting of spaces with continuously variable traffic patterns (Nuckolls, 1983).

2.1.6. Quantity of Light

The Quantity of light implies the amount of light required to perform a visual task. The amount of available light depends on the lighting system's lumen output and how much light is actually received by the workplane, called illuminance (DiLouie, 1994). Illuminance level or light level is the amount of light impacting the workplane and is measured in footcandles or lux with a light meter.

The 1981 Application Volume of the IES Lighting Handbook introduced the method of determining the recommended illuminance value, E_r, for various tasks. IES adopted a procedure that established a range of three illuminance values for nine task categories. The choice of one of the three illuminance values is based on a set of weighting factors. The E value ranges will be referred to as: (1)Lower value, (2)Middle value, and (3)Upper value.

The illuminance selection procedure requires knowledge of the: (1)Type of task, (2)Age of the worker, (3)Importance of speed/accuracy, and (4)Reflectance of room surfaces or task background.

The method lists 9 illuminance categories, designated "A" though "I" covering illuminance levels form 2 to 2000 footcandles (20 to 20,000 lux).

Categories A though C - where no task activity occurs or general lighting is used throughout a space.

Categories D through F - where activities involve a visual task

Categories G though I - suggested a combination of general and supplementary lighting on the task.

Appendix B shows the complete procedure to define the illuminance level.

For categories A through C, two factors must be considered in determining the weighting factor: worker's age and room surface reflectance, which is the weighted average reflectance value. Helms and Belcher (1991) stated weighted average reflectance(WAR) is :

$$WAR=\frac{(CR \times A(ceiling))+(WR \times A(walls))+(FR \times A(floor))}{A(ceiling)+A(walls)+A(floor)}$$

where: CR = ceiling reflectance

WR = wall reflectance

FR = floor reflectance

A = area

For categories D through I, three factors must be considered in determining the weighting factor: worker's age, importance of speed/accuracy and reflectance of the task background.

Procedure for determining illuminance:

1. Determine the category from table of recommended illuminance values (see Appendix B).
2. Determine the weighting factor by algebraically adding weighting factors (accounting for signs).

a. For Categories A through C,

(1) If the weighting factor $\leq$ -2, use " lower value".

(2) If the weighting factor $\geq$ +2, use "upper value".

(3) If the weighting factor is from +1 to -1, use " middle value".

b. For Categories D through I,

(1) If the weighting factor $\leq$ -2, use "lower value".

(2) If the weighting factor $\geq$ +2, use "upper value".

(3) If the weighting factor is from +1 to -1, use "middle value".

There are four basic design techniques for the determination of quantity of illuminance:

1. Inverse square method (ISM method)
2. Angular coordinate or Direct Illuminance Component (DIC method)
3. Flat rectangular source method
4. Zonal cavity method

2.1.6.1. Inverse Square Method

The inverse square method (ISM) could be used in many situations to calculate the direct component of illuminance at a point and is illustrated in Figure 4. One restriction on using this method is that the light source must be far enough away that it approximates a point source. In cases where this condition is not met, such as a very large source (a long fluorescent lamp), or a calculation point close to an area source, the inverse square method cannot be used. This method does not take into account the light from any other source or reflected light.

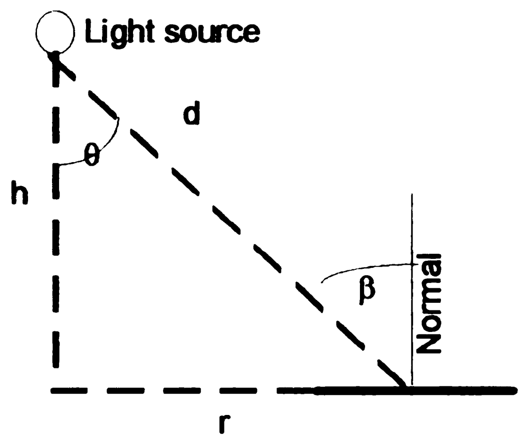


Figure 4. Inverse Square Method

The light ray arrives at the point of calculation on a horizontal surface, at an angle **θ** or **β** from vertical (Figure 4). The illuminance for a tilted plane or a plane perpendicular to line of light can also be determined. Referring to IES Lighting Handbook (1984), the equations are:

$$E_h = \frac{I \cos^3 \beta}{h^2}$$

where E_h = Illuminance at horizontal workplane in footcandles

I = Luminance intensity of light source in candelas

d = Diagonal distance between the light source and the point of calculation

h = Vertical distance (height) between the light source and the point of calculation

r = Horizontal distance between the light source and the point of calculation

The candle power of the source is at some specific time. The candlepower should be multiplied by an appropriate light loss factor. Light loss factor is a product of all considered factors that contribute to a lighting system's depreciated light output over a period of time including dirt and lamp lumen depreciation.

2.2.6.2. Direct Illuminance Component (DIC) Method

The DIC method (IES, 1984; Helms and Belcher, 1991) is an additional procedure for determining the direct component of illuminance at a point. It is most applicable to continuous rows of fluorescent luminaires, although it may also be used with individual luminaires that are separated. This procedure considers a flat luminous strip located in a plane that is parallel to the plane in which the calculation point lies. Figure 5 shows the geometry for the DIC method.

The governing equation for E is

Helm and Belcher (1991) evaluated this equation with the

$$E = LZ^2W\int_{-h2}^{h1}\frac{dy}{(x^2+y^2+z^2)^2}$$

following result:

$$E = \left[\frac{LZ^2W}{X^2+Z^2}\right]\left[\left(\frac{h1}{x^2+z^2+h1^2}\right)+\left(\frac{atan\frac{h1}{(x^2+z^2)^{\frac{1}{2}}}}{2\,(x^2+z^2)^{\frac{1}{2}}}\right)+\left(\frac{atan\frac{h2}{(x^2+z^2)^{\frac{1}{2}}}}{2\,(x^2+z^2)^{\frac{1}{2}}}\right)\right]$$

where:

E = Illuminance

L = Luminous intensity

z = Vertical distance between the light source to the point of calculation

w = Width of the light source

x = Horizontal distance between the light source to the point of calculation

y = Length of the light source

h1 = The distance between the projection point of calculation to the light source and to the one edge of the light source.

h2 = the distance between the projection point of calculation to the light source and to the other edge of the light source.

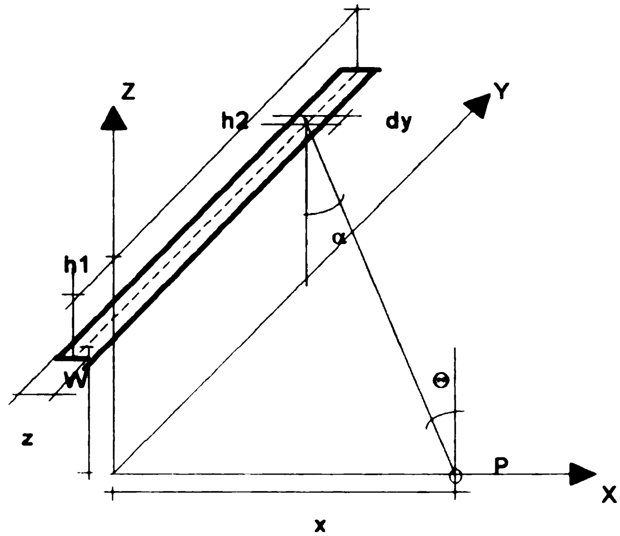


Figure 5. Geometry of DIC. Source: Helms and Belcher,1991

2.2.6.3. Flat Rectangular Source Method

Many large sources in office lighting are rectangular, such as windows. To develop expressions for these sources when the inverse square method and the direct illuminance component method can not be applied, a flat rectangular source method can be used and is illustrated in Figure 6.

The integral equation for a vertical workplane or parallel workplane ($E_{||}$) to light source (Figure 6), based on IES Lighting Handbook (1984) is:

$$E_{||} = \int_0^w \int_0^h \frac{LD^2 dw dh}{(D^2+w^2+h^2)^2}$$

where: $E_{||}$ = Illuminance at Paralel workplane

L = Luminous intensity

H = Height of source

h = Partial of H

W = Width of source

w = Partial of W

Helms and Belcher (1991) solved this equation which obtained:

$$E_{||} = \frac{L}{2}\left(\frac{H}{\sqrt{D^2+H^2}} x \arcsin\left(\frac{W}{\sqrt{D^2+W^2+H^2}}\right)\right) + \left(\frac{W}{\sqrt{d^2+W^2}} x \arcsin\left(\frac{h}{\sqrt{D^2+W^2+H^2}}\right)\right)$$

For a horizontal workplane or perpendicular workplane ($E_{|}$) (Figure 6), the equation is:

$$E_{|} = \int_0^w \int_0^h \frac{LDhdwdh}{(D^2+w^2+h^2)^2}$$

Helms and Belcher (1991) also solved this equation and yield:

$$E_{|} = \frac{L}{2}\left(atan\frac{W}{D} - \left(\left(\frac{D}{\sqrt{D^2+H^2}}\right) x \arcsin\left(\frac{W}{\sqrt{D^2+W^2+H^2}}\right)\right)\right)$$

The maintained illuminance can be found by multiplying the illuminance with an appropriate light loss factor.

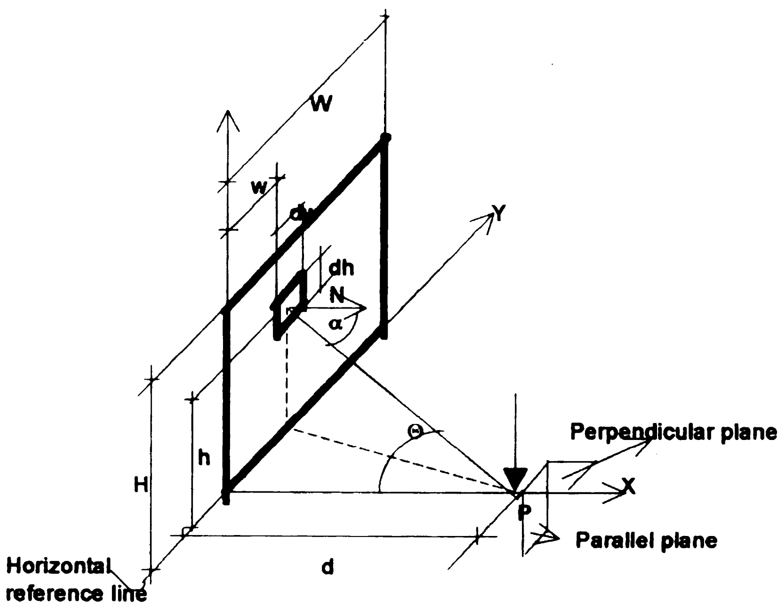


Figure 6. Flat Rectangular Source
Source: Helm and Belcher, 1991

2.1.6.4. Zonal Cavity Method

The zonal cavity method is used for calculating an average illumination level at the work surface when an even distribution is required through the space. This method is very suitable for an open office space, which has the possibility of relocating work surfaces. Light levels at a specific work surface will remain the same and not are a function of its location. In using the zonal cavity method, a room is divided into three spatial areas or "Cavities" (Figure 7). The ceiling cavity (CC) exists if there is space between the bottom of the luminaires and the ceiling. The room cavity (RC) is the space between the bottom of the luminaires and the top of the principal work surface. The floor cavity (FC) is the space between the floor and the top of the principal work surface. Each cavity has a specific effective reflectance with respect to the work plane and the other cavities.

