# A LECO SCREENING PROCEDURE FOR SURVEYORS

By

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## TABLE OF CONTENTS

Chapter Page

# LIST OF TABLES

## LIST OF FIGURES

## TERMINOLOGY

1. Coordinated Color Temperature (CCT)

   CCT describes the color of the light source, and the color of the light emanating from that source. For example, on a clear day, the sun appears yellow. The CCT (measured in degrees Kelvin) is a close representation of the color that a black-body would radiate at a certain temperature. Imagine a wire being heated. First it turns red (CCT = 2000K), as it gets hotter, it turns white (CCT = 5000K) and then blue (CCT = 8000K). Although a wire is different from a light source, in simple terms, CCT is a measure of the "warmth" of a light source. The lower the CCT, the "warmer" the source. A candle-light has a CCT = 1900K.

2. Color Rendering Index (CRI)

   CRI provides an evaluation of how colors appear under a given light source. The index range is from 0 to 100. The higher the number, the easier to distinguish colors. Generally, sources with a CRI > 75 provide excellent color rendition. Sources with a CRI < 55 provide poor color rendition. To provide a base-case, most T-12 Cool White lamps have a CRI = 62.

3. F32

   A four-foot T-8 lamp that is rated at 32 watts.

4. F40

   A four foot T-12 lamp that is rated at 40 watts.

5. T-8

   A type of lighting system which uses electronic ballasts and 32 watt lamps. A T-8 lamp is 1 inch in diameter.

6. T-12

   A type of lighting system which uses magnetic ballasts and 40 watt lamps. A T-12 lamp is 1.5 inches in diameter. Although some T-12 systems are available with electronic ballasts, this thesis uses T-12 to refer to magnetically-ballasted lighting systems.

7. Tandem Wiring
A wiring option in which a ballast is shared by two or more luminaires.

8. Time of Use Rate
An electricity consumption rate that changes throughout the day. For example, electricity may only cost $.05/kWh at 6:00AM. At 4:00PM, electricity may cost $.10/kWh.

9. Visual Comfort Probability (VCP)
A rating system for evaluating direct discomfort glare. This method is a subjective evaluation of visual comfort expressed as the percent of occupants using a space who will be bothered by direct glare from luminaires, or fixtures.

# CHAPTER I

# INTRODUCTION

In today’s cost-competitive, market-driven economy, facility managers are seeking technologies and methods to reduce expenses and environmental impact. Of all electricity conservation strategies, lighting energy conservation opportunities (LECOs), or lighting retrofits are most common and generally offer the greatest return on investment.

The willingness for facility managers to participate in lighting surveys and retrofits is evident by the growth of the Green Lights Program. Since it's founding in 1991, over 1,600 participants have joined the program. Through an intensive surveyor training program and technical support system, participants have saved a combined 1.1 billion kWh/year, worth $80 million/year. Due to reduced energy consumption, the annual avoided power plant emissions are estimated to be 1.4 billion pounds of $CO_2$, 11 million pounds of $SO_2$, and 5 million pounds of $NO_X$, the equivalent of removing over 130,000 automobiles from the road. (USEPA, 1995).

Recognizing the benefits of increased energy management and survey methods, O'Leary (1994) showed that the Department of Energy has not only increased its in-house energy management budget by 19.5%, but also allocated 30% of the new budget for surveys of facilities. A large percentage of these survey efforts are focused on identifying Lighting Energy Conservation Opportunities (LECOs). A LECO is any measure that reduces the annual amount of energy consumed by a lighting system.

Because the skill of the lighting surveyor has a dramatic influence on identification of LECOs, several lighting survey manuals have been developed to help facility managers conduct lighting surveys and retrofits. As lighting survey manuals focused on identifying nationally common LECOs, "standardized lighting surveys" were produced.

## The Problem Statement

Standardized lighting surveys are designed to identify the most common LECOs in facilities nation-wide. Typically, large amounts of data are collected on standardized survey forms and then the data is analyzed in hopes of identifying cost-effective LECOs. Because standardized survey forms may not allow surveyors to incorporate important site-specific concerns during the survey, an excess of data is collected on LECOs that are later determined to be economically infeasible. Conversely, standardized forms may not allow enough data collection for unique, feasible LECOs.

Standardized lighting surveys and retrofits may not be cost-effective for certain facilities. Poor cost-effectiveness may result when facilities have any of the following: low energy costs, low operational hours or high implementation costs. In these cases, facility-wide, standardized lighting initiatives are difficult to justify because the potential for identifying cost-effective LECOs is low.

Because a complex, facility-wide lighting survey and retrofit may overwhelm the capabilities of a small maintenance staff, it may be inappropriate for certain facilities. These types of surveys often recommend isolated, specialized systems which are difficult to maintain. If the lighting initiative appears to have a large maintenance cost/benefit ratio, facility managers may refuse to invest any time or money into lighting surveys, thereby foregoing cost-effective retrofits that may be present in parts of the facility. Therefore, there is a great need to make lighting surveys less intimidating.

Professional lighting surveyors, manufacturers and the U.S. government have produced comprehensive lighting retrofit computer programs to reduce the burdensome appearance of lighting surveys. Although these programs can reduce the number of calculations for the facility manager, the programs take time to learn and require massive amounts of data collection, post-survey data entry and analysis.

Because most computer programs dictate the "best" LECO strategy, fewer decisions are made by the surveyor during the actual survey. Surveyors are restricted to completing survey forms and are not as involved in the process of developing and evaluating LECOs. As a result, surveyor skills may be degraded by relying on standardized methods and computer programs to determine the "best" LECOs.

Because technological advances in the lighting industry are rapidly occurring, computer programs quickly become obsolete as new products become available. In addition, computer programs currently cannot incorporate important factors that affect lighting quality, including: glare, task lighting techniques, the impact of Visual Display Terminals and other aesthetic or site-specific considerations.

In summary, standardized lighting surveys and computer programs are time-intensive and may require the surveyor to collect data on economically infeasible LECOs. A more cost-effective survey procedure is needed. This need is greatest in facilities that do not have resources to commit to an extensive, standardized, facility-wide survey.

## The Purpose of the Study

*The purpose of this thesis is to develop an on-site LECO screening procedure for surveyors*. The screening procedure will not be a complete survey and evaluation manual. However, *a LECO Screening Tree will be developed to help the surveyor eliminate economically infeasible LECOs and improve the cost-effectiveness of the survey*. The LECO Screening Tree will be different from standardized methods because it helps the surveyor evaluate LECOs during the survey. Because economically infeasible LECOs would be identified and eliminated during the survey, surveyors using the LECO Screening Tree could spend the majority of their time on the LECOs with the most economic worth.

Because the LECO Screening Tree will place more emphasis on the survey, instead of post-survey analysis, factors affecting the lighting quality, retrofit costs and savings will be more accurately incorporated into the LECO analysis.

Most importantly, the on-site LECO Screening Tree will discard economically infeasible LECOs during the survey, thereby minimizing the amount of data collected and post-survey analysis.

## The Objectives of the Study

1. Develop a LECO Screening Tree to help surveyors quickly evaluate and eliminate economically infeasible LECOs.

2. To test and modify the LECO Screening Tree during a comprehensive lighting survey in an existing facility.

## Expected Outcomes

A LECO Screening Tree will be developed that will allow lighting surveyors to quickly evaluate the economic feasibility of potential LECOs. This tree will also provide surveyors with a qualitative list of parameters to "watch for" in developing the list of LECOs.

## Scope

Although the LECO Screening Tree will be developed from applications on the Oklahoma State University (OSU) campus, it will be useful at other institutions. However, every facility will have unique criteria and considerations which may affect the survey approach.

## Importance of the Study

A useful LECO screening procedure will assist surveyors by eliminating economically infeasible LECOs with minimal effort. The screening procedure will be most applicable at facilities with low potential for identifying cost-effective LECOs. At these facilities, standardized lighting surveys may appear too burdensome to initiate. The LECO Screening Procedure will reduce the amount of data collection on surveys and allow facilities with low potential for cost-effective LECOs a "middle ground" between doing nothing and conducting a time-intensive standardized survey.

## Contribution to the Field

The LECO Screening Tree is a contribution to the lighting survey process because:

- It incorporates multi-disciplinary factors into the LECO evaluation process. These factors are often overlooked in surveys designed by a manufacturer of a particular product or a professional in a particular field.
- It helps the surveyor assess factors affecting LECO feasibility during the survey, which allows surveyors to discard economically infeasible LECOs without extensive data collection and analysis.
- Influences the surveyor to think in an evaluative mode, rather than simply a survey-and-record mode.
- Teaches the surveyor to identify site-specific LECOs, which are often not included in standardized surveys designed to identify nationally common LECOs.

- Allows for a cost-effective survey to be completed in a facility where a standardized survey might not be appropriate.
- Sensitivity analysis will verify the logic of the LECO Screening Tree. By locating factors that have the greatest influence on LECO feasibility at the early stages of the LECO Screening Tree, the tree will be effective at removing the economically infeasible LECOs with minimal effort.

# CHAPTER II

# LITERATURE REVIEW

An overview of the literature related to the research objectives is presented in this chapter. This chapter is divided into five sections:

(1) Facilities where Standardized Lighting Surveys may not be Appropriate

(2) Limitations of Standardized Lighting Surveys

(3) Limitations of Lighting Retrofit Computer Programs

(4) The Need for a LECO Screening Procedure.

(5) Finding an Appropriate Facility for a Case Study

## Facilities where Standardized Lighting Surveys may not be Appropriate

Conducting standardized lighting surveys and implementing the resulting LECOs often leads to large-scale economic investments. However it may not be prudent to conduct an expensive survey in a facility that has low potential for identifying cost-effective LECOs. LECOs with poor cost-effectiveness often exist when facilities have low energy costs, low operational hours or high implementation costs.

Standardized surveys may also be inappropriate for facilities with relatively small maintenance staffs. These types of surveys often recommend isolated, specialized systems which are difficult to maintain. Facility managers are usually reluctant to invest in systems that require additional attention.

The following sections describe the conditions that cause LECOs to be economically infeasible.

### Facilities with Low Electricity Cost

If electricity costs are relatively low, the dollar savings from any LECO will also be relatively low. In this case, without additional incentives, facility managers may find it difficult to economically justify any electricity conservation measures. The low potential cost savings results in a low desire to conduct a lighting survey.

### Facilities with Low Operating Hours

If the annual operating hours of an existing lighting system are relatively low, the LECO won't have a large opportunity to save energy and dollars. This condition negatively impacts the cost effectiveness of any LECO.

### Facilities with High Implementation Costs

Standardized surveys often assume national averages for implementation costs. However, cost components such as material, labor and regulation compliance costs vary at each location. These fluctuations can have an impact on LECO cost-effectiveness, especially in facilities with low potential energy cost savings.

### Facilities with a Relatively Small Maintenance Staff

Standardized lighting survey and analysis manuals often assume that maintenance is a relatively available resource. In fact, fewer than half of U.S. commercial buildings receive regular maintenance. (Lovins, 1995). Even in well-staffed facilities, maintenance time and concentration may be difficult to obtain. Considering this perspective, the installation of complex lighting systems may overload the capabilities of the maintenance staff. Thus, there is less desire to survey the facility to identify complex, high-maintenance LECOs.

The following sections describe maintenance concerns that are often neglected or underestimated with standardized lighting surveys.

#### Time Allocation

Standardized survey manuals take time to read and understand. Often they are written by lighting designers or engineers who may use technical terms which are confusing to maintenance personnel. Although the Illuminating Engineering Society constructed the Lighting Energy Management Series 4 (LEM 4) with minimal text, it is a manual that contains all types of unique, highly technical terms. (IES, 1984). If the lighting survey appears to be burdensome, facility managers may not commit to it. This is especially true in facilities with low potential for cost-effective LECOs.

### Maintaining Inventories of Lighting Systems

The ability to inventory and maintain lighting systems can be a difficult task if multiple types of lighting systems are installed. Multiple re-lamping periods and multiple system lives can create confusion for maintenance attempting to group re-lamp one area at a time. If maintenance needs to make additional site visits to re-lamp or "fine-tune" special systems, such as dimmable fluorescent lighting systems, the labor costs may exceed the energy cost savings.

Standardized surveys rarely consider the opportunity cost of maintenance time. Maintenance personnel may have other projects and responsibilities that have higher economic importance. In facilities with low potential for energy cost savings, facility managers may not want to spend a great deal of time monitoring and "fine-tuning" a lighting system, if other maintenance concerns need attention.

Specialized Systems. Most lighting manuals prescribe specialized equipment or technologies to efficiently provide light for particular tasks. An example is dimmable ballasts. For areas that have sufficient daylight, dimmable ballasts can be used with integrated circuitry to reduce energy consumption during peak periods. As Xenergy, Inc. (1988) showed, large modern office buildings can shed 20-30% of the lighting load along the perimeter, with dimmable ballasts. However, shedding some of the lighting load along the perimeter may not reduce the building's total lighting load by a large percentage. Furthermore, applications of specialized technologies (such as dimmable ballasts) may be dispersed and isolated in several buildings.