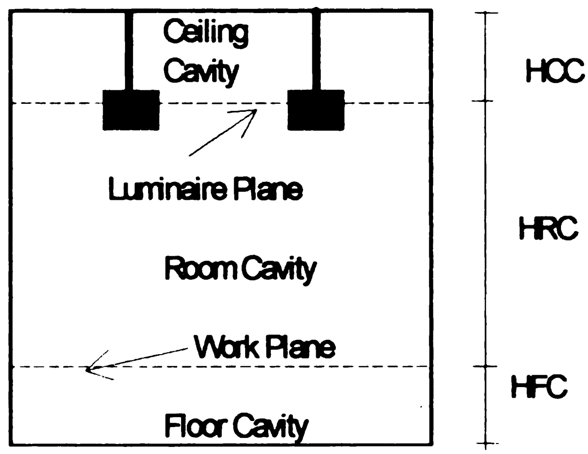


Figure 7. Zonal Cavity

Source: IES Lighting, 1984

The calculation procedure of zonal cavity method:

A. Determine cavity ratio

B. Determine the effective cavity reflectance

C. Determine the coefficient of utilization

D. Determine light loss factor

E. Determine the number of luminaire

<u>A. Determine cavity ratio</u>

When the cavity sizes and finishes have been established, numerical relationships for each cavity are calculated; these are called room cavity ratios (RCR).

$$RCR = 5\,h\left(\frac{L + W}{L \times W}\right)$$

where h = the height of the room or space

L = room length

W = room width

The ceiling cavity ratio (CCR) is determined using the following formula:

$$CCR = RCR \times \frac{h_{cc}}{h_{rc}}$$

where h_{cc} is the height of the ceiling cavity and h_{rc} is the height of the room cavity. The floor cavity ratio (FCR) is determined using the same formula but substituting h_{fc} (height of floor cavity) for the h_{cc} (height of ceiling cavity).

$$FCR = RCR \times \frac{h_{fc}}{h_{rc}}$$

B. Determine the effective cavity reflectance

Charts are available for determining this data in the IES Lighting Handbook chapter 9. Effective cavity reflectances must be determined since the size of the room and amount of vertical wall surface determine the amount of light reflected in the space. Recommended surface reflectances for office space are:

$\rho_{ceiling}$	80 % or more
ρ_{wall}	40 % - 70 %
ρ_{floor}	20 % - 40 %

The governing equation for the effective cavity reflectance is:

$$\rho_{eff}=\frac{\rho_B\rho_w f\left(\frac{2A_B}{A_w}(1-f)-f\right)+\rho_B f^2+\rho_w\frac{A_b}{A_w}(1-f)^2}{1-\rho_B\rho_W\frac{A_B}{A_w}(1-f)^2-\rho_w\left(1-2\frac{A_B}{A_W}(1-f)\right)}$$

where ρ_{eff} = Effective cavity reflectance

A_B, A_W = Areas of the cavity base and walls, respectively.

ρ_B, ρ_W = Reflectance of cavity base and walls, respectively.

f = Form factor between the cavity opening and the cavity base; where

$$f=\frac{2}{\pi xy}\left[\ln\left[\frac{(1+x^2)(1+y^2)}{1+x^2+y^2}\right]^{0.5}+y(1+x^2)^{1/2}\tan^{-1}\left[\frac{y}{(1+x^2)^{1/2}}\right]+x(1+y^2)^{1/2}t\right.$$

where

$$x=\frac{Cavity\ Length}{Cavity\ Depth}$$

and

$$y = \frac{Cavity\ Width}{Cavity\ Depth}$$

C. Determine the Coefficient of Utilization (CU)

The zonal cavity method requires a knowledge of the Coefficient of Utilization is (IES Lighting Handbook):

$$CU = \frac{2.5\rho_1 C_1 C_3 (1-D_G)\Phi_D}{G(1-\rho_1)(1-\rho_3)C_0} + \frac{\rho_2 C_2 C_3 \Phi_U}{(1-\rho_2)(1-\rho_3)C_0} + \left[1 - \frac{\rho_3 C_3 (C_1+C_2)}{(1-\rho_3)C_0}\right]\frac{D_G \Phi_D}{1-\rho_3}$$

where ρ_1, ρ_2, and ρ_3 are the reflectance of the walls, floor, and ceiling, respectively. C_1, C_2, and C_3 are the ratio of flux transfer in the workplane from the walls, ceiling, and floor, and are defined by:

$$C_1 = \frac{(1-\rho_1)(1-f^2_{2\text{-}3})G}{2.5\rho_1(1-f^2_{2\text{-}3}) + Gf_{2\text{-}3}(1-\rho_1)}$$

$$C_2 = \frac{(1-\rho_2)(1+f_{2\text{-}3})}{1+\rho_2 f_{2\text{-}3}}$$

$$C_3 = \frac{(1-\rho_3)(1+f_{2\text{-}3})}{1+\rho_3 f_{2\text{-}3}}$$

$C_0 = C_1 + C_2 + C_3$

where: G = The room cavity ratio

$f_{2\rightarrow3}$= form factor

$$f_{2\rightarrow3}=0.026+0.503\exp^{(-0.0270RCR)}+0.470\exp^{(-0.119RCR)}$$

RCR is the room cavity ratio (from step A)

D_G is the direct ratio calculated using

$$D_G=\frac{1}{\Phi_D\Phi_T}\sum_{n=1}^{9}(K_{GN}\Phi_N)$$

where

Φ_T is the total lamp lumens

Φ_D is the fractional downward flux from

$$\Phi_D=\frac{1}{\Phi_T}\sum_{N=1}^{10}\Phi_N$$

where

$$\Phi_N=2\pi I(\cos\theta_1-\cos\theta_2)$$

I = Mid-zone intensity

N = Zone

$$K_{GN}=\exp^{(-A\ RCR^B)}$$

K_{GN} is the zonal multiplier, which is the percentage of flux contained in each zone on the workplane. A and B are zonal multiplier equations from the IES Lighting Handbook.

The fractional downward flux is Φ_D and the fractional upward flux is Φ_U. These come from:

$$\Phi_D=\frac{1}{\Phi_T}\sum_{N=1}^{10}\Phi_N$$

and

$$\Phi_U=\frac{1}{\Phi_T}\sum_{N=10}^{18}\Phi_N$$

CU can be define by using the table published by the luminaire manufacturer for this purpose, or the IES Lighting Handbook if a manufacturer's table is not available.

D. Determine the light loss factors (LLF)

The LLF is the depreciation of light quantity over time. This factor is obtained by multiplying the LLD (Lamp Lumen Depreciation) factor supplied by the lamp manufacturer and the LDD (Luminaire Dirt Depreciation) factor. The LDD is determined by the physical construction of the luminaire, the degree of dirt contamination in the space, and the frequency of cleaning the luminaire.

The equation of light loss factor is:

LLF = Nonrecoverable x recoverable factor

or

$$LLF = (LAT \times VV \times BF \times LSD) \times (LDD \times RSDD \times LLD \times LBO)$$

where LAT	=	Luminaire ambient temperature
VV	=	Voltage variation
BF	=	Ballast factor
LSD	=	Luminaire surface depreciation
LDD	=	Luminaire dirt depreciation
RSDD	=	Room surface dirt depreciation
LLD	=	Lamp lumen depreciation
LBO	=	Lamp burn out

The detailed explanation and value of each factor can be found in the IES Lighting Handbook (1984). In practice, LLF is defined by the multiple of LDD and LLD.

E. Determine the number of luminaires required

in the given space to provide the recommended illuminance. The IES Lighting handbook (1984) equation is:

$$N = \frac{E \times A}{n \times L \times LLF \times CU}$$

where N	=	the number of luminaires
E	=	the illuminance
n	=	the number of lamps per luminaire
L	=	the number of lumens produced per lamp
LLF	=	the combined light loss factors
CU	=	the coefficient of utilization
A	=	the area of the working plane (or floor) that will be illuminated by the luminaires.

Once this information is known, placement of the luminaires can be worked out. It is important that the S/MH (space mounting height) ratio be considered in working out the final layout.

Computer program developed for entire lighting design in this literature review such as inverse square method, direct illuminance component method, flat rectangular method and zonal cavity method.

2.1.7. Quality of Light(Open Plan Office Space)

Within the lighting literature, quality has been discussed in numerous ways. For example, it has been described as light meeting biological, psychological, and aesthetic needs in contrast to quantity which fulfills functional needs. Stein and Raynolds (1992) define lighting quality to include all factors in a lighting installation not directly concerned with quantity. Specific items referred to are luminance ratios, diffusion, uniformity, chromaticity, uncomfortable brightness ratios, and the general notion of visual discomfort. Nuckolls (1983) has suggested that good (high quality) lighting is realized when the mood created is consistent with the function of each space, when the lighting provides spatial clarity, and when it promotes productivity.

Over the past decade, more office space has been designed as the open plan office space due to rising costs and more teamwork within corporations. In the open plan office, the "flow of production and communication" is more interactive and organizationable. From account handling to order processing, from estimating to scheduling, time movements of the activities can be shortened. The purpose of the open plan office is to support the overall corporate activities in an efficient manner.

Typically, the work performed in the office is repetitive and continuous task such as reading, writing, telephone work, data entry at a VDT (Visual Display Terminal), typing, faxing, and copying. VDT is the priority when designing the lighting system in the office space. IES mentions that one must assume that VDTs will be used in every office space. The geometry of VDT viewing, which has several variables including screen height and angle, position of the operator, and location of the VDT (which may be changeable), is factored into the lighting-design for visual comfort and good visibility.

2.2.7.1. Glare

"Too much light" becomes unwanted brightness, known as glare. Glare is a major problem to visual performance and can result in eye discomfort and eye fatigue. Helms and Belcher (1991) identify two types of glare: (1)Direct glare which occurs when brightness directly from the lamps falls in the field of view, and (2)Indirect glare which occurs when brightness from the luminaires comes to the eyes indirectly. There are two forms of indirect glare: reflected glare and veiling reflections. Reflected glare occurs when the image of the light source is reflected from a glossy working surface such as a polished desk, magazine, or VDT screen. Reflected glare can be just as horrible in a VDT screen if light colored support columns are reflected in the screen; or if people in white shirts stand or walk behind the person viewing the screen. Veiling reflections can occur when the angles of incidence for light on the horizontal work surface are within the observer's viewing zone or task zone.

Three zones are usually considered in terms of contrast relationships in lighting quality. The first zone refers to the task itself. A task is anything that is within the primary focus of the eye. The second zone is the surfaces immediately surrounding the task. The third zone is the general surrounding area. For example, when reading a book at a table, the book is zone one, the table top becomes zone two, and the room's walls and floor comprise zone three. The contrast comparisons are important between zones one and two and between zones one and three. It is unusual practice to directly compare the relationships between two and three. These comparisons are luminance ratios. When there is a large change in lighting levels between zones, eye fatigue result from eye adaptation .

In terms of office space containing VDTs, the IES Office Lighting Committee has provided recommendations for maximum luminance ratios, which is the brightness ratio of an object to the environment surface. These are shown in Table 5.

Clearly, the reflections seen on VDT screens and glare are the major concerns of the lighting system in the open plan office.

Table 5. Maximum Luminance Ratios for Offices containing VDTs

Description	Ratio
Between paper-based visual tasks and adjacent VDT screen	3 to 1
Between a visual task (paper or VDT) and adjacent dark surroundings	3 to 1
Between a visual task (paper or VDT) and adjacent light surroundings	1 to 3
Between a visual task (paper or VDT) and more remote dark surfaces	10 to 1
Between a visual task (paper or VDT) and more remote lighter surfaces	1 to 10

Source: IES Office Lighting, 1992

One way to evaluate glare is to use the visual comfort probability (VCP) data. Designers use this method as a guide for lighting spaces for the comfort of the user. The IES Lighting Handbook states that the VCP value represents the percentage of people that are unlikely to complain about the glare produced in the space. Moreover, Helms and Belcher (1991) state that the computation of VCP for a room is dependent on the following factors:

1. Room size and shape
2. Surface reflectance
3. Illumination level
4. Luminaire type, size, and distribution
5. Number, location, and orientation of luminaires
6. Luminance of the entire visual field
7. Observer location and line of sight
8. Differences in individual glare sensitivity
9. Equipment and furniture

The relationships between these factors are used to generate a simple table of VCP values, provided by the luminaire manufacturers. A VCP of 70 has been found to be the minimum for visual comfort in office situations. Standard tables are calculated for an illuminance of 100 foodcandles, but VCP values do not vary greatly with illumination level. VCP differences of 3-5 points are not particularly significant.