Applying specialized technologies in isolated locations presents an inventory challenge for maintenance personnel. In many cases, maintenance costs may escalate as personnel spend more time attempting to identify the location of a system needing repair. If the specialized system and the malfunction are identified, corrective repairs may require special components, that are rare and expensive.

If maintenance cannot effectively repair the complex technologies, the systems will fail and occupant complaints will increase. The isolated, complex technology that appeared to be a unique solution to a particular lighting issue, is often replaced with a system that is easy to maintain.

Snapback Potential. In addition to the often eventual replacement of technologies that are difficult to maintain, well intended repairs to the system may accidentally result in "snap-back". "Snap-back" occurs when specialized or isolated technologies are accidentally replaced with technologies more common within the facility. For example, if dimmable ballasts represent only 10% of a building's total ballasts, maintenance probably won't stock them. When replacement is needed, the maintenance personnel will probably accidentally install a regular ballast.

## Limitations of Standardized Lighting Survey Procedures

Standardized lighting surveys were developed to identify common LECOs in facilities nation-wide. (USEPA, 1994) (USDOE, 1993). Due to the variety of facilities and potential LECOs, the standardized process involves collecting massive amounts of data on the existing lighting systems, and then analyzing the data to identify LECOs. Inevitably, certain facilities will have unique considerations that are not addressed by standardized survey forms.

Standardized survey forms were developed to ensure the surveyor was collecting as much information about the lighting system as possible. However, this data collection process requires a great deal of time. Standardized surveys often collect data on LECOs that are later determined to be economically infeasible. Conversely, important data for feasible LECOs may not be collected because it is not on the survey form.

With standardized large-scale surveys and post-survey analysis, important factors which affect the economic feasibility of LECOs may not be realized until after the survey.

This section is divided into two primary parts: Estimating Potential Energy Savings and Estimating Implementation Costs. Each section presents sample factors that can have an impact on the cost-effectiveness of particular LECOs. Often, these factors are overlooked during standardized surveys.

## Estimating Potential Energy Savings

Input power, energy cost and operational hours have a significant effect on the cost effectiveness of LECOs. Because energy costs can be determined exactly, the survey-dependent variables are input power and the annual operating hours of a lighting system. With the surveyor's bias to identify significant energy savings, he/she may make estimated guesses which influence the results.

### Input Power

Power measurements are simple to make, however many standardized survey manuals fail to require this step. Most surveyors assume that ballasts within the existing system are consuming the specified wattage. Manufacturer's specifications are based on laboratory tests, where ballasts are kept at optimal operating conditions. These conditions are often unrealistic in actual field applications.

In addition to differences between specified and actual input power, ballasts in luminaires may be over 10 years old. Estimates for input power on these ballasts are usually not included in recent manufacturers' specification guides, which give detailed information about new ballasts. Lepak (1995) found various input wattages as ballasts in existing lighting systems varied from 5-20 years old.

### Inaccurate Operating Hours

In an evaluation of a lighting retrofit program involving 150 sites, Lepak (1995) found that there was a significant difference between engineering estimates and actual energy saved. For example, annual operation hours for a particular lighting system were over-estimated by a factor of six. This type of error occurs when a great number of quick estimates are made over large areas, which is typical with broad-scope estimates of standardized lighting surveys.

### Daylight Influence

Another common oversight of surveyors who are quickly estimating a facility, is the neglect of potential daylighting of interior spaces that may already exist. The influence of daylight can reduce a lighting system's annual operation hours. Standardized lighting surveys are often completed at night, when surveyors don't notice that electric lighting may not be used during many days, or parts of days throughout the year when an adequate amount of daylight is incident on the space.

### Convenience To Turn Off Lights

Often surveyors looking for occupancy sensor applications may dismiss the possibility that the lights could be turned off regularly when the last person leaves the room. If manual light switches are located near the entry and exits of a room, energy conscious occupants may regularly turn off the lights when leaving. This occurrence reduces the annual operating hours, and cost-effectiveness of occupancy sensor applications.

## Estimating Implementation Costs

Most standardized lighting survey manuals provide extensive detail on estimating lighting energy savings, yet only briefly describe installation considerations. A common mistake in LECO evaluations is underestimating the real cost of implementation.(Boron, 1994) Factors influencing implementation costs are site-specific and require careful consideration. In addition to implementation costs, ongoing maintenance costs should be included in LECO evaluations.

The Survey Section of the Lighting Upgrade Manual (USEPA, 1994) describes several qualitative variables associated with estimating system performance and many quantitative variables associated with energy savings. However, the manual says little about the costs of replacing the lighting system. A short discussion of factors affecting these costs is found in the Evaluation Section, which is typically used after the survey. With this procedure, surveyors may need to return to a particular site to gather information affecting installation cost estimates. Often with large surveys, a return visit may not actually be made, and costs can be underestimated.

There may be reasons why lighting manuals do not provide extensive information on installation costs. Fraser (1992) reiterated the claim that the installation cost component is a small fraction of the life-cycle cost of lighting systems. Although this is generally true, the installation cost may not be a small percentage of the energy cost savings. In facilities with low energy costs and/or low operational hours, installation and maintenance costs can be a significant influence on LECO cost-effectiveness. Thus, the return on investment may be less than the facility-established minimum.

As new LECOs become more common and understood throughout the facility management arena, maintenance installation costs usually decrease over time as more cost-effective installation methods are utilized. Standardized lighting manuals assume that maintenance will be able to implement the LECO with minimal difficulty. However, if facility managers attempt to use inexperienced, in-house maintenance to complete a lighting retrofit, installation costs can go over budget. The following sections provide several examples of cost considerations that are often neglected with standardized lighting surveys.

### Access

Although standardized lighting manuals may prescribe the location of luminaires for minimal energy consumption, they may neglect the difficulty of access at certain locations. Difficult access to lighting systems may significantly increase the amount of time and cost to re-wire, re-lamp or replace a lighting system. Access to the lighting system for surveys and retrofits is made difficult by several factors: luminaire mounting height, ceiling type and plenum space (space between the dropped ceiling and the structural ceiling). These factors and many others are rarely included in many survey forms. (Spain, 1992) (USDOE, 1993)(Advance Transformer, 1993) (USEPA, Project Kalc, 1994).

Mounting Height. If mounting height is high, access to the luminaire may require the use of elevated platforms, scaffolding, and other devices. Special training may be required for maintenance personnel exposed to danger. As Boron (1994) states, "The height of the ceiling, whether or not it is sloped or flat is important, since a sloped ceiling requires taking extra time to adjust scaffolding or lift equipment while working in the space." These types of considerations are usually neglected in the LECO survey and evaluation process.

Ceiling Type. The access to certain parts of a lighting system (ballasts, electrical wires, junction boxes, etc.) may require temporary removal of part of a dropped ceiling. Because ceiling types vary, ceiling tile disassembly time requirements can vary from a few minutes to over thirty minutes per fixture.

Plenum Space. The amount of plenum space available significantly influences the access for maintenance and feasibility of many LECOs. This space may also be used for HVAC ducts, and other electrical conduit. If lighting systems are to be relocated, replaced or re-circuited, such measures will only be feasible if there is enough plenum space to contain all the necessary equipment and provide maintenance personnel enough space to maneuver.

Work Scheduling. Lighting retrofits requiring building modifications may distract occupants. Most lighting evaluations don't consider that some of the work will need to be done during off-duty hours, which may require overtime labor, and additional delays due to time constraints. Distractions occurring over long periods of time can reduce occupant productivity.

In addition to retrofit labor costs, ongoing labor costs may be difficult to estimate. IES (1987) recommended that "aggressive maintenance programs be developed", such as: frequently cleaning luminaires with reflectors to maintain illuminance levels. However these costs and the cost of occupant distraction are typically not incorporated into evaluations of LECOs. Usually these costs are relatively small compared to energy savings, except in facilities with low potential for identifying cost-effective LECOs.

### Difficult Removal of an Existing System

Surveyors following standardized manuals often assume that removing or retrofitting the existing lighting system is a trivial task. However, several factors can impact the amount of effort needed to remove the luminaires. Sample factors include: the weight of luminaires, mounting materials and the presence of asbestos in the ceiling tile, plaster or other material in contact with the lighting system.

Asbestos. A major loophole of most lighting survey and analysis guides is the absence of asbestos considerations. If removing a lighting system involves remediation work with asbestos, implementation costs will increase significantly. Because asbestos remediation costs will decrease the cost-effectiveness of a project, lighting retrofits involving asbestos should be examined carefully.

Work Scheduling For Asbestos Removal. If asbestos removal or a remodeling project is necessary to upgrade a lighting system, entire occupant spaces may need to be evacuated. This action will have a significant influence on production and costs. As discussed earlier, if over-time labor is needed, the potential for expenses to exceed budget limitations is high.

### High Maintenance Labor Cost Rate

Installation costs may be higher than standardized estimates if facility managers include employee benefits and other factors. On the contrary, maintenance costs may be lower than standard estimates, by using part-time employees to perform the installation. However part-time employees, like building contractors, may not have the same commitment to quality as full-time maintenance staff. Long-term employees tend to remember that they will have to repair the system if it is installed incorrectly.

### Other Site-Specific Costs and Considerations

There are numerous other site-specific costs which are often overlooked as surveyors proceed through buildings with standardized forms. Surveyors should learn about considerations unique to each facility before the beginning of the survey. With this approach, the surveyor can evaluate cost-effectiveness of LECOs during the survey and avoid collecting as much unnecessary information as possible. In addition, the surveyor can spend more time collecting data for unique, cost-effective LECOs, which may not be included on standardized forms.

## Limitations of Lighting Retrofit Computer Programs

Lighting retrofit computer programs were developed to help facility managers by performing calculations to make LECO evaluation easier. In the past few years, there has been a great number of programs developed to reduce the burden of LECO evaluation for facility managers. (Spain, 1992) (USDOE, 1993)(Advance Transformer, 1993) (USEPA, Project Kalc, 1994).

In an effort to incorporate important considerations affecting lighting retrofits, computer programmers have developed comprehensive lighting retrofit models. Model complexity is linearly related to the number of input data points. Most commercially available models at this time are very complex, incorporating hundreds of variables to evaluate almost any illuminated space. (USEPA, Project Kalc, 1994)

The EPA's Green Lights Program has developed several computer models, from simple to highly complex. Although the Green Lights Program (USEPA, PojectKalc, 1994), Spain (1992) and others have advocated simplicity in calculations and data analysis, little emphasis has been placed on making the survey process easier. In fact, some limitations of standardized lighting surveys can be amplified with the use of computer programs.

The following sections discuss some of the limitations of lighting retrofit computer programs.

### Time to Learn Computer Programs

Computer modeling programs take a long time to learn how to use. Many programs are not Microsoft Windows compatible, and some have user's manuals which are over forty pages long. (USEPA, PojectKalc, 1994) (DOE, 1993). Some programs even offer workshop training sessions to help users understand the program. (USEPA, PojectKalc, 1994). The problem is that many facility managers simply do not have the time to learn how to use new programs.

Assuming that a facility manager will allocate a certain amount of time for lighting surveys and retrofits, managers that spend time learning how to run a computer program will have less time to learn valuable survey techniques. The same concept applies to extensive data collection and entry.

### Data Collection

Adding to the data collection requirements of standardized surveys, lighting computer programs require many data inputs to properly evaluate LECOs. The process of data entry also adds to the amount of time required to complete the analysis.

There are simple lighting retrofit programs that do not require extensive training or data entry. (Advance Transformer, 1993)(Tucker, 1993). However as Tucker (1993) showed simple programs can have poor accuracy in economic evaluations and performance estimates. In any case, if computer modeling programs require training to use, and require a great deal of data entry and analysis, less time and emphasis will be spent on the actual survey.

### Surveyors' Involvement in LECO Evaluation

Because standardized survey forms and the use of computer programs for LECO evaluation are becoming popular, the surveyor is becoming less involved with the development and evaluation of LECOs. Facility-wide, standardized surveys and analyses are often undertaken as a group effort, with different personnel involved in surveying, data entry and evaluation. Kessel (1988) described the survey technique used at the University of California:

> "We developed a form to record survey data for every space in a building. . . . Ten engineering students were hired and trained to use the survey form. Five million square feet of occupied space in sixty campus buildings was surveyed in a period of approximately three months.
>
> . . . . . . . . . . . . . . . . . . . . . . . . .
>
> The forms for each building were entered into a computer as a data base file. . . . Once a building's data base was completed, analysis of the lighting could begin."

Although the University of California's lighting retrofit was successful at reducing electricity costs, the stringent use of standardized survey forms did not allow surveyors to exercise creativity to identify LECOs. In addition, because a computer program was used to determine the most efficient LECO, the surveyors were less involved in the decision-making process.

Because the surveyors were not involved in the LECO evaluation process, and they were only temporary employees, they probably were less concerned with the retrofit's long-term success.

Lindsay (1992) observed, "The key to properly evaluating the long-term implications of a lighting retrofit lies in a thorough understanding of the factors which affect the ongoing performance of the lighting study." Perhaps additional savings could have been possible at the University of California, if the surveyors were given survey flexibility and more involved in the analysis of LECOs.

## Computer Programs Can't Incorporate all Factors Relative to the Visual Environment

Even with sophisticated simulation programs, all factors relating to the reality of the lighting retrofit cannot be duplicated. While describing his program, Spain (1992) stated, "Data categories and items are listed below with descriptions. Where appropriate, limitations or inherent assumptions are identified and references cited." In addition to the acknowledgment that programs can't include all factors, they cannot distinguish which factors are most important for a particular space.

### Lighting Quality

Sieben (1994) emphasized the importance of lighting quality in particular spaces. "Lighting quality considerations, especially in such an important national treasure as the White House, must be the dominant factor in the design of successful energy-efficient solutions."

The manual for the Lighting Technology Screening Matrix states its own limitations, "The actual design of a system requires more detailed consideration of tasks, layout, glare, comfort, color, maintenance, etc., before final selection of equipment be made". (USDOE, 1993, p. 1.2).

Because computer models are not subjective and cannot realize the factors that produce a quality lighting environment in all spaces, the facility manager who is computer program dependent may receive a lighting retrofit that actually reduces lighting quality.

### Energy Savings and Occupant Performance

As Selkowitz (1986) stated, "Buildings are not built to save energy; they are built to convert energy and other physical resources to produce a useful output." Lighting quality has a significant impact on occupant visual comfort and productivity. Occupant comfort and performance are worth more than energy savings. Because annual lighting costs range from \$.50-\$1.00/ft$^2$, and annual labor costs range from \$100-300/ft$^2$, a small change in worker productivity easily overshadows any energy savings. (USEPA, Green Lights Workshop, 1994).

Wilkins (1989) showed that good lighting quality can decrease the number of reported headaches and incidence of eye strain. However, computer programs will recommend the retrofit with the greatest savings. Considering the impacts of current survey and retrofit procedures, Wilkins (1993) stated, "energy efficiency, therefore may or may not create visual comfort and improved health, depending on the way the energy savings are achieved."

### The Visual Display Terminal Environment

As visual display terminals (VDTs), or computer monitors, became popular in office spaces, new challenges were created for lighting designers to produce an environment with good visual comfort. Reed (1987) found in one study that 40% of office workers complained about lighting. Since that study, computers have become even more common in offices, and it is a safe assumption that VDTs will continue to expand and penetrate other visual environments.

To address VDT issues, the Illuminating Engineering Society developed a guide titled "Recommended Practice for Lighting Offices Containing Computer Visual Display Terminals". (IES, 1989). However, to the average facility manager, this publication may be difficult to understand, and computer programs have not yet incorporated these methods into the evaluation process.

Computer programs may not ever be able to completely incorporate VDT concerns, due to the subjective nature of potential solutions. Ford (1990) showed that VDT screen glare conditions are more difficult to evaluate and mitigate, because VDT reflections change from workstation to workstation.

## Programs are Often Focused on Re-design

Generalized room illuminance models and power limit programs typically prescribe re-designing the entire lighting system. In many cases, re-design and remodeling produces a lighting system that consumes the least amount of energy. However this is a complicated procedure that must incorporate VDT considerations and other factors. Often several important factors are neglected. If facility managers had an unlimited budget, they could periodically remodel rooms and utilize task lighting techniques. However, these measures may not be cost effective if potential savings are less than potential costs.

Completely redesigning a lighting system to suit a particular office arrangement may also limit the flexibility for future changes of the system. Because the visual tasks and needs of office spaces have changed significantly during the past few years, facility managers may deem it short-sighted to customize lighting to an existing office plan.

## Computer Program Useful Life

Finally, considering the rapid advances in lighting technology, lighting retrofit computer programs quickly become obsolete as new products and methods become available.

## The Need for a LECO Screening Procedure

Standardized lighting surveys and computer programs advocate collection of massive amounts of data. Due to the constraints of facilities with minimal maintenance personnel and/or facilities with low potential for cost-effective LECOs, a more efficient survey procedure is needed.

Fetters (1990) stated, "savings are substantially affected by information collected during the survey." Therefore, if LECOs could be evaluated and eliminated on-site, a more accurate evaluation will be made. In addition, data from economically infeasible LECOs would not need to be collected. The reduction of data collected would reduce the amount of time spent on the survey and reduce post-survey analysis. Thurston (1994) described this process as the "Decision-Analytic Approach", because it narrows the number of possible alternatives and identifies the best LECOs.

The development of an on-site LECO screening procedure would not require abandonment of standardized survey methods or the use of computer programs. In fact, a screening procedure would improve the efficiency of standardized methods.

The benefits of an on-site LECO screening procedure are wide-spread. Improving the efficiency of lighting surveys will assist all types of facilities. If the survey process is perceived to be easier, more facilities will commit to lighting surveys and LECOs.

## Finding an Appropriate Facility for a Case Study

The development of this screening procedure would require a case study for testing and analysis. The facility chosen should present parameters that challenge the ability of the screening procedure to effectively remove LECOs that would be economically infeasible. A suitable facility should have either low energy cost, low operating hours, high implementation costs, an understaffed maintenance department, or a combination of these factors.

Educational facilities typically have lower than average operating hours and lower than average concentration of workers. However, while these facilities have a relatively low gross energy consumption, they consume more energy per operating hour per worker than many other facility types. (Energy Information Administration, 1992).

Colleges and universities usually have a diverse variety of facilities: laboratories, offices, classrooms and dormitories. Each facility has its own level of energy intensity, and occupant use patterns can vary by season. Due to bulk energy purchasing, large institutions can often obtain low energy unit costs. Therefore, a large university would be a good selection to conduct a case study.

# CHAPTER III

# METHODOLOGY

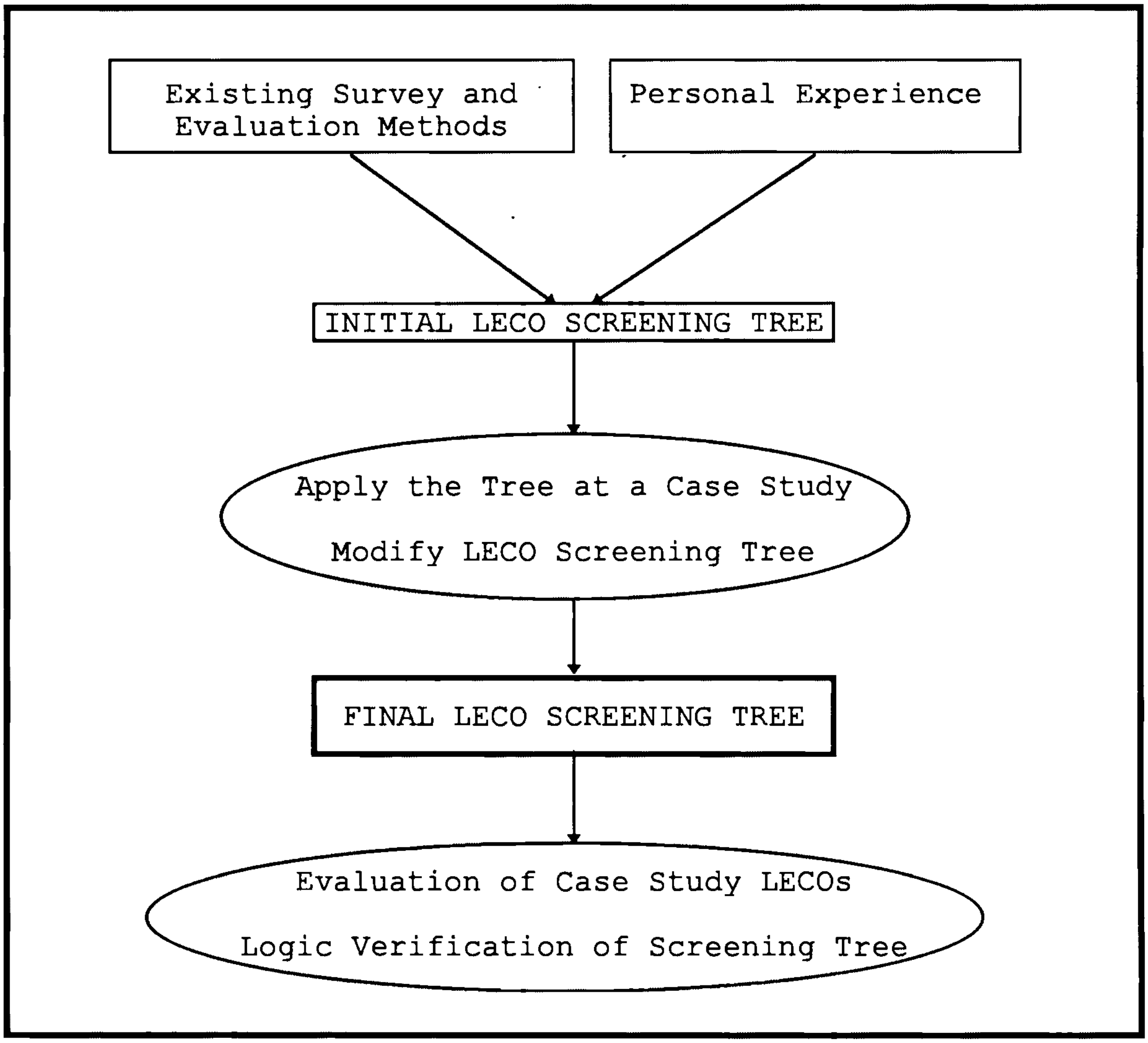
## Development of a LECO Screening Tree

Developing a LECO Screening Tree for surveyors was a complex task. Using a step-by-step process, an initial tree was developed using a combination of existing survey and evaluation methods along with personal experience from actual applications. After the initial LECO Screening Tree was developed, it was used in an actual facility as a case study.

During the case study, the LECO Screening Tree was repeatedly modified to incorporate additional factors affecting LECO feasibility. The final modifications incorporated site-specific considerations of the case study. The final tree eliminated all but eight LECOs, which were further analyzed to determine if the LECO Screening Tree was logical and effective at eliminating economically infeasible LECOs.

The primary steps for the development of the LECO Screening Tree are shown in Figure 3.1 and further described in the following paragraphs.

FIGURE 3.1 DEVELOPMENT OF THE SCREENING TREE



Utilizing existing survey and evaluation methods along with personal experience from actual applications, an initial LECO Screening Tree was developed. The initial tree added multi-disciplinary considerations to the standardized evaluation procedures. The primary difference was that the LECO Screening Tree located the evaluation techniques within the survey process.

The tree format was chosen because it allows the surveyor quick reference and guidance to evaluate LECOs. If the surveyor needs additional explanation, reference text for each branch of the tree is also available.

Because the LECO Screening Tree is not a complete survey method, but a LECO screening process, the short graphical format was effective at presenting the most important information in an easy-to-read format. The tree can be used in conjunction to standardized surveys to reduce the amount of data collection.

## Applying the LECO Screening Tree in a Case Study

Once formulated, the LECO Screening Tree was applied and tested during a case study at Oklahoma State University (OSU). The case study involved an extensive lighting survey and analysis in eleven buildings at OSU, totaling over two million square feet. The selected buildings were some of the most intensively used buildings on campus. The entire survey and analysis was completed in four months by one graduate student working ten hours per week.

The survey identified numerous technologies, energy use patterns and types of visual tasks. Due to the variety of lighting systems at OSU, a broad spectrum of standardized LECOs were available. However, because OSU had relatively low energy unit costs, low operational hours and a limited maintenance staff, the potential for identifying cost-effective LECOs was low. Due to these conditions OSU was an excellent application for the LECO Screening Tree. The case study was also an excellent opportunity to validate the effectiveness of the LECO Screening Tree.

During the survey, the LECO Screening Tree was modified and optimized to work efficiently on the OSU campus. The modifications to the tree improved the ability of the tree to filter economically infeasible LECOs at OSU.

## Performing Sensitivity Analysis to Verify Logic of the LECO Screening Tree

After the OSU LECOs had been identified, a sensitivity analysis was performed to test the logic of the LECO Screening Tree. A sensitivity analysis reveals which factors have the greatest influence on LECO economic feasibility. A logical tree would be one that incorporates the most important factors into the early stages of the screening tree. The analysis and evaluation of the LECO Screening Tree is presented in greater detail within Chapter V.