The degree of glare from a luminaire reflection on a VDT screen can be decreased by arrangement of the cut-off angle. For example, some parabolic louver or baffle luminaires are designed to provide a cut-off angles that decreases such reflections in a room with various ceiling heights. One way to quickly assess this is to check the depth and cell size of the louver or baffle. If the luminaire has a baffle depth greater than 3 inches and baffle spacing of about 5 inches, a space with 8-12 foot ceiling heights using this luminaire will show good glare control. Louvers that are shallower than 3 inches in depth and greater than 6 inches in spacing should be carefully reviewed for glare (Steffy, 1991). Moreover, in order for the VDT operator to see no glare in the screen, the luminaires luminance cut-off angle must be equal or less than the sight-line angles . Thus, if the range of sight-line angles is known, the luminaire luminance cut-off angle can be determined. Furthermore, an anti-glare filter screen is sometimes used to help solve a glare problem.

Steffy (1990) did a study about materials that can be used to control glare. These materials range from simply using low-transmission glass such as tinted gray or bronze to solar shades.

2.2.7.2 Color rendering

Color rendering of the lighting system may contribute psychologically to a worker's mood. A unit measurement used in color rendering is the color rendering index (CRI). CRI deals with the appearance of colored objects illuminated by a light source and how that appearance compares with the color appearance of objects illuminated by a reference source. The CRI is in widespread use and is based upon a test color method recommended by the International Commission on Illumination. It uses a scale which ranges from 0 to 100, where an index value of 100 (R_S = 100) means a light source renders colors the same as the defined reference source at a given chromaticity. CRI values can give a measure as to which of two light sources will render colors better, but only if the two sources have the same chromaticity reference or color temperature (Helms and Belcher, 1991). The standard fluorescent sources being taken off the market in the U.S. have CRI's between 50 to 60, while CRI values above 75 indicate very good color rendition properties.

2.2. ECONOMIC

The most important part of this study is the energy efficiency of lighting systems. This concept, admittedly, is not easily defined because energy efficiency may mean different things to different people. However, this concept will be defined so that it can be operationalized in this study based on existing energy conservation legislation.

2.2.1. The Energy Management Challenge

Energy consumption in the twentieth century has increased drastically, even though the world has always known resource limits. Food and water problems are still with us. Now, energy management is also a challenge. Scientific and technical experts will meet this challenge by finding new energy sources and by developing new equipment and appliances that use less energy. Energy management could also include the substitution of some travel with electronic communication, changes in land use patterns to reduce energy use for space conditioning (such as high-density dwellings and total energy systems), and changes in transportation. Innovations will have to be supported by government action (regulatory, legislative, or tax incentives) and by energy users. The public needs to change its value system as well as habits that squander energy. A changed perception of energy resources and values and the tools to manage energy use wisely, to eliminate waste, and to reduce inefficiency are needed (Reis et al., 1991).

While good energy management is obviously advantageous, the environmental effects inherent in the various forms of energy usage range from inconsequential to substantial. The energy resources must be utilized with concern for preserving the environment. Thus, people have to balance society's need for energy against the need for a livable environment, at the same time giving appropriate attention to important economic, technical, and social factors.

2.2.2 Economic Analysis of Energy Efficiency

An economic analysis helps in decision making. An economic analysis in this study, could be for a new office building, to compare the use of system A, which has a low first cost and a high operation cost will system B, which is the opposite. In a remodelling project, would a retrofit project which changes partial components of the luminaires be a better choice than complete replacement of all components of the luminaires. The economic analysis helps in comparing the financial consequences of alternative investments (Lindsey, 1991). The basic questions in the lighting system project here are: (1)Will the investment be recovered? (2)How much risk is inherent in that investment? (3)How does that return compare with other possible investments? There are two common types of economic analyses which are used to analyze the economic factors, simple payback analysis and life cycle cost analysis.

2.1.2.1 Simple Payback Analysis

The simplest form of payback analysis makes no allowance for the time value of money. The only concern is how rapidly the investment will pay off.

Despite its lack of sophistication, the simple payback method has some advantages over the life cycle cost analysis and is widely used by industry to evaluate potential investments. It is easy to prepare and requires only minimal information: costs and savings.

Table 6 is a form that can be used for simple payback analysis for lighting systems (Lindsey, 1991). The analysis has several parts, including power cost savings, installation cost, and replacement lamp cost. For more detailed information on how to fill out this form see reference-Lindsey (1991).

Brown and Yanuck (1980) define the payback period as the length of time necessary to recover the initial investment of a project. The funds available for the recovery are the total net savings on an after-tax basis and the depreciation tax benefit.

Table 6: Economic Analysis using Simple Payback - New Fixtures

Power Cost Savings (Annual)

Existing System ___(1)___ x ___(2)___ watts = ___(3)___ watts

Proposed System ___(4)___ x ___(5)___ watts = ___(6)___ watts

Watt Reduction = ___(7)___/1000 = ___(8)___KW

___(9)___ KW x $ ___(10)___/KW Demand charge = $ ___(11)___

___(12)___KW x ____(13)___ Hrs/Mo.x $ ___(14)/KW___= ____(15)___

Total MonthlySavings = $ ___(16)___ x 12 =$___(17)___/Yr

Installed Cost

___(18)___ Fixtures x $ ___(19)___ / Fixt =$ ___(20)___
___(21)___ Lamps x $ ___(22)___/ lamp = $___(23)___
Subtotal = $___(24)___ + _tax (25)__ = $___(26)___

Labor

___(27)___ Fixtures x $ ___(28)___/Fixtures = $ ___(29)___
Total Installed Cost = $ ___(30)___

Replacement Lamp Cost

Existing Lamp ___(31)___ Net Cost $ ___(32)___ + ___(33)___ (tax) = $ ___(34)___

Labor Cost to Replace 1 lamp = $ ___(35)___

Total Replacement Cost per Lamp = $ ___(36)___

___(37)__% Burnouts x ____(38)____ x $ ___(39)___ / lamp =$___(40)___/yr

(# lamps)

Proposed lamp ___(41)___ Net Cost $ ___(42)___ + ___(43)___(tax) = $ ___(44)___

Labor Cost to Replace 1 Lamp = $ ___(45)___

Total Replacement Cost per Lamp = $ ___(46)___

__(47) % Burnouts____ x ___(48)___ x $ ___(49)___ / lamp = $ ___(50)___

(# lamps)

Added Savings / Cost $ ___(51)___

Total Annual Savings

$ ____(51)___ Power Cost Savings (+ -) $ ___(52)___ Revamping Cost / Savings

$ ___(53)___ Net Savings

Saving Payback

$ ___(54)___ Installed Cost / $ ____(55)___ Net Savings = ___(56)___

Source: Lindsey, 1991.

2.2.2.2 Life Cycle Cost analysis

Brown and Yanuck (1980) stated that life cycle cost (LCC) is a method of calculating the total cost of ownership over the life span of the asset. Initial cost and all subsequent expected costs of significance are included in the calculations as well as disposal value and any other quantifiable benefits to be derived

Life cycle cost (LCC) is justified when one needs a decision to make an acquisition of an asset which will require substantial operating and maintenance cost over its life span. Macedo,et al (1978) defined LCC as the systematic evaluation of some alternative possibilities and the comparison of their projected total owning, operating, and maintenance costs over the economic life of the investment. Brown and Yanuck (1980) discussed four major factors which may influence the economic feasibility of applying LCC analysis:

1. Energy intensiveness. LCC should be considered when the anticipated energy costs of the purchase are expected to be large throughout its life.
2. Life expectancy. For commodities with long lives, costs other than purchase price take on added importance. For commodities with short lives, the initial costs become a more important factor.
3. Efficiency. The efficiency of operation and maintenance can have significant impact on overall costs. LCC is beneficial when savings can be achieved through reduction

of maintenance cost.

4. Investment Cost. As a general rule, the larger the investment the more important LCC analysis becomes.

How is LCC to be used? An energy-efficient lamp, for example, is not a large investment and its life is relatively short, yet it is a proper subject for LCC analysis because the key element is the post-purchase cost. LCC is a combination of initial and post-purchase costs. When the interest is considered in an economic analysis, the concept of equivalence is introduced: a present sum of money, plus interest, is equivalent (equal) to a future sum. This concept is used to express all expenditures, both present and future, in today's dollars.

It must be stressed that an economic analysis may be used only to evaluate the financial implications of an investment. It says nothing about the suitability of the equipment, nor does it recognize intangibles such as comfort, convenience, status symbols, or pride of ownership. The value of the intangible factors cannot be included in an economic analysis, but there may be occasions when they are important enough to override the economic factors.

Components of LCC for calculating energy efficiency in this study are: initial cost, annual energy cost, annual surveillance cost, annual maintenance cost, occasional repairs, occasional replacement, life time, discount rate, energy escalation rate, maintenance escalation rate, and replacement escalation rate.

The question is how much is the average annual cost of the investment? Brown and Yanuck (1980) developed the model for solving this problem. LCC is the total of the initial cost, present value of occasional costs and present value of terminal cost. Present value of occasional cost is the total annual costs of maintenance, repairs, and replacement. Present value of terminal cost is the total annual cost for energy and surveillance.

TPWC = IC + PVEC + PVSC + PVMC + PVOC + PVOR

where TPWC = Total Present Worth Value

IC = Initial Cost

PVEC = Present Value of Energy Cost

PVSC = Present Value of Surveillance Cost

PVMC = Present Value of Maintenance cost

PVRC = Present Value of Repair Cost

PVOR = Present Value of Replacement Cost

The model of present value occasional cost for annual repair (PVRC) is:

$$PVRC = RC\left[\frac{1 + RR}{1 + i}\right]^{YS}$$

where RC = Repair cost

RR = Replacement escalation rate and

YS = Years between occasional replacement

i = Discount Rate

This model can be applied for the others present value of occasional cost in this model.

One of the terminal costs is the annual energy cost. Using EC to represent this cost, PVEC is :

$$PVEC = EC\ \frac{\frac{1+ER}{1+i}\left[1-\left[\frac{1+ER}{1+i}\right]^{n}\right]}{\left[1-\left[\frac{1+ER}{1+i}\right]\right]}$$

where ER = Energy escalation rate

n = Number of years

The average annual cost (AAC) is found by multiplying the TPWC by the uniform capital recovery factor that is:

$$AAC = TPWC\ \frac{i(1+i)^{n}}{(1+i)^{n}-1}$$

The AAC is calculated either manually or by computer. The average annual cost is a constant annual amount which is paid throughout the assumed life cycle of the lighting system. As an alternative in the decision making process, AAC converts all of the expenditures occurring over a number of years to a constant annual amount. Method of analysis to simplify the comparison to the alternative. Using AAC for computing a constant annual dollar value for each alternative, the alternative with the lowest annual dollar is the most cost effective (Macedo et al., 1978).

Lowest initial or first cost may appear to be the most efficient option in the short run, but over a long-term period it may not be the most cost-effective option. The LCC method shows how to obtain the most cost effective system in the long run. A benefit of using life-cycle cost as a decision aid is that actual and estimated future costs are made explicit.

2.3. **Management of a Lighting System**

2.3.1. Renovation Management of a Lighting System Project

A renovation of a lighting system may result from an owner's desire to improve office performance. This may include other design materials such as carpets, walls, and furniture, but this discussion restricted to addresses only the lighting system. To achieve that purpose the owner may hire a design professional.

Traditionally, in the management of renovation, the design professional and the renovator/ contractor are each bound to the owner by independent contract, such as the owner-design professional agreement for services, and the owner-contractor contract for the construction of the project facilities. The design professional and the constructor have no contractual agreement, and all lines of their contractual responsibility run to and through the owner. According to Ritz the relationship and the responsibility of the owner, design professional and contractor/ renovator are:

The owner is responsible for:

1. Providing project financing
2. Stating project requirements
3. Defining organization of the project team
4. Setting up lines of coordination and communication
5. Selecting other team members and contracting for professional design services and construction of project facilities
6. Operating the project after construction is completed

On preparing for the construction phase, the owner is responsible for:

1. Evaluating the financial, material, and human resources available to the project
2. Defining the contracting strategy
3. Determining the field organization for construction of project facilities

As the design phase is completed and project activities point toward the construction phase, the selection of a qualified constructor is an owner's responsibility and decision. The owner, assisted by the design professional, is also responsible for the review and acceptance or rejection of the constructor's submittal.