# CHAPTER IV

# THE LECO SCREENING TREE

## Introduction

A Lighting Energy Conservation Opportunity (LECO) is any measure that can reduce the energy consumption of a lighting system, and thereby reduce energy expenses.

The LECO Screening Tree was developed to aid surveyors by eliminating economically infeasible LECOs during the survey, thereby minimizing the amount of data to be collected and evaluated. The tree helps the surveyor incorporate multi-disciplinary factors which affect the feasibility of each LECO. The tree is flexible and can incorporate site-specific factors which influence LECO feasibility.

The LECO Screening Tree is not a survey manual, but it can increase the efficiency that lighting surveys are conducted. The tree was developed primarily for use in existing facilities.

The LECO Screening Tree is actually composed of two separate decision trees: the Occupancy Sensor Tree and the

Source Upgrade Tree. Each tree represents a different type of LECO. The Occupancy Sensor Tree could also be titled "upgrading lighting controls tree". The surveyor can use one tree, or evaluate potential LECOs with both trees and pick the LECO type most appropriate. Under certain circumstances, both types of LECOs can be appropriate and implemented together.

## Choosing a Tree

The percentage of time that a space is occupied is the determining factor influencing which tree to use. Use the Occupancy Sensor Tree if an area is frequently vacant. Use the Source Upgrade Tree for areas that are occupied most of the time. If a decision cannot be made early, it is usually best to proceed through the Occupancy Sensor Tree first.

Perhaps even more important than determining which tree to use, there must be a sufficient amount of energy being used in order for a reduction to be possible. If the annual operating hours of a lighting system is low, most LECOs will not be economically feasible. For example, a closet light might only be on 100 hours per year. Because a source upgrade only saves energy (relative to the initial system) when it is on, 100 hours per year won't allow a new source to save much energy. An occupancy sensor would not be feasible because there simply aren't many hours to save.

Therefore, LECOs require a significant quantity of annual operation hours to be feasible.

Although the energy cost and financial information (such as interest rate) are not survey-dependent variables, they should be considered before the survey, because these factors can have dramatic effects on LECOs. In addition, these factors may favor a specific type of LECO. For example, utilities may offer rebates to facilities implementing source upgrades.

Although each tree helps the surveyor evaluate the feasibility of either installing occupancy sensors or upgrading the light source, a third option is to implement both types of LECOs. To estimate the cost-effectiveness of a LECO which involves a source upgrade and occupancy sensors, a more complicated analysis is necessary. First, add the implementation costs from both trees. Calculating savings involves two steps: use the Source Upgrade Tree with an adjusted Annual Operating Hours to incorporate the effect of the occupancy sensors. Then use the Occupancy Sensor Tree with an adjusted Input Watts per Fixture, to account for the increased efficiency of the new light sources. Add the savings estimates from both trees and divide by the combined implementation costs to yield simple payback.

## How to Use the Tree

Each tree is a structure of multiple screening levels. Each level presents factors that may influence LECO feasibility. Going from the top of the tree to the bottom, the tree branches and incorporates more detailed factors. As the factors increase in detail, there is less chance that they will apply to every LECO. However, the "A" level factors will influence almost every LECO.

For example, an "A" level factor, such as Savings, represents a major branch of the tree. The detailed factors affecting the importance of each major branch are found on the "B" levels and downward. An example of a "B" level factor would be the Annual Operating Hours. A lower level factor would be something that influences the Annual Operating Hours, such as Daylight Availability. Each factor on the tree is supported and further described by reference text, which is indexed according to tree level.

In addition to the "A", "B" and "C" level hierarchy, each level's decisions are prioritized. For example, on a particular branch, B1 should be considered before B2 and B3. This prioritization of factors can be customized for any facility by re-arranging the factors on the tree. However, the prioritization established in this tree was constructed and validated using the case study as discussed in Chapter V.

After a tree has been selected, proceed through the screening levels, one at a time. Consider all the "A" factors, then all the "B" factors, then all the "C" factors, and then all the "D" factors. The tree is structured so that the factors which usually have the largest influence on the feasibility are considered first. With this design, the tree will allow the surveyor to systematically identify factors that will severely impact the cost-effectiveness of a LECO.

After all relevant factors have been considered, the surveyor must decide whether he believes the LECO will be feasible. Although this is primarily a qualitative decision, the systematic nature of the tree can allow the surveyor to establish minimum requirements for implementing LECOs. For example, if a LECO satisfies the requirements for the Savings and Quality branches of the tree, yet has a slight uncertainty regarding the removal of the existing lighting system, the LECO would probably be feasible.

Because every facility will have its own set of factors that significantly influence LECO cost-effectiveness, the surveyor must develop a pass/fail criteria for each facility. With the LECO Screening Tree, important site-specific factors can be added to any part of the tree. All factors can be rearranged on the tree so that the most important factors are considered first.

Figure 4.1 shows the Occupancy Sensor Tree. Figures 4.1.1 through 4.1.3 present more detailed figures of each branch of the Occupancy Sensor Tree. Figure 4.2 shows the Source Upgrade Tree. Figures 4.2.1 through 4.2.3 present more detailed figures of each branch of the Source Upgrade Tree.

Following the figures is the reference text for each decision level. Two examples are provided, each presenting a "step-by-step" view of how each tree can be used.