When stating project requirements, structuring the project team, and organizing communication, the owner may find it useful to employ the design professional in order to benefit the owner's expertise in all phases of the project

(initiation phase, design phase, and construction phase)

During the project initiation phase, the design professional is responsible for:

1. Refining and amplifying previous written statements of project requirements
2. Formulating and studying alternative methods and arrangements for meeting project requirements.
3. Data gathering and an area-by-area survey
4. Selecting the most favorable alternative
5. Completing project conceptualization and planning
6. Developing preliminary facility layouts and other project design criteria
7. Making investigations, performing studies, accomplishing project planning, preparing reports, and other tasks under the owner's direction (Ritz, 1991).

During the project design phase, the design professional is responsible for:

1. Producing the completed design for the owner's approval
2. Planning and managing the design
3. Coordinating and communicating during the design phase
4. Monitoring and controlling design costs and schedules
5. Providing professionally qualified staff
6. Performing design-related quality control functions
7. Designing in compliance with codes and standards, laws and regulations, and regulatory agency requirements
8. Arranging for appropriate design reviews,

constructability reviews, operability and maintanability review, and peer reviews (Ritz, 1991)

During the preparation for construction phase, the design professional is responsible for:

1. Preparing the bid package and contract documents for the owner's approval
2. Assisting the owner in administering the bidding process
3. Evaluating bids or proposals received
4. Awarding contracts
5. Maintaining the quality of materials and workmanship
6. Considering and taking timely action on the contractors requests for modification of construction contract terms
7. Maintaining current estimates and making timely payments under the terms of contracts and agreements
8. Monitoring construction progress
9. Building the project record, using all forms of written communication (Ritz, 1991)

Although the design professional has no contractual relationship with the contractor, s(he) is involved in construction activities under the terms of the owner/design professional agreement. During the construction phase, the design professional is responsible for:

1. Providing technical services
2. Sometimes the owner authorize the design professional to perform certain administrative duties (Ritz, 1991)

The contractor is responsible for:

1. Performing in accordance with the terms of the contract and for renovating the facility described in the contract documents
2. Defining specific compliance with the owner/contractor contract
3. Planning and enforcement of site programs, means, and methods
4. Sequencing the renovation
5. Managing the payment of subcontractors and suppliers
6. Doing quality control related to construction activities
7. Meeting applicable codes, permit, and other regulations.
8. Submitting information for the review and acceptance, or the approval of the owner (Ritz, 1991)

Cotts and Lee (1992) state that professional designers should be project managers during renovations. That fixes responsibility, allows for rapid decisions on changes and means a single contract from concept through project completion. Optimization of the project could be done in the planning stage or the constructing stage. Even though lighting design is not a large part of the overall project, the lighting designers should manage that part of the job. Thus the designer can continually play in two variables of the project: cost and time. Related to cost and time, Mizuno (Figure 8) gives the idea of examination procedures to shorten a project. This method and model of planning has been discussed in detail by Antil and Eugene, 1982; Thamhain, 1984; Barrie and Paulson, 1992.

Barrie and Paulson (1992) discussed S curves or progress curves as a tool of control. The authors stated that the shape of a progress curve, which resembles the letter S, results from integrating progress per unit of time (day, week, month, etc) in order to obtain cumulative progress. On most projects, expenditures of resources per unit time tend to start slowly, build up to a peak, and then taper off near the end. This causes the slope of the cumulative curve to start low, increase during the middle, and then flatten near the top. Progress curves or S curves are related to forecasting and planning.

Amos and Sarchet (1981) state that 'a forecast' is a determination of events that will occur in the future. Forecasting should be distinguished from planning. Cleland and Kocaoglu (1981) state that the major difference between forecasting and planning is that a forecast is a statement of what is likely to happened in the future while planning related to strategies. Forecasting is not based on recommended strategies like planning, because forecasting is not based on available information. The purpose of forecasting is to give some idea to the decision maker about the trend or prediction of the case, especially if planning can not be done because of lack of data/information.

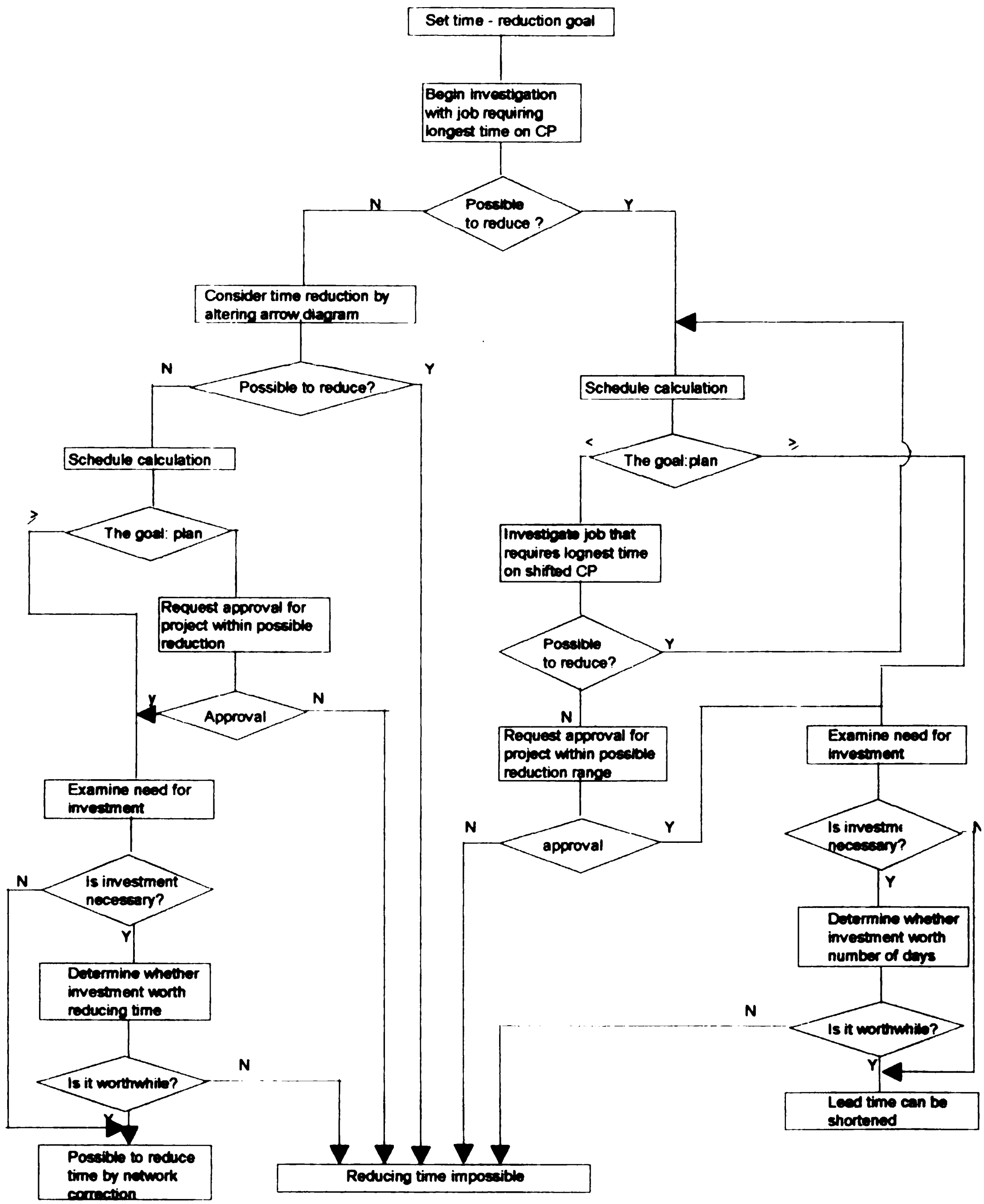


Figure 8. Evaluation Procedure to Shorten a Project Schedule

Source: Mizuno, 1979.

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Brondon and More (1983) used the DHSS (Department of Health and Social Security) formula for forecasting the progress curve or S curve. That formula is:

$$Y = S\left[X+CX^2-CX-\frac{1}{K}(6X^3-9X^2+3X)\right]$$

where Y = cumulative timely valuation

X = time in which expenditure Y occur divided by the contract period

S = contract sum

C & K = constants depending on contract value.

2.3.2. Decision Analysis of Lighting system

Using an economic analysis, either simple payback or life cycle analysis, several cost alternatives for the lighting system can be produced for comparisons. The selection of a lighting system should not be made on the lowest cost because a lighting system should provide quality light for tasks being performed.

A decision analysis can be used to select the type of lighting system. A model for decision analysis is (Markland et al., 1987)

$$P(A_i) = \sum_{j=1}^{4} (S_j, A_i)$$

where $P(A_i)$ = The total value of lighting system evaluation

A_i = The alternative of lighting system

S_j = The needs of open plan office space, such as performance, comfort, ambiance, and cost effectiveness

Philips lighting developed the maximum value of each lighting system's need in open plan offices (Column 2-Table 6). Assume the ranges of values is in Column 3-Table 6. More detail about the application of this model is given with the case study projects.

Table 7. The Range of Forecast Evaluation based on the Value of Needs in Open Plan Office Space

Description of Need	Max Value	Range
Performance	5	5 - above or on the min light level 2 - below the min light level
Comfort	3	3 - CRI : 90 - 100 2 - CRI : 80 - 90 1 - CRI : 70 - 60 0 - CRI : 50 - 60
Ambience	1	1 - above or on $3500^{0}K$ 0 - below 3500 ^{0}K
Cost Effectiveness	5	5 - the lowest cost 1 - the highest cost

3. COMPUTER PROGRAM

3.1. MODELLING PROCESS

In developing a computer program, one needs to understand the tasks that are to be solved as well as how a computer works, what its limitations are, and how problems should be structured for the computer. Figure 9 shows the process (QuickBasic, Microsoft., 1991).

Start	-	Start the computer
Understand the task	-	Refer to the previous explanation
Design the program	-	Apply the logic thinking of this thesis
Write the program	-	Use QuickBasic computer language
Test for errors	-	Refer to the actions that determine whether a program runs correctly.
Debugging	-	the subsequent activity of finding and removing the errors.

One objective of this study was to write a computer program which combines lighting design, economic analysis, and management decisions (Figure 10). The general principles involved in developing a computer program can be summarized as follows (Brandon and Moore, 1983):

1. Develop subprograms consisting of several modules.

Modules within the system should be accessible to other related modules of the subprogram.

2. Every subprogram should be debugged before it integrated with the other subprograms using main menu.
3. Data within the data base should be properly structured and addressed in a uniform manner for ease of access by any subprogram.
4. The operation of the system should be such that users can quickly and efficiently access and operate any part.
5. The system should be able to be expanded when required to encompass new data.

It is necessary in many programs to actually validate the model used (particularly if it differs manual techniques) and to test it before its implementation into the project. Many programs have failed, not because they are poor at calculations or the model is inadequate, but because they are not suited to project practice. The test for errors in the computer programs developed for this study focused on comparison between the design obtained IES tables and the values calculated using the computer program.

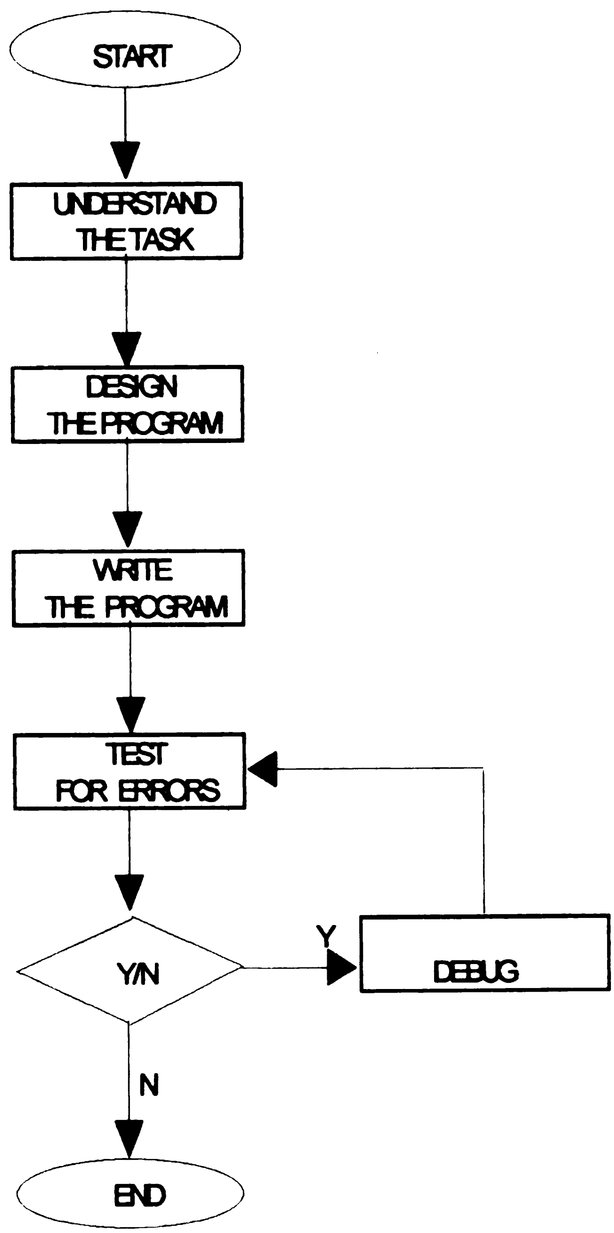

Figure 9. The programming process

Source: QuickBasic Microsoft, 1991

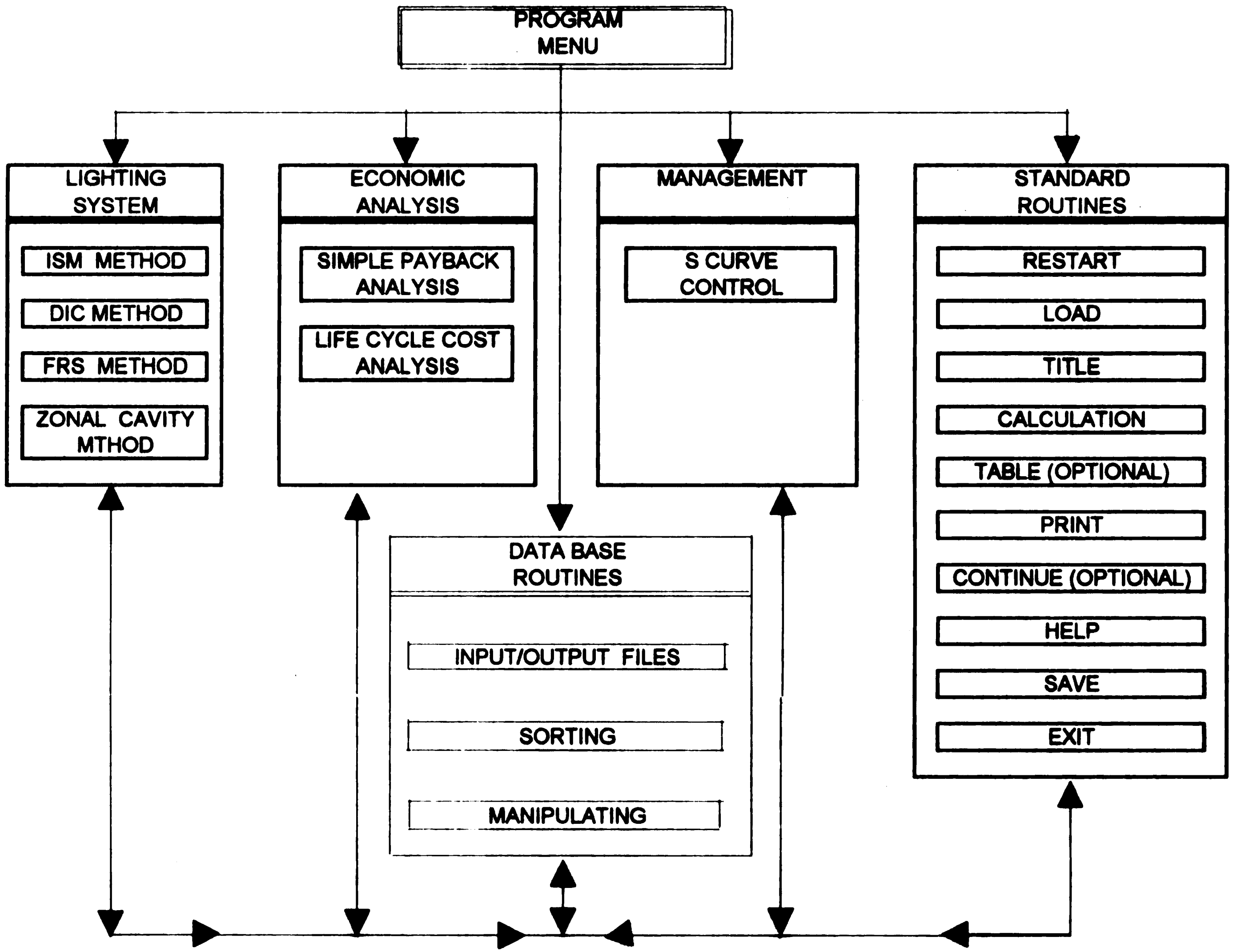

Figure 11. Computer model

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Each category in Figure 10 can be explained as follows :

3.1.1. Lighting Design

In many developing countries, the availability of data for lighting system designs is not sufficient for obtaining a valid calculation. Many luminaire manufacturers provide brochures with limited information. The available data have to be evaluated in order to get the essential values such as the coefficient of utilization. The tabulated data which is available in many handbooks often is not usable because of a different approach for determining lighting factors. Therefore, the computer program should calculate these factors using the appropriate formulas.

A good starting place in lighting design is to define the source of the artificial light. The lighting source can be considered to be a point, a line, or an area. There are four methods of lighting design analysis. The equation for each method were given in chapter 2.

1. Inverse Square Method

The Point of interest (pivot point) is evaluated by a lighting source as a point.

2. Angular Coordinate-DIC Method

The point of interest (pivot point) is evaluated by treating the lighting source as a line.

3. Flat Rectangular Source Method

The point of interest (pivot point) is evaluated by considering the lighting source as an area.

4. Zonal Cavity Method)

The zonal cavity method treats the lighting source as a point, a line or an area with the concern being to produce an even lighting distribution on the work plane. This method is detailed in the IES Lighting Handbook.

3.1.2. Economic Analysis

Economic analysis of a lighting system in this model enables the users to analyze a number economical option for lighting systems with economical options. After evaluating the selected lighting design, the next step is to conduct the economic analysis. There are two options in this analysis: first, a simple pay back analysis gives an idea of the break even point of the investment of the new lighting system compared to the existing systems. Second, the full economic analysis (life cycle) considers depreciation, escalation, and discount rate for economic analysis (Chapter 2).

3.1.3. Management

In this portion, the program addresses the progress curve or S-curve projection. The purpose of using this curve is to give an idea of how well the progress of the project matches the schedule. The model used to predict the S curve is same as the S curve model discussed in Chapter 2. A QuickBasic program was written based on the information given by Brandon and More (1983).

4. CASE STUDIES

4.1 Case 1. Office Space

This case study is a redesign of the lighting in an existing office space that has adequate light but with glare making visual tasks difficult.

After a survey, it was found that the office has 2'x4' fluorescent troffers using prismatic lenses. There were 44 fixtures producing 75 footcandles. Each fixtures contained four, 40-watt cool white fluorescent lamps. There were workstations with 65" panels in most of the office area which was 2542 ft^2.

A study of the office area started with a measurement of the existing illuminance. The average illuminance was 75 fc. Using the IES recommendations and the procedure discussed in Chapter 2, it was determined that 75 fc was enough for the lighting level in the office. After the recommendation of lighting level was determined, several lighting design options were evaluated using the computer program created in for this study. This study used lighting option :

- Fixtures from Metalux-Cooper Lighting (see reference)
- Lamps from GE Lighting (see reference)
- Ballast from GE Lighting (see reference)

The lighting system data and results are summarized:

1. Table 7 which is based on the value needs in the open plan office space (see Table 6 in chapter 2) and simple pay back analysis shows that alternative two is the best alternative. Alternative two consist of:

Fixture: 2P2GAX-340S36H (see reference Cooper Lighting)

Lamp : F32T8/SP35 (see reference GE Lighting)

Ballast: Electronic Rapid Start (see reference GE Lighting)

2. Table 8, which is a comparison between simple payback and life cycle analysis, shows that alternative one has the lowest average annual cost of life cycle analysis. Alternative one consist of:

Fixture: 2P2GAX/340S36H (see reference Cooper Lighting)

Lamp : F40T8/SP35 (see reference GE Lighting)

Ballast: Hi efficiency (see reference GE Lighting)

The best alternative in this case study is alternative two, because of electronic ballast. Since the purpose of the study to provide a good quality of lighting system, electronic ballast is more preferable (see ballast subdivision in chapter 2)

Table 8. Evaluation of case 1: Office Space
(based on the value of needs in Open Plan Office Space)

No of Alter-native	DESCRIPTION	Design			Simple Payback Analysis				Grade of Quality				Total Grade
		CU	LLF	No of Fixt	Power Saving ($)	Installation ($)	Replacement Lamp ($) (Saving/Cost)	Simple Payback Period (Yr)	Perform-ance	Comfort	Ambiance	Cost	
1	Fixture: 2P2GAX/340S36H	0.72	0.87	28	1886.21	4466.42	13.1	2.23	4	1	1	5	11
	Lamp: F40T8/SP35												
	Ballast: Hi efficiency												
2	Fixture: 2P2GAX/340 S36 H	0.72	0.87	36	1841.66	6087.89	18.08	3.11	5	1	1	4.51	11.51
	Lamp: F32T8/SP35												
	Ballast: Electronic Rapid Start												
3	Fixture: 2P2GAX-2U6S44H	0.63	0.87	72	1178.11	8759.92	29.75	6.84	5	0	0	2.24	7.42
	Lamp : F40W/U6/WM												
	Ballast: Electronic Rapid Start												
4	Fixture: 2PAGAX-2U1-5/8S55I	0.58	0.87	79	985.33	10358.54	24.15	9.38	5	0	0	1	6
	Lamp: F40W/U6/WM												
	Ballast: Electronic Rapid Start												
5	Fixture: 2P2GAX-440S46H	0.65	0.87	30	1721.86	6074.2	10.24	3.29	5	1	1	4.41	11.41
	Lamp: F32T8/SP35												
	Ballast: Electronic Rapid Start												

Table 9. Comparison between Simple Payback Analysis and Life Cycle Cost of Case 1: Office Space

No of Alter-native	DESCRIPTION	Simple Payback Analysis				LCC
		Power Saving ($)	Installation ($)	Replacement per Lamp ($) (Saving/Cost)	Simple Payback Period (Yr)	Average annual cost
1	Fixture: 2P2GAX/340S36H Lamp: F40T8/SP35 Ballast: Hi efficiency	1886.21	4466.42	13.1	2.23	3983.93
2	Fixture: 2P2GAX/340 S36 H Lamp: F32T8/SP35 Ballast: Electronic Rapid Start	1841.66	6087.89	18.08	3.11	4261.03
3	Fixture: 2P2GAX-2U6S44H Lamp : F40W/U6/WM Ballast: Electronic Rapid Start	1178.11	8759.92	29.75	6.84	6386.62
4	Fixture: 2PAGAX-2U1-5/8S55I Lamp: F40W/U6/WM Ballast: Electronic Rapid Start	995.33	10358.54	24.15	9.38	7169.51
5	Fixture: 2P2GAX-440S46H Lamp: F32T8/SP35 Ballast: Electronic Rapid Start	1721.86	6074.2	10.24	3.29	4481.24

4.2 Case 2. The Taubman Company

The president of the Taubman Company requested a review of the lighting for on the third floor of the West wing of the building offices, on 200 East Long Lake Rd,in Bloomfield Hills, Michigan. The office plan is attached.

The president stated that his current office space has plenty of light but that he is getting complaints about glare on the computer screens. He also stated that the present fluorescent lighting makes people look pale.

During a visit, it was found that the office has 2'x4' fluorescent troffers with prismatic lenses. There were 330 fixtures in the third floor west wing of the building area 21049 ft^2 producing 100 footcandles. Each fixture contained four, 40-watt cool white fluorescent lamps. There were workstations with 65" panels in two-thirds of the open area which contained.