Figure 4.1 Occupancy Sensor Tree

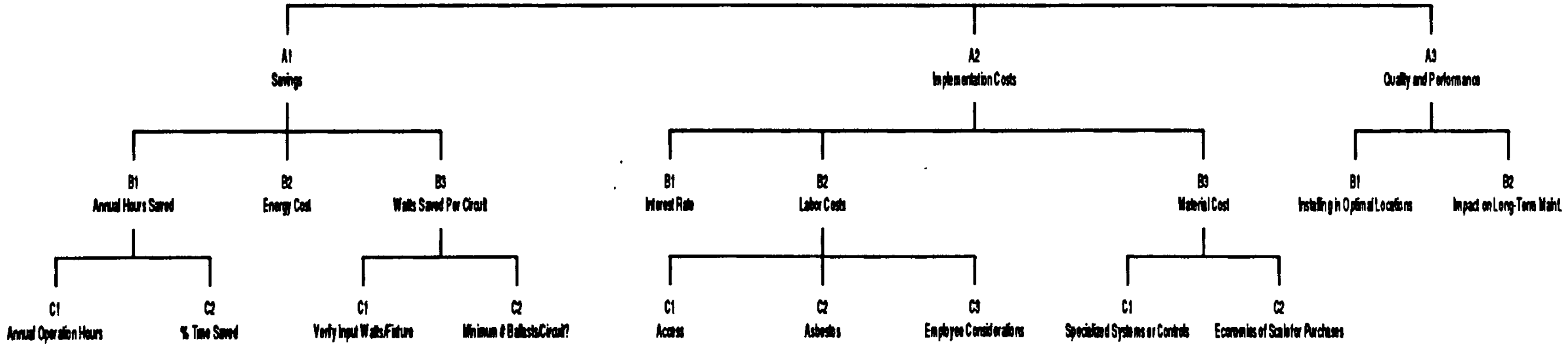


FIGURE 4.1.1 OCCUPANCY SENSOR TREE-
SAVINGS BRANCH

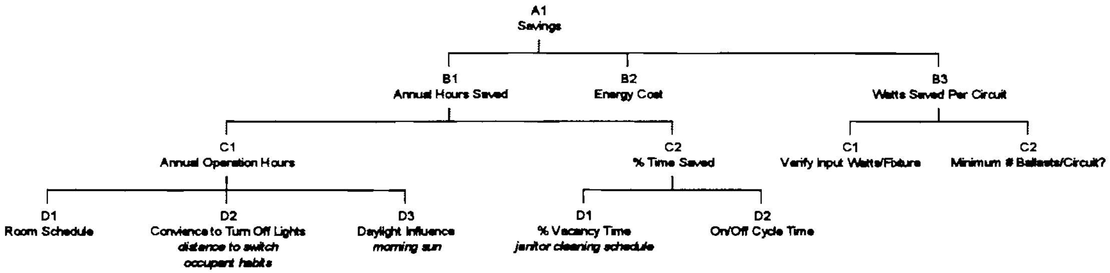


FIGURE 4.1.2 OCCUPANCY SENSOR TREE
IMPLEMENTATION COSTS BRANCH

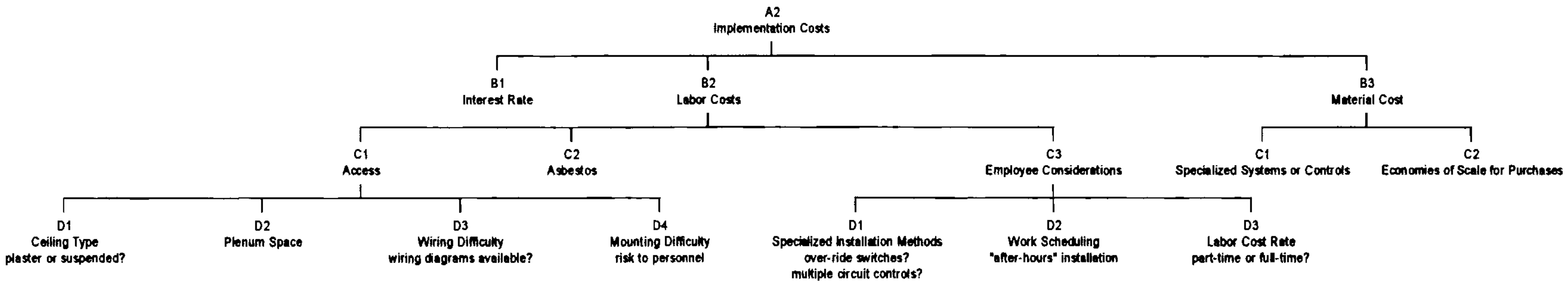


FIGURE 4.1.3 OCCUPANCY SENSOR TREE-
QUALITY AND PERFORMANCE BRANCH

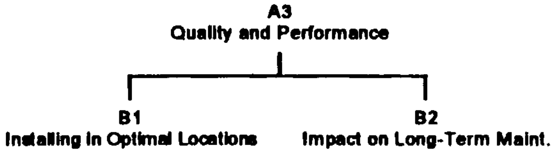


Figure 4.2 Source Upgrade Tree

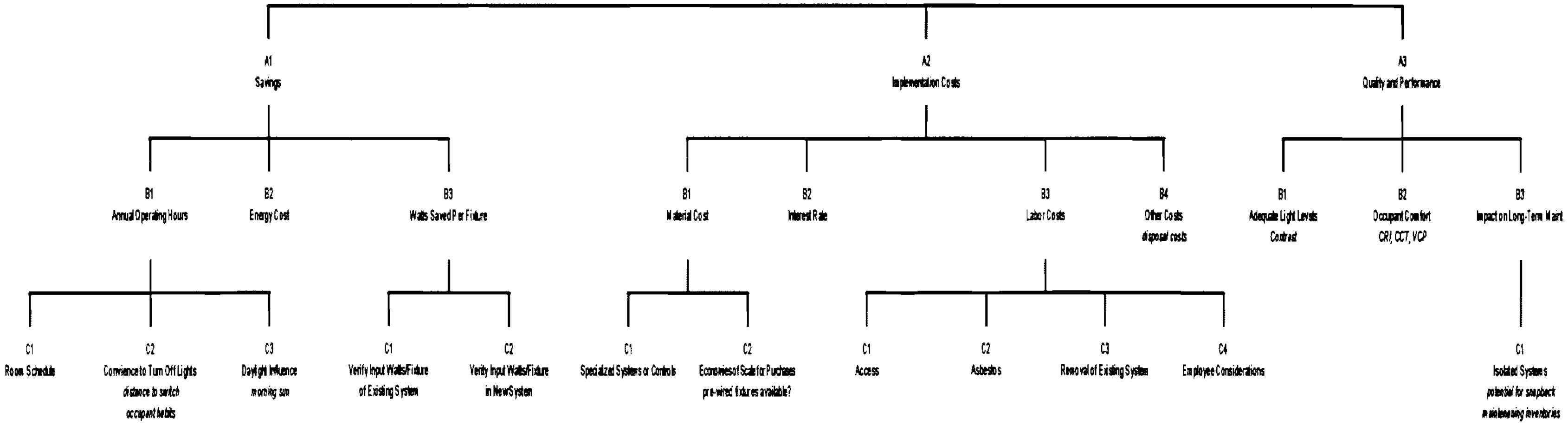


FIGURE 4.2.1 SOURCE UPGRADE TREE-
SAVINGS BRANCH

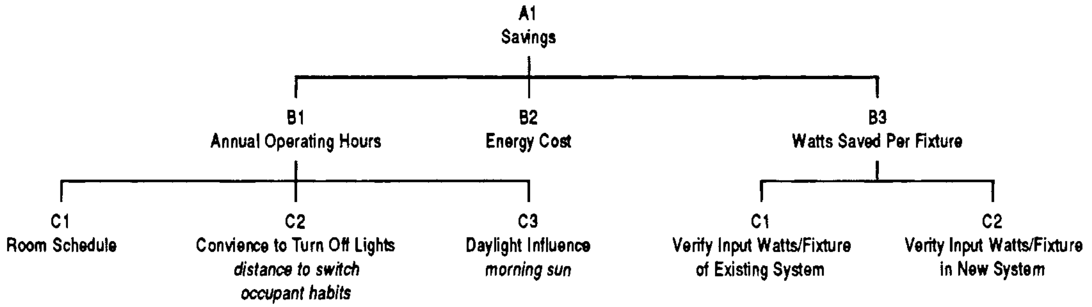


FIGURE 4.2.2 SOURCE UPGRADE TREE-IMPLEMENTATION COSTS BRANCH

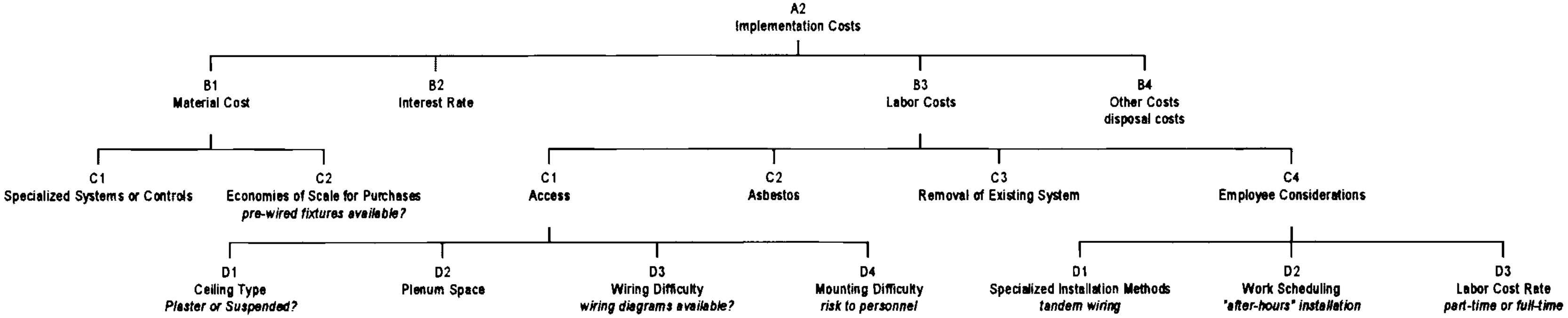
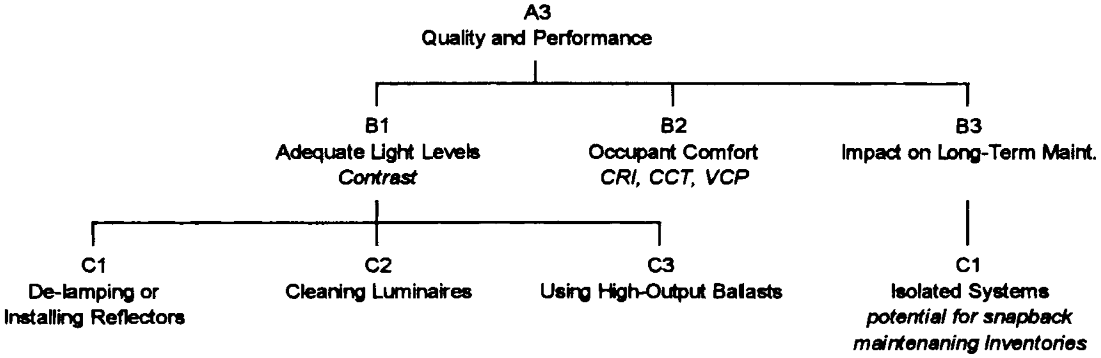


FIGURE 4.2.3 SOURCE UPGRADE TREE-
QUALITY AND PERFORMANCE BRANCH



## Reference Text For Decision Trees

## TABLE 4.1 REFERENCE TEXT FOR OCCUPANCY SENSOR DECISION TREE

TABLE 4.2 REFERENCE TEXT FOR SOURCE UPGRADE DECISION TREE

## Occupancy Sensor Tree

### A1 Savings

The annual energy cost savings is dependent on three factors: Annual Hours Saved, Energy Cost and Watts Saved per Circuit. If any of these factors are relatively low, the cost-effectiveness of the LECO will be small.

### A1B1 Annual Hours Saved

The actual annual hours saved by an occupancy sensor depends on the annual hours the system is in use and the possible percent time that the lights can be turned off.

### A1B1C1 Annual Operating Hours

Several factors can influence the actual annual operating hours of a system. However, such factors are often ignored, resulting in incorrect estimates and inaccurate annual savings.

### A1B1C1D1 Determine Schedule of Area

Identify the schedule of the area. Interview occupants and janitorial staff to identify the actual amount of time the lights are on. Considering post-workday cleaning schedules, the actual operating hours may be far greater than the typical 8am to 5pm working schedule.

### A1B1C1D2 Convenience to Turn off Lights

If it is easy to turn the lights off, there is a good chance that occupants may do so upon leaving. Look for switches that are near common exits. If switches are difficult to locate, or located such that the occupant must turn off the lights and walk to the exit in the dark, there is a better chance the occupant will leave the lights on when leaving the area.

Inspect the area just after an occupant has left. Interview occupants and estimate how often they actually do turn off lights.

### A1B1C1D3 Daylight Influence

If daylight is sufficiently available, occupants may turn off electric lights during part of the day. The surveyor should be aware of the possibility that occupants may forget to turn on their lights in the morning when enough daylight is available. Therefore, instead of lights being on from 8am to 6pm, they may only actually be on from 11am-6pm, which is a decrease of 30%. Consider these possibilities when estimating annual operating hours.

### A1B1C2 Percent Time Saved

The potential percent time saved is very important to the feasibility of occupancy sensors. If the percent savings is low, occupancy sensors may not be feasible. Because a surveyor is making educated guesses about the amount of time that could be saved, the surveyor must use all available information to make that estimate. Usually, the best sources of information are occupants.

The percent time saved is influenced by the amount of time a room is vacant with the lights on, and the frequency that the room is entered.

### A1B1C2D1 Percent Vacancy Time

Estimate the amount of time the lights are on when the room is vacant. Interview occupants and janitorial staff to determine if there is a large time period between the time the last occupant leaves and the cleaning staff enters.

Interview occupants about their own use patterns. For example, ask if a space is used primarily in the morning, afternoon or intermittently throughout the day. If intermittent, at what intervals? The most accurate method is to install occupancy meters in sample areas to determine true occupancy patterns. However, collecting data for a long period of time is usually not possible.

### A1B1C2D2 On/Off Cycle Time

The frequency at which occupants enter a room makes a difference in the actual percent time savings possible. Occupancy sensors save the most energy when applied in rooms that are not used for long periods of time. If a room is frequently used and occupants re-enter a room before the lights have had a chance to turn off, no energy will be saved. Therefore, a room that is occupied every other hour will be more appropriate for occupancy sensors than a room occupied every other minute, even though the percent vacancy time is the same.

In addition, installing occupancy sensors in a system that has rapid on/off cycles will decrease the life of lamps and ballasts.

### A1B2 Energy Cost

Although the energy cost is an important factor regarding LECO feasibility, it is not a survey dependent variable for occupancy sensors. Installing occupancy sensors cannot guarantee demand savings, which are common with source upgrade LECOs.

### A1B3 Watts Saved per Circuit

Because energy is power multiplied by time, it is important to determine the actual power (watts) saved per fixture. It is also important to determine the minimum number of watts saved per circuit if occupancy sensors are to be installed.

### A1B3C1 Verify Actual Input Watts per Fixture

Taking watt meter readings is the most accurate way to determine system wattage. However, this takes a great deal of time. Therefore, inspecting or sampling a sufficient number of fixtures of the same age and type is usually an acceptable method to determine input watts per fixture.

Identify when the lighting system was installed. Typically, all the fixtures in a particular installation will have the same components and roughly the same watt consumption rates.

### A1B3C2 Minimum Number of Ballasts per Circuit

For an occupancy sensor to be economical, it must turn off a certain number of fixtures, or ballasts. For example, it is usually not economical to install a sensor to control only one fixture. The material cost and labor cost do not increase linearly with the amount of fixtures on a occupancy sensor circuit. Based on Annual Hours Saved and Energy Cost, a sensor must control a certain number of fixtures to be economical.

After estimating the potential Annual Hours Saved for an area, calculate the minimum number of ballasts needed per occupancy sensor circuit to make a LECO feasible. After the minimum has been determined, any room that does not have the minimum can be eliminated, unless it can be easily re-circuited, so that more fixtures are turned off by the sensor.

## A2 Implementation Costs

After determining the annual savings from a LECO, the deciding factor is usually the implementation cost. The implementation cost of any LECO is composed of many factors which vary by facility.

### A2B1 Interest Rate

Although the interest rate on borrowed money is an important factor regarding LECO feasibility, it is not a survey dependent variable for occupancy sensors. However, if the interest rate is high LECOs which have short payback periods may be favored.

### A2B2 Labor Costs

Labor costs may vary widely and can enhance or destroy the feasibility of a LECO.

#### A2B2C1 Access

The ease that maintenance personnel can access lighting systems may have a significant influence on the time necessary to inspect, re-lamp or retrofit systems. Several factors can inhibit access and cause labor costs to escalate due to delays.

##### A2B2C1D1 Ceiling Type

If the ceiling is a suspended metal grid type with acoustical tile (or other material) that can be easily removed, access is easy. However, plaster ceilings, or ceilings with fixed tiles can significantly increase the time to remove and install systems. These types of delays can increase maintenance costs by over 200 percent.

### A2B2C1D2 Plenum Space

Occupancy sensor low voltage cable, electrical relays and other equipment require space. If the plenum space is small, maintenance will have a difficult time installing occupancy sensor equipment. Any ceiling plenum space with less than one foot height will cause delays in wiring and installation because access will be limited.

Access may be further limited due to HVAC ducts, insulation or other equipment that may be present in the plenum space. The surveyor should understand what obstacles in the plenum space will cause installation delays.

### A2B2C1D3 Wiring Difficulty

If electrical wiring is complicated, it may be difficult to identify the correct wires and systems to replace. Installing an occupancy sensor to control a specific set of isolated fixtures may become a very difficult task, even for an electrician.

If wiring diagrams are not available, the existing electrical wires may need to be mapped. This process could be significantly influenced by the complexity of the older system and access space for observation.

### A2B2C1D4 Mounting Difficulty

Mounting occupancy sensors in ideal locations may require the use of elevated platforms and special safety precautions may need to be taken. Any installation that poses a risk to maintenance personnel will result in increased labor costs.

### A2B2C2 Asbestos

If asbestos is present and needs to removed in order to implement a LECO, the costs may significantly overshadow the potential energy savings. Asbestos remediation costs and the cost of lost productivity from evacuation of a space will almost always make a LECO economically unjustifiable. Therefore, any LECO involving asbestos should be carefully considered.

### A2B2C3 Employee Considerations

The following factors influencing workers, installation schedules and labor cost rates can influence the overall labor cost.

### A2B2C3D1 Specialized Installation Methods

Many spaces may require special features that take extra time and labor costs to install. The installation of over-ride switches, multiple circuit controls and electrical relays can increase labor costs.

### A2B2C3D2 Work Scheduling

Scheduling installations to occur at one time can reduce costs by utilizing economies of scale. Because the retrofit process may distract occupants if done during normal working hours, scheduling the installation work during weekends or evenings may be required. After-hours labor may increase costs due to delays, interruptions and the over-time cost of labor. Depending on the facility, the scheduling of the installation work may affect the total implementation cost.

### A2B2C3D3 Labor Cost Rate

If specially trained electricians are needed to install a complicated occupancy sensor system, the labor cost rate may be high. The same principles apply when using full-time personnel and including employee benefits within the labor costs. Additional costs may result when over-time labor, (usually more expensive) is necessary. An alternative is to use part-time employees if the installation is not very complicated. However, part-time employees may not produce the same quality or efficiency as skilled electricians or full-time employees. In either case, the labor cost rate can have an impact on the installation cost.

### A2B3 Material Cost

Although not a survey-dependent variable, materials chosen to retrofit a lighting system can have a significant influence on LECO feasibility. In addition, the volume of purchases and the unit cost also influence LECO cost-effectiveness.

### A2B3C1 Specialized Systems or Controls

If specialized or custom systems are necessary for a particular LECO, material costs are likely to be high. The need for expensive components should be carefully considered.