The analysis of this problem started with the measurement of the existing illuminance which was 100 fc. After doing some research based on IES recommendations, and following the procedure discussed in Chapter 2. It was decided that 75 fc was more than enough for the office space. After the recommended of the lighting level was determined, several lighting design options were evaluated using the computer program. This study used lighting option :

- Fixtures from Metalux-Cooper Lighting (see reference)
- Lamps from GE Lighting (see reference)

- Ballast from GE Lighting (see reference)

The lighting system data and results of case 2 are summarized:

1. Evaluation of Table 9, which is based on the value needs in the open plan office space and simple pay back analysis, shows that alternative five is the best. Alternative 5 consist of:

   Fixture: 2P2GAX-440S46H (see reference Cooper Lighting)

   Lamp : F32T8/SP35(See reference GE Lighting)

   Ballast: Electronic Rapid Start (See reference GE lighting)

2. Table 10, which is a comparison between simple payback and life cycle analysis, shows that alternative five has the lowest average annual cost of life cycle analysis.

The best alternative in this case study is alternative five.

Table 10. Evaluation of case 2: The Taubman Company
(based on the value of needs in Open Plan Office Space)

No of Alter-native	DESCRIPTION	Design			Simple Payback Analysis				Grade of Quality				Total Grade
		CU	LLF	No of Fixt	Power Saving ($)	Installation ($)	Replacement Lamp ($) (Saving/Cost)	Simple Payback Period (Yr)	Perform-ance	Comfort	Ambiance	Cost Effecti-veness	
1	Fixture: 2P2GAX/340S36H Lamp: F40T8/SP35 Ballast: Hi efficiency	0.8	0.87	210	14146.56	33498.15	98.26	2.23	4	1	1	5	11
2	Fixture: 2P2GAX/340 S36 H Lamp: F32T8/SP35 Ballast: Electronic Rapid Start	0.8	0.87	265	13981.44	44813.62	133.1	3.05	5	1	1	4.29	11.38
3	Fixture: 2P2GAX-2U6S44H Lamp : F40W/U6/WM Ballast: Electronic Rapid Start	0.7	0.87	540	8835.84	65699.42	223.1	6.84	5	0	0	1	6
4	Fixture: 2PAGAX-2U1-5/8S55I Lamp: F40BX/SP35 Ballast: Electronic Rapid Start	0.63	0.87	457	10301.18	59922.2	139.73	5.37	5	1	1	2.27	9.27
5	Fixture: 2P2GAX-440S46H Lamp: F32T8/SP35 Ballast: Electronic Rapid Start	0.7	0.87	203	13893.89	41102.1	138.53	2.79	5	1	1	4.51	11.51

Table 11. Comparison between Simple Payback Analysis and Life Cycle Cost of Case 2: The Taubman Company

No of Alter-native	DESCRIPTION	Simple Payback Analysis				LCC
		Power Saving ($)	Installation ($)	Replacement Lamp ($) (Saving/Cost)	Simple Payback Period (Yr)	Average annual cost
1	Fixture: 2P2GAX/340S36H	14146.56	33498.15	98.26	2.23	26325.84
	Lamp: F40T8/SP35					
	Ballast: Hi efficiency					
2	Fixture: 2P2GAX/340 S36 H	13981.44	44813.62	133.1	3.05	25778.04
	Lamp: F32T8/SP35					
	Ballast: Electronic Rapid Start					
3	Fixture: 2P2GAX-2U6S44H	8835.84	65699.42	223.1	6.84	41618.84
	Lamp : F40W/U6/WM					
	Ballast: Electronic Rapid Start					
4	Fixture: 2PAGAX-2U1-5/8S55I	10301.18	59922.2	139.73	5.37	35167.91
	Lamp: F40BX/SP35					
	Ballast: Electronic Rapid Start					
5	Fixture: 2P2GAX-440S46H	13893.89	41102.1	138.53	2.79	25196.49
	Lamp: F32T8/SP35					
	Ballast: Electronic Rapid Start					

4.3 Examples of Computer output

4.3.1. Inverse Square Method

The Inverse Square Method of calculating illuminance does not account for light reflected from walls and ceilings, and is based on the assumption that the luminaries is relatively small. It is generally used as a hand calculated technique to evaluate accent lighting or the light falling on a task. Calculations were done for the open office space shown in Figure 11. The computer output is given in Table 11.

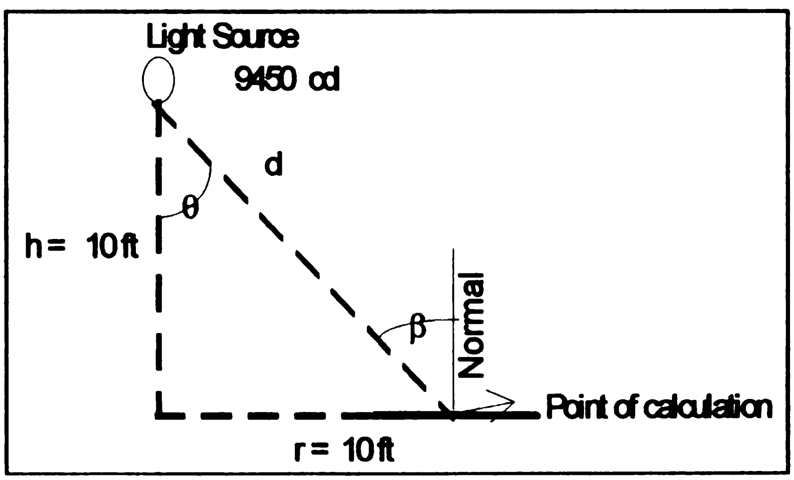


Figure 11. Example of Inverse Square Method

Table 12. Calculated Values for The Inverse Square Method

Inverse Square Method

CASE 3 OPEN OFFICE SPACE

DATA VALUES

Source = 9450.00 cd
Height = 10.00 ft
Horizontal = 10.00 ft

RESULT VALUES

Illuminance = 33.41 fc

GENERATE TABLE

Start Height 7.00 ft
Start Distance 8.00 ft

H	8	9	10
Illuminance 9450 cd			
7	48.81 55.1	52.13 44.6	55.01 36.4
8	45.00 52.2	48.37 43.3	51.34 36.0
9	41.63 48.7	45.00 41.2	48.01 34.9
10	38.66 45.0	41.99 38.8	45.00 33.4

4.3.2. Direct Illuminance Component

A row of three 2 x 4 ft, fluorescent luminaries, which has a luminance of 200 cd/ft^2, is mounted 10 ft above the work plane, and the distance to the point of calculation is 5 ft as shown in Figure 12. The computer output is given in Table 12.

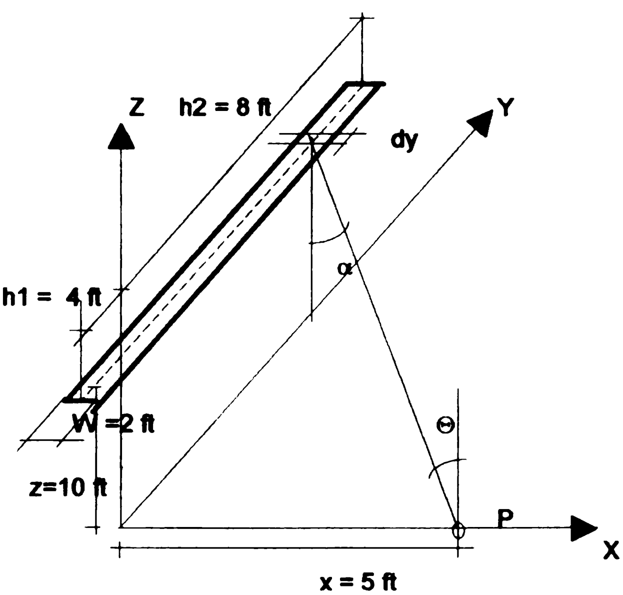


Figure 12. Example of Direct Illuminance Component

Table 13. Calculated Values for The Direct Illuminance Component Method

CASE 4 RENOVATION

DATA VALUES

Luminance	=	200.00 cd/ft²
H e i g h t	=	10.00 ft
Distance	=	5.00 ft
W i d t h	=	2.00 ft
Pivot length1	=	4.00 ft
Pivot length2	=	8.00 ft

RESULT VALUES

Illuminance	=	27.35 fc

TABLE

3	4	5
uminance	200	cd
23.20 50.9	29.74 41.9	35.54 33.6
20.56 44.9	26.57 38.4	32.01 31.9
18.43 39.6	23.96 34.7	29.05 29.7
16.70 34.9	21.80 31.2	26.57 27.4

4.3.3 Flat Rectangular Source Method

The illuminance produced by many large rectangular sources in architectural lighting is important. The computer program evaluated the illuminance using Flat Rectangular Source Method such as 6 ft. x 6 ft. windows, at the point of calculation P on a 6 ft. line perpendicular to one corner of the source, or in a 6 ft. plane parallel to the source as shown in Figure 13. The calculation values are given in Table 13.

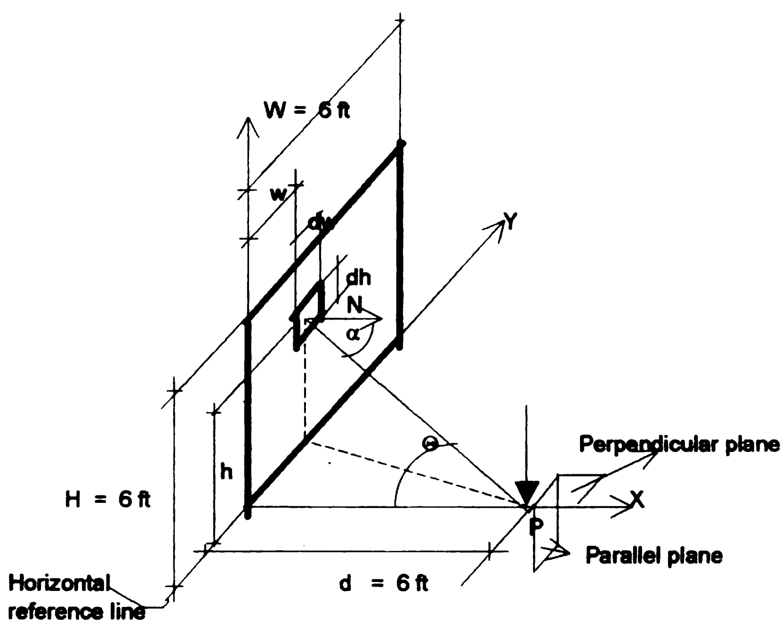


Figure 13. Example of Flat Rectangular Source

Table 14. Calculated Values for The Flat Rectangular Source - Parallel

CASE 5

DATA VALUES

Luminance	=	100.00cd/ft
Source Height	=	6.00 ft
Source Width	=	6.00 ft
Pivot Point	=	6.00 ft

RESULT VALUES

Illuminance	=	22.20 fc

TABLE

Start Height	3.00 ft
Start Distance	4.00 ft
Start Width	3.00 ft

Illuminance 100 cd/m2,width= 6 ft

H	4	5	6
3	53.13 26.7	59.04 20.9	63.43 16.6
4	45.00 29.3	51.34 23.9	56.31 19.6
5	38.66 29.9	45.00 25.4	50.19 21.4
6	33.69 29.4	39.81 25.7	45.00 22.2

4.3.4. S Curve, Renovation Lighting System Project

Jack Up, a contractor prepares a forecasting of his expenditure for a lighting system project. The contract sum is $ 300,000 and the contract length is 10 weeks. The computer program given assistance with his forecasting using the Department Health and Social Security expenditure method for forecasting. A computer output of the results are given in Figure 14.

```
Contract Sum     =$ 300000.00
Contract Length =          10 weeks


        CASE 6.  FORECASTING LIGHTING SYSTEM PROJECT

                                            Forecast  Difference
  1  --*                                       19431
  2  -----*                                    48308
  3  ---------*                                83970
  4  --------------*                          123754
  5  -------------------*                     165000
  6  -----------------------*                 205045
  7  ----------------------------*            241229
  8  -------------------------------*         270891
  9  ---------------------------------*       291368
 10  ----------------------------------*      300000
```

Figure 14. Example of S Curve

5. SUMMARY

The national Energy Policy Act (NEPA) of 1992 mandated energy efficiency. In the section related to lighting design, the minimum efficiency for selected electric lamps is defined, forces architects and designers to lower the energy consumption while delivering high quality lighting to an office. This will be accomplished using new innovative lamps, luminaires, controls, and design techniques that are now available.

Quality lighting not only determines "how well" or "how poorly" the workers see, but also how well they perform visual tasks. Light quality includes factors of uniformity and glare, which can change significantly within a room.

Uniformity is affected by the light distribution form luminaires and the amount of space between the luminaires. In order to avoid uneven lighting levels, the space-mounting height ratio from the manufacturer's test data should be followed.

Investment decisions on lighting projects are base on a variety of economic analyses. In this study discussed a simple payback analysis and a life cycle cost analysis were discussed. A simple payback analysis considers the lumens life, and lamp cost.

A Basic measure of lighting value was developed using the idea of cost per unit of light delivered. This method has been labeled the "cost of light" by GE Lighting. The "cost of light" was also evaluated using life cycle analysis. the reasons for this analysis are:

1. The lowest initial or first cost may appear the most efficient option in the short run, but over a long-time period it may not be the most cost effective option.
2. Life cycle cost analysis is broadly applicable. It can be applied to many different facility decisions, such as whether to accept or reject a lighting system option or what is the most cost-effective system.
3. A benefit of using life cycle cost analysis as a decision aid is that you must make an explicit estimate of the future.
4. Life cycle cost analysis like any procedure has its limits. It only can be used to compare functionally comparable projects. It does address qualitative factors that can affect decisions. It is not applicable to all aspect of uncertainty and risk that are associated with decisions concerning the future. However, there are other decision aids that supplement and support life cycle analysis. They address qualitative factors, uncertainty and risk.

A computer program, written using the QuickBasic language, was developed. This software incorporated calculations for lighting design using the equations given in the lighting literature with the economic options of the simple payback method, life cycle cost analysis, planning and forecasting.

The development of the software was the primary part of this study. The availability of data for lighting system design in Indonesia is not sufficient for obtaining good results. Many luminaire manufactures provide brochures with limited information. The available data is basic data and calculations are needed to obtain the design values such as the coefficient of utilization. The tabulated data available in some handbooks often con not be used because the data for some of the parameters is not available. The software developed for this study incorporated the basic data and calculates several of the parameters provided by the companies that manufacture lighting fixtures in the United States but are not provided by similar companies in Indonesia.

The individual components of the lighting calculations, such as the inverse square method and direct illuminance component method, were check against values given in tables. Sample outputs for these individual components are presented in the thesis. The analysis of an open space lighting system were done by hand and using the software to verify that the software performed the complete set of calculations correctly.

Two different open space office lighting system were analyzed. Five different design were proposed and analyzed for each. The lighting system selected by the weighting method that incorporated the lighting quality and the economic analysis seemed to be a reasonable selection in each case.

The analysis of an open space lighting system indicated that a triphoshor lamp such as T8/SP35 and an electronic ballast were the best selection. The effect of the longer life time for an electronic ballast was significant.

6. RECOMMENDATIONS

1. The computer software should be used to solve 10 to 20 more problems in order to validate its accuracy, to evaluate the user interfaces and determine if any other lighting calculations should be incorporated into the software.
2. Extend the computer software to include graphic layouts of the office space.
3. the calculated values given by the computer software should be validated with experimental data.
4. Further study on the optimal lighting system components under different project conditions is recommended.

GLOSSARY

Alternative	The different choices, propositions or methods by which objectives may be attained.
Candela (cd)	The international unit (SI) of lumious intensity. The term has evolved form considering a standard candle. Some time the term "Candlepower" is used to describe the relative intensity of source (see "Lumen").
Candle power (cp)	See "Candela".
Candle power Distribution Curve	A graphic presentation of the distribution of light intensity.
Coefficient of Utilization (CU)	A percent of initial lamp lumens that reaches the work plane as determined by surface reflectances, room shape (RCR) and fixture efficiency.
Color Rendering Index	The method that indicates how colors will look under a given source. A color rendering index (CRI) number is assigned to a light source based on its ability to make pigments look as they would under certain test sources when compared to other sources having the same color temperature.
Color Temperature	Apparent color temperature (or correlated color temperature) of a light source indicates its degree of warmth or coolness with the highter number being cool.
Cost effective	Estimated benefits (savings) from an energy conservation investment project are equal to or exceed the costs of the investment, where both are assessed over the life of the project.

Depreciation — Depreciation is the allocation of the original cost of a facility or equipment to those time periods in which the asset is used.

Discount rate — A rate used to relate present and future dollars. This is expressed as a percentage used to reduce the value of future dollars in relation to present dollars to account for the time value of money. It reflects the fact that dollars spent or received in the future are worth less than dollars spent or received in the present. The discount rate may be the interest rate or the desired rate of return.

Economic life — The economic life is defined as that period over which an investment is considered to be the lowest cost alternative for satisfying a particular need.

Efficacy — See "Lumens per watt"

Electromagnetic spectrum — An orderly arrangement of radiant energy by wavelength or frequency. In the visible spectrum 380 nanometers (violet) and 780 nanometer (red).

Equivalent uniform annual cost — The total of all costs for a given decision or alternative, expressed as a uniform annual equivalent over the years in the analysis life cycle.

Footcandle — The unit of illuminance equal to 1 lumen uniformly incident upon an area of 1 square foot; also equal to the illuminance at a point 1 foot distant from a 1 candela source. Light striking a surface.

Footlambert — The unit of luminance or brightness equal to 1 lumen uniformly reflected or emitted by an area of 1 square foot. Visual impression.

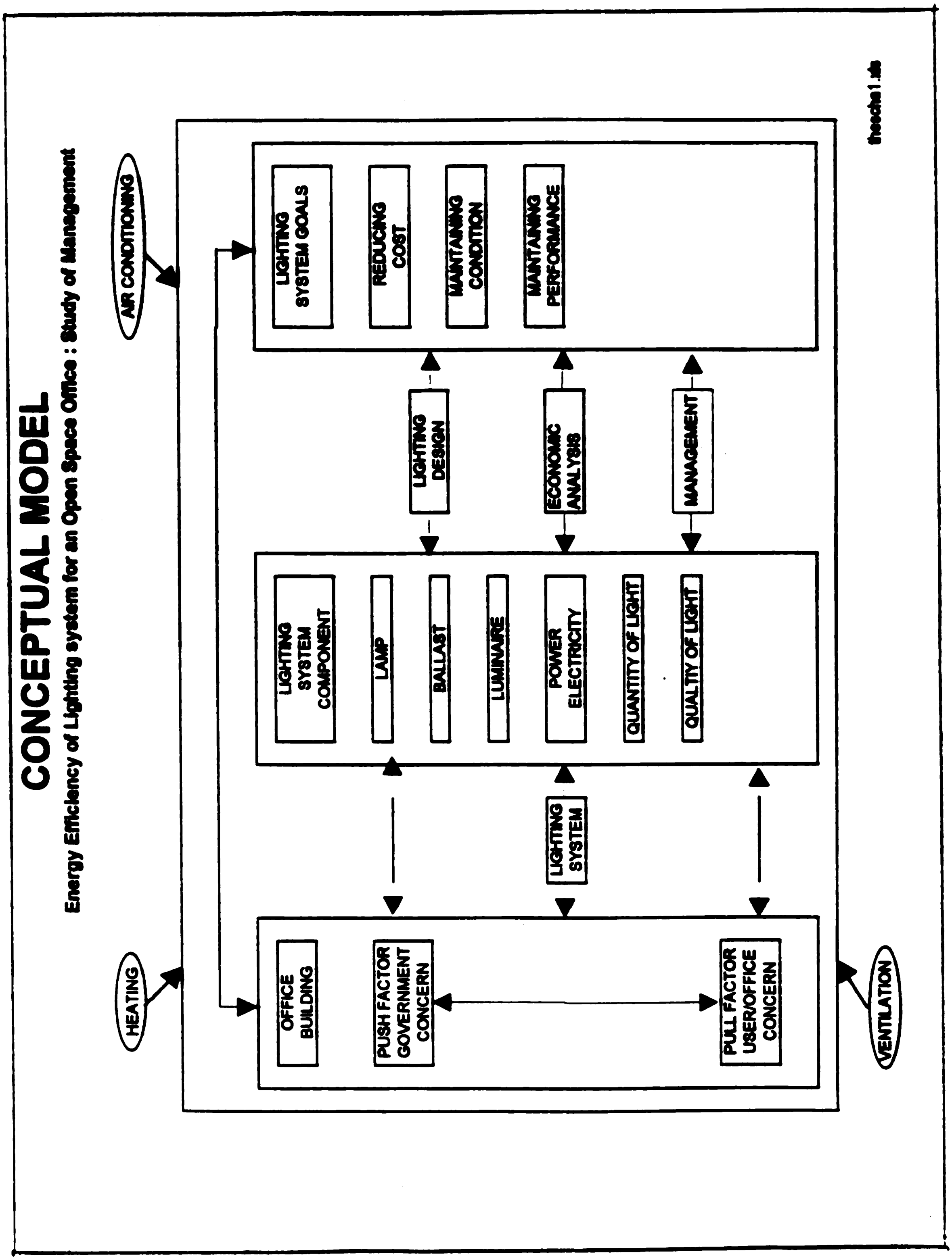
Future worth (Value)	The future value of a present amount, given the time value of money.
Initial capital investment cost	Costs associated with the initial planning, design and construction of a facility.
Interest rate	The interest rate represents the annual time value of money and is referred to as the discount rate.
Glare	Visual discomfort caused by excessive brightness; can be direct or indirect.
Illuminance (E)	The quantity of light (footcandles, lux) at a point on a surface.
Life cycle costing	Life cycle costing is a method of expenditure evaluation which recognizes the sum total of all costs associated with the expenditure during the time it is in use.
Light loss factor (LLF)	The product of all considered factors that contribute to a lighting system's depreciated light output over a period of time including dirt and lamp lumen depreciation.
Lumen	The international unit of luminous flux or quantity of light. If a uniform point source of 1 candela is at the center of a sphere of 1 foot radius which has an opening of q square foot area at its surface, the quantity of light that passes through is called a lumen.
Luminaire efficiency	The ratio of lumens emitted by a luminaire to those emitted by the lamp or lamps used.
Lumen per watt	A ratio expressing the luminous efficacy of a light source. Light out divided by power watt.

Luminance (L)	Practically, the brightness of an object: that which the eye perceives. Luminance of a surface is equal to: illuminance multiple by reflectance (see footlambert)
Lux	The SI (international system) unit of illumination: one lumen uniformly distributed over an area of one square meter.
Mounting height	Distance from the bottom of the fixture to either the floor or workplane, depending on usage.
Nanometer	A unit of wavelength equal to 10^{-9} meter
Payback period	The payback period is the length of time necessary to recover the initial investment of a project.
Present value	Present value is the concept that a sum of money invested today will earn interest. It is based on the premise that a dollar today is worth more than a dollar to be received in the future by the amount of interest it earns.
Reflectance	The ratio of light reflected from a surface to that incident upon it.
Room cavity ratio (RCR)	Takes into account length and width of room and height from the fixtures to the work plane.
Spacing to mounting height ratio	Ratio of fixture spacing to mounting height above the work plane. Sometimes called spacing criterion.
Time value of money	The time value of money is the difference between the value of a dollar today and its value at some future point in time if invested at a stated rate of interest.

Ultraviolet radiation	For practical purposes, any radiant energy within the range of 100-380 nanometers. Some wavelengths (180-220) produce ozone: Some (220-300) bactericdal; and (280-320) erythemal (reddens human skin); and others (320-400) cause secondary luminance (blacklight).
Veiling reflections	Effective reduction in contrst between task and its background caused by the reflection of light rays. Sometimes called reflected glare.
Visual comfort probability	VCP is a ratio of a lighting system expressed as a percent of people who when viewing from a specific location and in a specific direction find the system acceptable.
Visual task	The objects and details that must be seen to perform an activity
Work plane	The plane at which work is done and at which illumination is specified and measured. Unless otherwise indicated, this is assumed to be a horizontal plane 30 inches above the floor having the same area as the floor.