### A2B3C2 Economies of Scale for Purchases

Discounts may be available if materials are purchased at one time. Therefore, if a great number of similar occupancy sensors are specified, the unit costs may decrease. If materials are ordered in bulk, it may be possible to purchase directly from manufacturers at lower unit costs.

## A3 Quality and Performance

Although rarely considered in standardized survey methods and computer programs, the lighting quality resulting from a LECO can significantly influence its desirability. Quality issues are difficult to quantify, but a small increase in occupant performance can easily pay for the cost of a lighting retrofit. Conversely, a small decrease in occupant performance can offset the energy savings from a lighting retrofit.

The amount of long term maintenance required for a LECO also may affect its feasibility.

### A3B1 Installing Occupancy Sensors in Optimal Locations

Occupancy sensor systems that will consistently operate properly should be installed in optimal locations. Along with considerations common in standardized surveys, the surveyor should make sure that false switching rarely occurs because it can distract occupants and degrade worker performance. Installing occupancy sensors in areas where their applications are marginal, may result in such occupant dissatisfaction that the occupancy sensors are disabled or removed.

### A3B2 Impact on Long-Term Maintenance

Some LECOs may require a more aggressive maintenance routine to maintain energy savings. However, LECOs should not be prescribed if maintenance workers are unwilling or unable to invest additional effort. If the maintenance department doesn't have the resources to repair a new lighting system or controls, the system will fail and occupants will complain.

For example, with occupancy sensors, the system may need to be frequently adjusted as office work patterns change. In addition, occupancy sensors that cause rapid on/off switching may reduce lamp life and actually increase the amount of re-lamping necessary. Although this extra cost would be subtracted from annual energy savings, the important issue here is that maintenance workers might not be able to frequently re-lamp areas or fine-tune and adjust sensors.

## Source Upgrade Tree

### A1 Savings

The annual energy cost savings is dependent on three factors: Annual Operating Hours, Energy Cost and Watts Saved per Fixture. If any of these factors are relatively low, the potential for cost-effective LECOs will also be low.

### A1B1 Annual Operating Hours

Several factors can influence the actual annual operating hours of a system. However, such factors are often ignored, resulting in incorrect estimates and inaccurate annual savings.

### A1B1C1 Determine Schedule of Area

Identify the schedule of the area. Interview occupants and janitorial staff to identify the actual amount of time the lights are on. Considering post-workday cleaning schedules, the actual operating hours may be far greater than the typical 8am to 5pm working schedule.

### A1B1C2 Convenience to Turn off Lights

If it is easy to turn the lights off, there is a good chance that occupants may do so upon leaving. Look for switches that are near common exits. If switches are difficult to locate, or located such that the occupant must turn off the lights and walk to the exit in the dark, there is a better chance the occupant will leave the lights on when leaving the area.

Inspect the area just after an occupant has left. Interview occupants and estimate how often they actually do turn off lights.

### A1B1C3 Daylight Influence

If daylight is sufficiently available, occupants may turn off electric lights during part of the day. The surveyor should be aware of the possibility that occupants may forget to turn on their lights in the morning when enough daylight is available. Therefore, instead of lights being on from 8am to 6pm, they may only actually be on from 11am-6pm, which is a decrease of 30%. Consider these possibilities when estimating annual operating hours.

### A1B2 Energy Cost

Because light source upgrades often result in demand savings, it is important to record if the lighting system operates during utility peak periods. If a Time-of-Use Rate is used by the utility, systems operating at different times of the day may have different potential cost savings.

### A1B3 Watts Saved per Fixture

Because energy is power multiplied by time, it is important to determine the actual watts saved per fixture.

The best method is to actually measure the input watts per fixture with a watt meter.

### A1B3C1 Verify Input Watts per Fixture of Existing System

Taking watt meter readings is the most accurate way to determine system wattage. However, this takes a great deal of time. Therefore, inspect or sample a sufficient number of fixtures of the same age and type is usually an acceptable method to determine input watts per fixture.

Identify when the lighting system was installed. Typically, all the fixtures in a particular installation will have the same components and roughly the same watt consumption rates.

### A1B3C2 Verify Input Watts per Fixture of New System

It is optimal to test the new system with the same watt meter used to collect data from the existing system, however this is often not feasible. Rather than just relying on manufacturer's test data on the new system, retrofit one new fixture as a trial installation. Measure the input watts per new fixture while it is subject to the same conditions as the existing fixtures.

This step could be done as a verification measure to predict accurate savings estimates.

## A2 Implementation Costs

After determining the annual savings from a LECO, the deciding factor is usually the implementation cost. The implementation cost of any LECO is composed of many factors which vary by facility.

### A2B1 Material Cost

Although not a survey-dependent variable, materials chosen to retrofit a lighting system can have a significant influence on LECO feasibility. In addition, the volume of purchases and the unit cost also influence LECO cost-effectiveness.

#### A2B1C1 Specialized Systems or Controls

If specialized or custom systems are necessary for a particular LECO, material costs are likely to be high. The need for expensive components should be carefully considered.

#### A2B1C2 Economies of Scale for Purchases

Discounts may be available if materials are purchased at one time. Therefore, if a great number of similar light fixtures or components are specified, the overall cost per unit may decrease. Often if systems can be purchased in bulk they can be pre-wired and ready for immediate installation. In addition it may be possible to purchase materials directly from manufacturers at lower unit costs.

### A2B2 Interest Rate

Although the interest rate on borrowed money is an important factor regarding LECO feasibility, it is not a survey dependent variable. However, if the interest rate is high, LECOs which have short payback periods may be favored.

### A2B3 Labor Cost

Labor costs may vary widely and can enhance or destroy the feasibility of a LECO.

### A2B3C1 Access

The ease that maintenance personnel can access lighting systems may have a significant influence on the time necessary to inspect, re-lamp or retrofit systems. Several factors can inhibit access and cause labor costs to escalate due to delays.

### A2B3C1D1 Ceiling Type

If the ceiling is a suspended metal grid type with acoustic tile (or other material) that can be easily removed, access is easy. However, plaster ceilings, or ceilings with fixed tiles can significantly increase the time to remove and install systems. These types of delays can increase maintenance costs by over 200 percent.

### A2B3C1D2 Plenum Space

Fixtures, electrical wires, relays and other equipment require space. If the plenum space is small, maintenance will have a difficult time installing the new system and its controls. Any ceiling plenum space with less than one foot height will cause delays in wiring and installation because access will be limited.

Access may be further limited due to HVAC ducts, insulation or other equipment that may be present in the plenum space. The surveyor should understand what obstacles in the plenum space will cause installation delays.

### A2B3C1D3 Wiring Difficulty

If electrical wiring is complicated, it may be difficult to identify the correct wires and systems to replace. Installing electrical wires to control a specific set of isolated fixtures may become a very difficult task for the electrician.

If wiring diagrams are not available, the existing electrical wires may need to be mapped. This process could be significantly influenced by the complexity of the older system and access space for observation.

### A2B3C1D4 Mounting Difficulty

Installing new lighting systems in ideal locations may require the use of elevated platforms and special safety precautions must be taken. Any installation that poses a risk to maintenance personnel will result in increased labor costs.

### A2B3C2 Asbestos

If asbestos is present and needs to removed in order to implement a LECO, the costs may significantly overshadow the potential energy savings. Asbestos remediation costs and the cost of lost productivity from evacuation of a space will almost always make a LECO economically unjustifiable. Therefore, any LECO involving asbestos should be carefully considered.

### A2B3C3 Removal of Existing Systems

With a source upgrade, sometimes it is necessary to replace the existing fixtures. However, many standardized survey instructions neglect the labor cost to remove the existing system. Existing systems are most likely to have rusted bolts, stripped threads and other factors that delay maintenance and increase costs. If the removal of existing systems requires special maintenance attention, extraction costs could easily double.

### A2B3C4 Employee Considerations

The following factors influencing workers, installation schedules and labor cost rates can influence the overall labor cost.

### A2B3C4D1 Specialized Installation Methods

Many spaces may require special features that take extra time and labor costs to install. The installation of multiple circuit controls, electrical relays or dimming control devices may require specialized electricians, which could increase labor costs.

Other considerations include properly estimating the time to install non-standard systems. For example, tandem wiring becomes a very labor intensive task, because the fixtures cannot be pre-wired for easy installation. Labor intensive tasks can double the estimated cost of implementation.

### A2B3C4D2 Work Scheduling

Scheduling installations to occur at one time can reduce costs by utilizing economies of scale. Because the retrofit process may distract occupants if done during normal working hours, installation work during weekends or evenings may be required. After-hours labor may increase costs due to delays, interruptions and the over-time cost of labor. Depending on the facility, the scheduling of the installation work may affect the total implementation cost.

### A2B3C4D3 Labor Cost Rate

If specially trained electricians are needed to install a complicated occupancy sensor system, the labor cost rate may be high. The same principles apply when using full-time personnel and including employee benefits within the labor costs. Additional costs may result when over-time labor, (usually more expensive) is necessary. An alternative is to use part-time employees if the installation is not very complicated. However, part-time employees may not produce the same quality or efficiency as skilled electricians or full-time employees. In either case, the labor cost rate can have an impact on the installation cost.

### A2B4 Other Costs

Every facility will have site-specific costs that affect LECO feasibility. Lost productivity can become a major cost component if occupants are displaced during a lighting retrofit. Because source upgrades typically require more time than occupancy sensors to install, there is a greater chance that upgrades will disrupt the normal occupant work schedules.

Ballast and lamp disposal costs may also become a factor. These costs vary widely between states.

## A3 Quality and Performance

Although rarely considered in standardized survey methods and computer programs, the lighting quality resulting from a source upgrade can significantly influence its desirability. Quality issues are difficult to quantify, but a small increase in occupant performance can easily pay for the cost of a lighting retrofit. Conversely, a small decrease in occupant performance can offset the energy savings from a lighting retrofit.

Lighting quality must not be sacrificed in a LECO where occupant performance is important. Interviewing the occupant to identify existing lighting quality problems, may allow retrofits to mitigate the problems, and improve lighting quality.

The amount of long-term maintenance required for a LECO also may affect feasibility.

### A3B1 Adequate Light Levels

During the survey, light levels should be measured and compared to desired illumination levels for a particular task. Any source upgrade should provide adequate or improved light levels or contrast for tasks. Several options are available to alter light levels: de-lamping, using reflectors, cleaning luminaires or using higher output ballasts. However, these discussion of the various options is beyond the scope of the LECO Screening Tree.

### A3B1C1 De-lamping or Installing Reflectors

De-lamping can be effective at reducing light levels. However, partially-lamped fixtures may be noticed by occupants and become a source of complaints. Maintenance personnel may accidentally re-lamp the fixtures that appear to have burned out lamps.

Energy savings from de-lamping does not include ballasts losses, which are usually 10-15% of the lighting system. Therefore, if de-lamping is completed, ballasts must also be disconnected to achieve full savings.

Reflectors improve fixture efficiency. The largest improvements occur in fixtures that contain only 2 lamps. Typically, reflectors are installed after 50% of the original lamps are removed. Although fixture efficiency is improved, light levels will decrease from a four-lamp fixture without a reflector.

The installation of reflectors will focus more light downward, which may cause problems in uniformity.

Due to these considerations, it is highly recommended that trial installations be completed for LECOs involving these types of retrofits. This is the only way to address lighting quality issues.

### A3B1C2 Cleaning Luminaires

To improve light levels without installing additional sources, many lighting survey manuals will recommend LECOs that require fixtures to be periodically cleaned. However, if maintenance personnel do not regularly clean the fixtures, light levels will decrease and lighting quality could be degraded.

### A3B1C3 Using High-Output Ballasts

To obtain desired light levels, ballasts with high output may be installed, but this can lead to luminaire glare, which affects lighting quality.

### A3B2 Occupant Comfort

The occupant visual comfort should be improved with a light source upgrade. The most important factors to consider involve color rendering index, color temperature, the visual comfort probability and the impact of visual display terminals. Because these factors vary with every illuminated space, the surveyor should be at least aware of these concerns and incorporate them into the design process.

### A3B3 Impact on Long-Term Maintenance

Some LECOs may require a more aggressive maintenance routine to maintain energy savings. However, LECOs should not be prescribed if maintenance workers are unwilling or unable to invest additional effort. If the maintenance department doesn't have the resources to repair a new lighting system or controls, the system will fail and occupants will complain.

### A3B3C1 Isolated Systems

The installation of isolated, specialized systems may create a difficult system to inventory. If inventory and routine maintenance are neglected the system could fail, or systems that consume more energy could be accidentally installed. The accidental installation of inefficient systems is called "snap-back".