APPENDIX A

APPENDIX A


CONCEPTUAL MODEL
Energy Efficiency of Lighting system for an Open Space Office : Study of Management
AIR CONDITIONING
HEATING
VENTILATION
LIGHTING SYSTEM GOALS
REDUCING COST
MAINTAINING CONDITION
MAINTAINING PERFORMANCE
LIGHTING DESIGN
ECONOMIC ANALYSIS
MANAGEMENT
LIGHTING SYSTEM COMPONENT
LAMP
BALLAST
LUMINAIRE
POWER ELECTRICITY
QUANTITY OF LIGHT
QUALTIY OF LIGHT
LIGHTING SYSTEM
OFFICE BUILDING
PUSH FACTOR GOVERNMENT CONCERN
PULL FACTOR USER/OFFICE CONCERN

APPENDIX B

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE

1. Identify the visual task.

2. Refer to **TABLE A**. Determine the ILLUMINANCE CATEGORY for that task.

3. Refer to **TABLE B**. Select the ILLUMINANCE RANGE pertinent to the determined category.

4. Refer to **TABLE C**.

   A. Evaluate the TASK AND WORKER CHARACTERISTICS, select the appropriate WEIGHTING FACTOR for each.

   B. Add the weighting factors.

5. Determine the DESIGN ILLUMINANCE from within the range established in Step 3.

FOR CATEGORIES A THROUGH C:	
If the sum of the Weighting Factors (Step 4,B.) is:	Design for Illuminance by selecting the:
-2	Lowest Value
-1, 0 or +1	Middle Value
+2	Highest Value

FOR CATEGORIES D THROUGH I:	
If the sum of the Weighting Factors (Step 4,B.) is:	Design for Illuminance by selecting the:
-3 or -2	Lowest Value
-1, 0 or +1	Middle Value
+2 or +3	Highest Value

NOTE: TABLE D MAY BE USED TO CONSOLIDATE STEPS 3, 4 and 5

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APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

TABLE A: TYPICAL RECOMMENDED ILLUMINANCE CATEGORIES	
OFFICE/SCHOOL FUNCTIONS	
AREA/ACTIVITY	**ILLUM. CAT.**
CONFERENCE ROOMS	D
OFFICES	
General and private offices (see READING -)	
Lobbies, lounges, reception areas	C
Mail sorting	E
Off-set printing and duplicating	D
READING - Copied tasks	
Ditto copy	E
Micro-fiche reader	B
Xerography, 3rd generation and greater	E
READING - Electronic data processing	
CRT screens	B
Keyboard reading	D
READING - Handwritten tasks	
#2 Pencil and softer leads	D
#3 pencil	E
#4 pencil and harder leads	F
Ball-point pen	D
Handwritten carbon copies	E
Chalkboards	E
READING - Printed tasks	
6-point type	E
8- and 10-point type	D
Glossy magazines	D
Newsprint	D
Typed originals	D
Typed second carbon and later	E
Telephone books	E
EDUCATIONAL FACILITIES	
Classrooms (see READING -)	
Science laboratories	E
LIBRARIES	
Book stacks (vertical illumination) -	
Active	D
Inactive	B
Card files	E

NOTE: The above is only a portion of the complete listing in the IES Lighting Handbook, 1987 Abblication Volume.

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

TABLE A: (Continued)

INDUSTRIAL FUNCTIONS

AREA/ACTIVITY	ILLUM. CAT.
ASSEMBLY	
Simple	D
Moderately difficult	E
Difficult	F
Very difficult	G
Exacting	H
LOCKER ROOMS	C
MACHINE SHOPS	
Rough bench or machine work	D
Medium bench or machine work	E
Fine bench or machine work	G
Extra fine bench or machine work	H
MATERIALS HANDLING	
Wrapping, packing, labeling	D
Picking stock, classifying	D
Loading, inside truck bodies and freight cars	C
PLATING	D
PAINT SHOPS	
Dipping; simple spraying; firing	D
Rubbing; hand painting; finishing art; stencil; special spraying	D
Fine hand painting and finishing	E
Extra-fine hand painting and finishing	G
SERVICE AREAS	
Stairways, corridors	B
Elevators, freight and passenger	B
Toilets and washrooms	C
STORAGE ROOMS OR WAREHOUSES	
Inactive	B
Active - rough, bulky items	C
Active - Small items	D

NOTE: The above is only a portion of the complete listing in the IES Lighting Handbook, 1987 Application Volume.

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

TABLE B: ILLUMINANCE CATEGORIES & VALUES FOR GENERIC TYPES OF ACTIVITIES IN INTERIORS

Type of Activity	Illum. Cat.	Ranges of Illuminances		Reference Work-Place
		Lux	Footcandles	
Public spaces with dark surroundings	A	20-30-50	2-3-5	General lighting throughout work-place
Simple orientation for short temporary visits	B	50-75-100	5-7.5-10	
Working spaces where visual tasks are only occasionally performed	C	100-150-200	10-15-20	
Performance of visual tasks of high contrast or large size	D	200-300-500	20-30-50	Illuminance on task
Performance of visual tasks of medium contrast or small size	E	500-750-1000	50-75-100	
Performance of visual tasks of low contrast or very small size	F	1000-1500-2000	100-150-200	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	2000-3000-5000	200-300-500	Illuminance on task, obtained by a combination of general and local (supplementary lighting)
Performance of very prolonged and exacting visual tasks	H	5000-7500-10000	500-750-1000	
Performance of very special visual tasks of extremely low contrast and small size	I	10000-15000-20000	1000-1500-2000	

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

TABLE C: WEIGHTING FACTORS TO CONSIDER IN SELECTING SPECIFIC ILLUMINANCE WITHIN RANGES OF VALUES FOR EACH CATEGORY

- Assess the task and worker characteristics. Select the pertinent weighting factor. ADD the weighting factors. Apply that sum to the considered Illuminance Category in Table B and extract the appropriate illuminance value.

1. If the sum is less than or equal to -2, design for the lowest value.
2. If the sum is equal to -1, 0 or +1, design for the middle value.
3. If the sum is equal to or greater than +2, design for the highest value.

1. For Illuminance Categories A through C:

Room and Occupancy Characteristics	Weighting Factor		
	-1	0	+1
Occupants ages	Under 40	40-55	Over 55
Room surface reflectances*	Greater than 70 percent	30 to 70 percent	Less than 30 percent

2. For Illuminance Categories D through I:

Task and Worker Characteristics	Weighting Factor		
	-1	0	+1
Workers ages	Under 40	40-55	Over 55
Speed and/or accuracy**	Not important	Important	Critical
Reflectance of task background***	Greater than 70 percent	30 to 70 percent	Less than 30 percent

* *Average weighted surface reflectances, including wall, floor and ceiling reflectances, if they encompass a large portion of the task area or visual surround. For instance, in an elevator lobby, where the ceiling height is 7.6 meters (25 feet), neither the task nor the visual surround encompass the ceiling, so only the floor and wall reflectances would be considered.*

** *In determining whether speed and/or accuracy is not important, important or critical, the following questions need to be answered: What are the time limitations? How important is it to perform the task rapidly? Will errors produce an unsafe condition or product? Will errors reduce productivity and be costly? For example, in reading for leisure there are no time limitations and it is not important to read rapidly. Errors will not be costly and will not be related to safety. Thus, speed and/or accuracy is not important. If however, prescription notes are to be read by a pharmacist, accuracy is critical because errors could produce an unsafe condition and time is important for customer relations.*

*** *The task background is that portion of the task upon which the meaningful visual display is exhibited. For example, on this page the meaningful display includes each letter which combines with other letters to form words and phrases. The display medium, or task background, is the paper, which has a reflectance of approximately 85 percent.*

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE, Continued

TABLE D: ILLUMINANCE VALUES, MAINTAINED IN FOOTCANDLES, FOR A COMBINATION OF ILLUMINANCE CATEGORIES AND USER, ROOM AND TASK CHARACTERISTICS (FOR ILLUMINANCE IN LUX, MULTIPLY BY 10)

I. General Lighting Throughout Room

Weighting Factors		Illuminance Categories		
Average of Occupants' Ages	Avg. Room Surface Reflectance (percent)	A	B	C
Under 40	Over 70	2	5	10
	30-70	2	5	10
	Under 30	2	5	10
40-55	Over 70	2	5	10
	30-70	3	7.5	15
	Under 30	5	10	20
Over 55	Over 70	3	7.5	15
	30-70	5	10	20
	Under 30	5	10	20

II. Illuminance on Task

Weighting Factors			Illuminance Categories					
Avg. of Workers' Ages	Demand for Speed and/or Accuracy*	Task Background Reflectance (percent)	D	E	F	G**	H**	I**
Under 40	NI	Over 70	20	50	100	200	500	1000
		30-70	20	50	100	200	500	1000
		Under 30	30	75	150	300	750	1500
	I	Over 70	20	50	100	200	500	1000
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	C	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
40 to 55	NI	Over 70	20	50	100	200	500	1000
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	I	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	C	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	50	00	200	500	1000	2000
Over 55	NI	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	I	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	50	00	200	500	1000	2000
	C	Over 70	30	75	150	300	750	1500
		30-70	50	100	200	500	1000	2000
		Under 30	50	100	200	500	000	2000

* NI - not important, I - important, C - critical

** Obtained by a combination of general and supplementary lighting

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE, Continued

TABLE D: ILLUMINANCE VALUES, MAINTAINED IN FOOTCANDLES, FOR A COMBINATION OF ILLUMINANCE CATEGORIES AND USER, ROOM AND TASK CHARACTERISTICS (FOR ILLUMINANCE IN LUX, MULTIPLY BY 10)

I. General Lighting Throughout Room

Weighting Factors		Illuminance Categories		
Average of Occupants' Ages	Avg. Room Surface Reflectance (percent)	A	B	C
Under 40	Over 70	2	5	10
	30-70	2	5	10
	Under 30	2	5	10
40-55	Over 70	2	5	10
	30-70	3	7.5	15
	Under 30	5	10	20
Over 55	Over 70	3	7.5	15
	30-70	5	10	20
	Under 30	5	10	20

II. Illuminance on Task

Weighting Factors			Illuminance Categories					
Avg. of Workers' Ages	Demand for Speed and/or Accuracy*	Task Background Reflectance (percent)	D	E	F	G**	H**	I**
Under 40	NI	Over 70	20	50	100	200	500	1000
		30-70	20	50	100	200	500	1000
		Under 30	30	75	150	300	750	1500
	I	Over 70	20	50	100	200	500	1000
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	C	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
40 to 55	NI	Over 70	20	50	100	200	500	1000
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	I	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	C	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	50	00	200	500	1000	2000
Over 55	NI	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	30	75	150	300	750	1500
	I	Over 70	30	75	150	300	750	1500
		30-70	30	75	150	300	750	1500
		Under 30	50	00	200	500	1000	2000
	C	Over 70	30	75	150	300	750	1500
		30-70	50	100	200	500	1000	2000
		Under 30	50	100	200	500	1000	2000

* NI - not important, I - important, C - critical

** Obtained by a combination of general and supplementary lighting

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

ILLUMINANCE SELECTION PROBLEM #2

1. Define Visual Task, Area: General Office

Tasks:		CATEGORY
	Reading CRT screens	________
	Reading Xerography, 3rd generation	________
	Reading 6-point type	________

2. Select Illuminance Category: ______________

3. Define Illuminance Range: ______ ______ ______

4. Evaluate Task and Worker Characteristics:

CHARACTERISTICS	WEIGHTING FACTOR
Occupant Ages (20 to 55)	
Speed & Accuracy (Critical)	
Reflectance of Task Background (Greater than 70%)	
SUM	

5. Select Illuminance Level: ________

APPENDIX B

PROCEDURE FOR DETERMINING ILLUMINANCE (Continued)

ILLUMINANCE SELECTION PROBLEM #1

1. **Define Visual Task, Area: Office Lobby**

2. **Select Illuminance Category: ____________**

3. **Define Illuminance Range: ______ ______ ______**

4. **Evaluate Task and Worker Characteristics:**

CHARACTERISTICS	WEIGHTING FACTOR
Occupant Ages (20 to 80)	
Room Surface Reflectances (70/20/10) (Small Room W/High Ceilings)	
SUM	

5. **Select Illuminance Level: ________**

LIST OF REFERENCE

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