## Sample Applications of the LECO Screening Tree

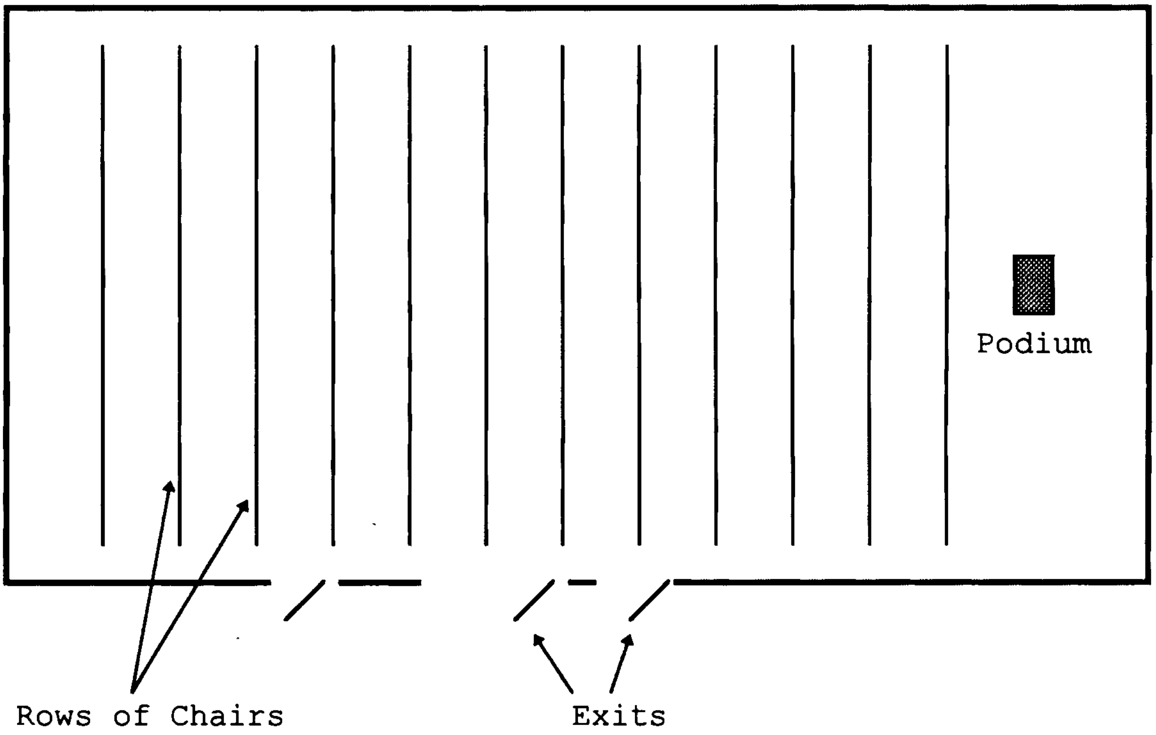
The following two examples present the observations and evaluations of a surveyor using the LECO Screening Tree during a lighting survey. The surveyor's notes provide the details on factors affecting each branch of the tree. Each relevant factor is referenced in the order in which it was evaluated. For simplicity of explanation, tree branches were evaluated one-at-a-time and non-survey dependent factors were omitted.

The text below explains the surveyor's observations on the relevant factors. The easiest way to follow the surveyor's notes is to keep track of the surveyor's progress on the LECO Screening Tree while reading the observations and evaluations described in the following text.

### Example for Occupancy Sensor Evaluation

The sample application is a medium-sized, 150 seat lecture hall, as shown in Figure 4.3. The room has no windows. Bolted to the sloped floor, rows of chairs cover the entire space up to the speaker's podium.

FIGURE 4.3 PLAN VIEW OF SAMPLE APPLICATION
FOR INSTALLING OCCUPANCY SENSORS



The hall has an F40 T-12 fluorescent lighting system, recessed into an 18′ high, suspended acoustical tile ceiling. The light levels are adequate and no lighting complaints have been reported. Because the occupancy is infrequent, the LECO under consideration is to install four occupancy sensors, which would cover the entire area. Therefore, the Occupancy Sensor Tree was chosen. The surveyor's notes will show how this LECO was screened.

## A1 EVALUATING THE SAVINGS BRANCH

### B1 The Annual Hours Saved

#### C1 Annual Operating Hours

The total annual operating hours that the lights are believed to be "on" can be influenced by factors D1 and D2.

(D1) The room's operational schedule was confirmed by a janitor to be 12 hours/day, 6 days/week, 45 weeks/year. This works out to be 3,240 hours per year.

(D2) The light switches are located at the speaker's podium, and away from the exits. People leaving the room must switch off the lights and walk in darkness to the exit. This event is not desired by occupants. Furthermore, people typically would not want to walk into a dark room and try to find the light switch. Thus, the lights are inconvenient to turn off, and are probably left on between classes. For these reasons, it is expected that the lights are left on for all of the room's scheduled operational hours of the day.

(D3) Daylight is not a factor, because the room has no windows.

#### C2 Percent Time Saved

(D1) As confirmed by the janitor, the room is only occupied 55%. Therefore 45% of the Annual Operating Hours are used when the room is vacant. Being conservative, occupancy sensors are estimated to save 35%.

(D2) The on/off cycle time is moderately long because each day, there is a 2 hour period between classes when the room is unoccupied. In addition, after the last class, a 3 hour period passes before the janitorial staff enters for cleaning. Because there are long periods between occupancy periods, the lights will be off for significant periods during each cycle.

### Energy Cost

This facility has a relatively high electricity cost of 8 cents per kilowatt hour. This will improve the cost-effectiveness of all LECOs.

### B3 Watts Saved per Circuit

(C1) A few measurements should be taken to determine the actual input watts per fixture. However, this measurement should only be made after the LECO has "passed" the screening procedure, and if there is a good chance the LECO will be economically feasible. Because this LECO was determined to be feasible, input watts per fixture was measured and recorded as 78 watts for each 2-lamp magnetic ballast.

(C2) There are 32 fixtures in the room. Each fixture has two magnetic ballasts. Thus, 64 ballasts would be controlled by the four occupancy sensors. 16 ballasts represent a significant amount of energy being saved per sensor, more than the pre-determined minimum of three ballasts per sensor.

*After evaluating the Savings Branch, the potential for savings is considered to be greater than average. The Annual Operating Hours and the Percent Time Saved are relatively large quantities. Because the each sensor controls many fixtures, the Watts Saved per Circuit is relatively large. The high Energy Cost will also improve the cost-effectiveness of this LECO.*

## A2 EVALUATING THE IMPLEMENTATION COST

### B2 Labor Costs

#### C1 Access

(D1 & D2) Ceiling type is suspended and plenum space is adequate, however wiring (D3) may be difficult because control wires will need to be "threaded" or "fished" through small spaces that exist in the ceiling-to-wall transition. Mounting occupancy sensors (D4) will require scaffolding to reach the 18′ high ceiling, which is above the rows of permanently mounted chairs. Note, if the chairs were moveable, perhaps an easier mounting procedure would be possible.

### C2 Asbestos

Fortunately, no asbestos was present in the ceiling or plenum space in this room.

### C3 Employee Considerations

(D1) As specified by professors, override sensors will need to be installed to enable manual control of the lighting system for visual presentations. Electrical relays will need to be installed so that signals from multiple sensors can be integrated into the control system. Therefore, these extra requirements may increase installation costs slightly.

(D2) Because the installation can be completed during the late afternoon after the last class, work scheduling will not present a major challenge. (D3) In-house labor can be used.

## B3 Material Costs

(C1) No specialized materials are required for purchase.

(C2) Although this installation only requires four occupancy sensors, similar models will be installed in other classrooms and economies of scale can be realized.

*After evaluating the Implementation Cost Branch, the Labor Costs may be slightly greater than average. This is because the Access and Wiring Difficulty may present complicated challenges, which will require extra maintenance time to resolve.*

## A3 EVALUATING THE QUALITY AND PERFORMANCE BRANCH

Potential for maintaining lighting quality (B1 & B2) is good because occupancy sensors can be installed in optimal locations, and false switching should be rare. Because the on/off cycle time is long, the need to re-lamp should not become more frequent, therefore long-term maintenance costs should not increase. Note that if on/off cycle time was less than one hour, re-lamping might be needed more often. Because the labor cost to re-lamp is relatively expensive, (due to mounting height & scaffolding), additional re-lamping costs could degrade the cost-effectiveness of this LECO.

*Considering all the branches, the LECO should be implemented. The costs may be a little high, but the watts saved per sensor and potential savings will be much greater than average. There should not be a potential reduction in lighting quality. A summary of this LECOs screening results is shown in Table 4.3.*

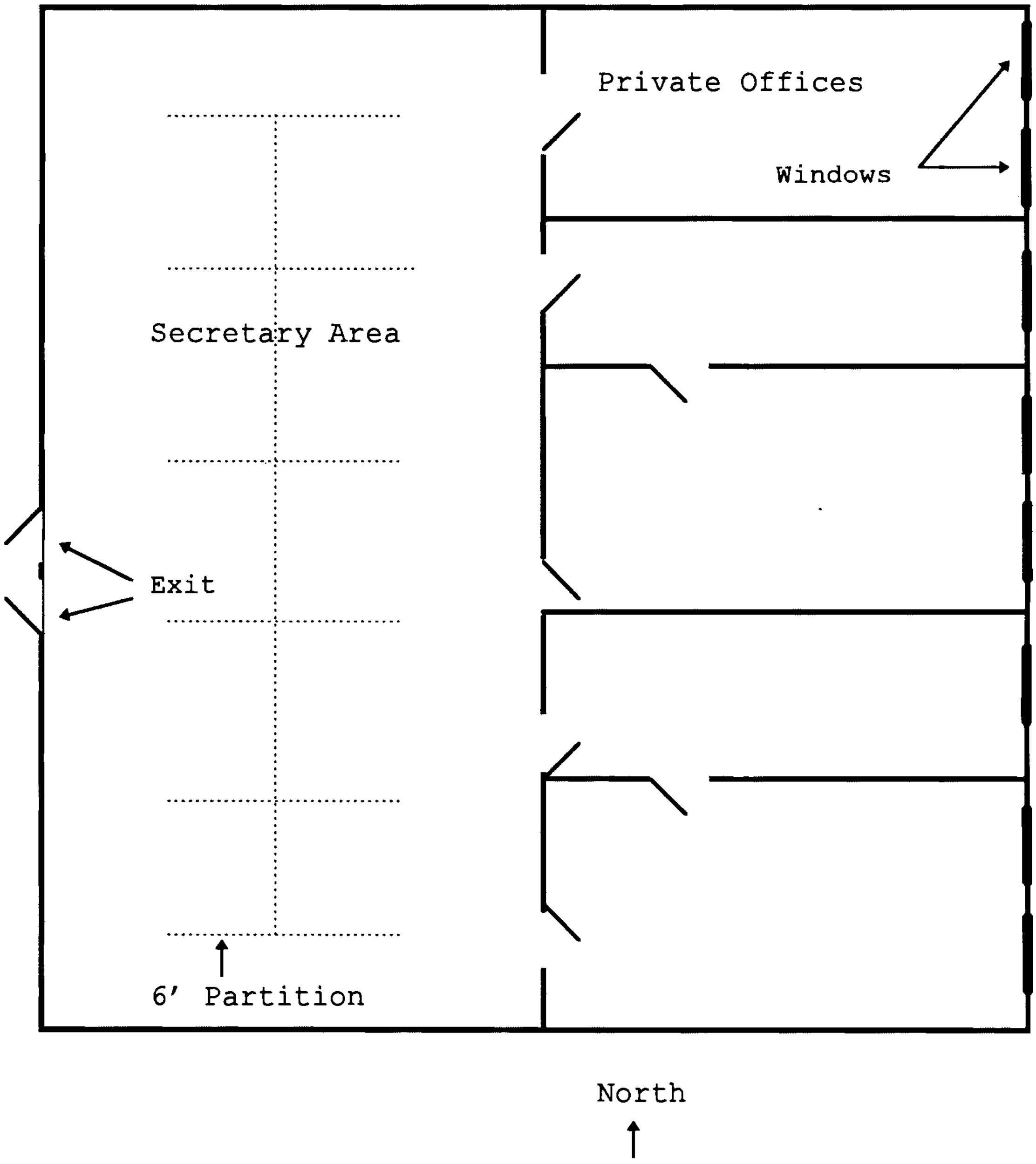
## TABLE 4.3 SUMMARY OF FACTORS THAT IMPACT COST-EFFECTIVENESS OF A SAMPLE OCCUPANCY SENSOR INSTALLATION

| Relevant Factors | Improves LECO Cost-Effectiveness |  | Reduces LECO Cost-Effectiveness |  |
|---|---|---|---|---|
|  | Significantly | Moderately | Moderately | Significantly |
| Annual Operating Hours | X |  |  |  |
| Percent Time Saved | X |  |  |  |
| Watts Saved per Fixture | X |  |  |  |
| Access |  |  | X |  |
| Employee Considerations |  |  | X |  |

Example for Source Upgrade Evaluation

The sample application is a large office room with east-facing windows. As Figure 4.4 shows, the office is equally divided into two sections.

FIGURE 4.4 PLAN VIEW OF SAMPLE APPLICATION FOR RETROFITTING T-12 TO T-8



The interior is open-plan, with several low partitions, creating individual work areas for secretaries. The area next to the windows is composed of fully-walled private offices. Each private office has at least one east-facing window.

The entire office space has an F40 T-12 fluorescent lighting system, recessed into an 8′ high, suspended acoustic tile ceiling. The light levels are adequate and no lighting complaints have been reported. Because the space is occupied 90% of the time that the lights are on, the LECO under consideration is to upgrade to a F32 T-8 lighting system. The potential for using dimmable ballasts along the windows should also be evaluated. Therefore, the Source Upgrade Tree was chosen. The following surveyor's notes will show how this LECO was screened.

## A1 EVALUATING THE SAVINGS BRANCH

### B1 The Annual Operating Hours

The total annual operating hours that the lights are believed to be "on" can be influenced by factors C1 through C3.

(C1) The room's operational schedule (including janitorial cleaning) is 10 hours/day, 5 days/week, 50 weeks/year. This works out to be 2,500 hours per year. The office is rarely occupied during evenings or weekends.

(C2) The light switches for the open-plan office are located near the main exit. Private offices have their own switches just inside each private office door. Occupants regularly turn the lights off when leaving at the end of the day.

(C3) Daylight is incident on all of the private offices during the morning, and occupants often leave lights off when sufficient daylight is available. After speaking to several occupants, they claimed to prefer natural daylight and did not turn lights on in the morning 40% of the time. Thus, the annual operating hours in the private offices may be much less than the open-plan area.

### B2 Energy Cost

Because this LECO would reduce the kW load in the building, demand charges would be reduced. However, this office is not billed for demand. In addition this facility has a relatively low electricity cost of 3.4 cents per kilowatt hour.

### B3 Watts Saved per Fixture

(C1) A few measurements should be taken to determine the actual input watts per fixture. However, this measurement should only be made after the LECO has "passed" the screening procedure, and if there is a good chance the LECO will be feasible.

(C2) Verifying the actual input watts of the new lighting system could be done after a few private offices are retrofitted as a trial installation. However, this is not a critical step during the screening procedure.

*After evaluating the Savings Branch, the potential for savings might be very low. According to the schedule, the Annual Operating Hours of the lighting system is only 2,500 hours per year. This is relatively low compared to other areas of this building which average 4,000 hours per year. In addition, the actual operating hours for the private offices may be less than the open-plan offices, due to daylight influence, the convenience to turn off lights and the energy-conscious habits of occupants.*

*Because the energy cost is relatively low, the energy cost savings from any LECO will also be relatively low.*

## A2 EVALUATING THE IMPLEMENTATION COST

### B1 Material Costs

(C1) If dimmable ballasts are specified for the private office, they would be unique because non-dimmable ballasts have already been specified for use throughout the remainder of this office and the entire facility. Because dimmable ballasts would not be purchased in volume, material prices could be high.

(C2) Economies of scale would be realized for non-dimmable electronic ballasts. If new fixtures were installed, they could be pre-wired, thus reducing maintenance costs. However, the dimmable ballasts and control components would be unique items.

### B3 Labor Costs

#### C1 Access

(D1 & D2) Ceiling type is suspended acoustical tile and plenum space is adequate. Wiring (D3) will be relatively easy because existing wiring diagrams are available that clearly illustrate the existing system, and in-house maintenance is familiar with the plenum conduit and ductwork. Mounting (D4) new fixtures, or retrofitting the existing fixtures will not be a major challenge because the ceiling is low and the acoustical ceiling tiles are easy to remove.

#### C2 Asbestos

Fortunately, no asbestos was present in the ceiling or plenum space in this room.

#### C3 Removal of Existing System

Because the existing lighting system is a very common type, removal should not require special techniques. Thus, the removal should not become a major cost factor.

### C4 Employee Considerations

(D1) Unless dimmable lighting systems are installed in the private offices, specialized installation methods will not be required. Dimming controls should be relatively easy to install due to the abundant plenum space. These systems would need to be "fine-tuned", which would take a few hours per room.

(D2) This installation would need to be completed during off-duty hours, to avoid distracting occupants.

(D3) In-house labor can be used, however it may only be available at an "over-time" price.

*After evaluating the Implementation Cost Branch, the Material Costs should be about average. Due to easy Access, the Labor Costs should be slightly less than average. However, if dimmable ballasts are installed, the Material and Labor Cost should increase.*

## A3 EVALUATING THE QUALITY AND PERFORMANCE BRANCH

### B1 Adequate Light Levels

(C1, C2 and C3) The new lighting system should provide similar light levels as the existing system. Therefore, adequate light levels should be attained.

### B2 Occupant Comfort

Potential for improving lighting quality is good because the T-8 system will improve the color rendition of the illumination. The Visual Comfort Probability could be improved if new fixtures are installed. If the dimmable systems are "tuned" properly, they should not distract occupants.

### B3 Impact on Long-Term Maintenance

The non-dimmable T-8 system will provide similar light levels with lamps that last as long as the T-12 system. Therefore the non-dimmable T-8 system should not negatively impact the long-term required maintenance.

The dimmable system will require occasional "tuning" and maintenance attention. The dimmable system for perimeter offices will be an isolated system, which will be more difficult to inventory and maintain.

*Considering all the branches, the LECO will not be cost-effective. The implementation costs may be moderate, but the potential energy savings are low. Because the Energy Cost is low, the energy cost savings would also be low. Because occupants already turn off lights when sufficient daylight is available, dimmable ballasts might not save a great deal of energy. Although the LECO Screening Tree would* *eliminate this LECO, the lighting quality would have been slightly improved, if the LECO was implemented.*

*A summary of this LECOs screening results are shown in Table 4.4.*

TABLE 4.4 SUMMARY OF FACTORS THAT IMPACT COST-EFFECTIVENESS OF A SAMPLE T17 TO T-8 RETROFIT

| | Improves LECO Cost-Effectiveness | | Reduces LECO Cost-Effectiveness | |
|---|---|---|---|---|
| Relevant Factors | Significantly | Moderately | Moderately | Significantly |
| Annual Operating Hours | | | | X |
| Energy Cost | | | | X |
| Material Cost | | | X | |
| Access | X | | | |
| Employee Considerations | | | X | |
| Impact on Long-Term Maintenance | | | X | |

# CHAPTER V

# DATA ANALYSIS OF THE CASE STUDY

To evaluate the effectiveness of the LECO Screening Tree, this chapter will present an analysis of the data collected from the case study at Oklahoma State University (OSU). Although OSU is a unique facility, requiring unique considerations to determine economic feasibility of LECOs, important factors affecting LECO cost-effectiveness will most likely be common at other facilities. Therefore, this data analysis should provide an indication whether the LECO Screening Tree will be effective at other facilities.

An effective screening procedure should filter out economically infeasible LECOs and allow only cost-effective LECOs to remain. The performance of the LECO Screening Tree was assessed by judging how early important factors that affect LECO feasibility were incorporated into the decision process. An optimal screening tree would consider the factors having the greatest impact on feasibility very early in the evaluation process. A poorly designed tree would consider important factors late in the evaluation process,

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An effective screening procedure should filter out economically infeasible LECOs and allow only cost-effective LECOs to remain. The performance of the LECO Screening Tree was assessed by judging how early important factors that affect LECO feasibility were incorporated into the decision process. An optimal screening tree would consider the factors having the greatest impact on feasibility very early in the evaluation process. A poorly designed tree would consider important factors late in the evaluation process, much like many standardized surveys, which advocate extensive data collection before any analysis is completed.

This chapter is divided into two major sections: The Case Study and Data Analysis. The Case Study Section describes the facility and the types of LECOs identified. The Data Analysis Section presents traditional economic evaluations of each LECO, and sensitivity analysis to determine which factors had the greatest impact on LECO economic feasibility.

## The Case Study at OSU

An extensive lighting survey and analysis was conducted in eleven buildings at OSU, totaling over two million square feet. The selected buildings were some of the most intensively used buildings on campus. The entire survey and analysis was completed in four months by one graduate student working ten hours per week.

Because OSU had relatively low energy unit costs, low operational hours and a limited maintenance staff, the potential for identifying cost-effective LECOs was low. Due to these conditions, OSU was an excellent application for the LECO Screening Tree. With the LECOs resulting from the case study, an opportunity existed to validate the effectiveness of the LECO Screening Tree.

## Data Analysis

### Traditional LECO Evaluation Methods

Several evaluation methods are available to compare LECO alternatives. The facility management personnel at OSU were receptive to evaluation using Simple Payback Period (SP) because it was the easiest to understand. However, Present Worth (PW) and Internal Rate of Return (IRR) are more complete evaluation methods, incorporating interest rates and the time value of money.

The Present Worth Index (PWI) is an additional LECO measurement of value. The PWI normalizes Present Worth over the implementation cost. (Riggs, 1977). The result is an economic indicator of Present Worth per dollar spent. The PWI was used in this thesis because it allows LECOs of various present worths to be compared and graphed.

Table 5.1 shows the Present Worth of each LECO in the OSU study at various discount rates. Simple payback, Internal Rate of Return and PWI (at i=10%) are also included. Equations 5.1 through 5.4 present calculations that were used to obtain the SP, PW, IRR and PWI for LECO #3. Similar calculations were used for the remaining LECOs.

TABLE 5.1 LECO ECONOMIC EVALUATION

| LECO # | Present Worth i= 0% | i =9% | i= 10% | i=12% | i=15% | SP (years) | IRR | PWI (i=10%) |
|---|---|---|---|---|---|---|---|---|
| 1 | $ 164,422 | $ 86,730 | $ 81,640 | $ 72,737 | $ 61,949 | 0.3 | 318% | 23.21 |
| 2 | $ 31,059 | $ 15,675 | $ 14,667 | $ 12,904 | $ 10,768 | 1 | 101% | 6.68 |
| 3 | $ 48,509 | $ 23,500 | $ 21,861 | $ 18,995 | $ 15,523 | 1.5 | 65% | 3.94 |
| 4 | $ 33,982 | $ 10,180 | $ 8,621 | $ 5,893 | $ 2,589 | 5.1 | 18% | 0.49 |
| 5 | $ 23,397 | $ 6,763 | $ 5,674 | $ 3,768 | $ 1,458 | 5.2 | 17.4% | 0.45 |
| 6 | $ 280,324 | $ 67,836 | $ 53,915 | $ 29,566 | $ 62 | 5.8 | 15% | 0.30 |
| 7 | $ 36,570 | $ 3,692 | $ 1,538 | $ (2,230) | $ (6,795) | 7.3 | 10.8% | 0.04 |
| 8 | $ 184,440 | $ (157,917) | $ (180,345) | $ (219,577) | $ (267,113) | 11.3 | 3.8% | -0.32 |

Notes:

LECO #1: Source Upgrade: Incandescent to Compact Fluorescent Lamps
LECO #2: Source Upgrade: Incandescent to Compact Fluorescent Lamps
LECO #3: Source Upgrade: Incandescent Exit Signs to Light Emitting Diode
LECO #4: Installing Occupancy Sensors in Classrooms
LECO #5: Source Upgrade: T-12 Lighting to T-8 Lighting
LECO #6: Source Upgrade: T-17 Lighting to T-8 Lighting
LECO #7: Installing Occupancy Sensors in Offices
LECO #8: Source Upgrade: T-12 Lighting to T-8 Lighting

SP = Simple Payback
IRR = Internal Rate of Return
PWI = Present Worth Index = PW/Implementation Cost

Planning Horizon = 15 years
Interest Compounded Annually
Equipment Salvage Value = 0

Background information on LECO #3:

Annual savings = $3,604
Implementation costs = $5,551
Planning horizon = 15 years
Salvage value = $0
Interest = 10% compounded every year.

To find the Simple Payback for LECO #3:

SP=(Implementation Costs)/(Annual Savings) [5.1]
SP=($5,551)/($3,604)
SP= 1.5 years

To find the Present Worth of LECO #3:

PW=-(Implementation Costs)+(Annual Savings)$(P|A_{10,15})$ [5.2]
PW=-($5,551)+($3,604)(7.6061)
PW= $21,861

To find the Internal Rate of Return of LECO #3, set Present Worth equal to zero and solve for the interest rate.

IRR: 0 = -(Implementation Costs)
+(Annual Savings)$(P|A_{IRR,15})$ [5.3]
IRR: (Implementation Costs)=(Annual Savings)$(P|A_{IRR,15})$
IRR: ($5,551)=($3,604)$(P|A_{IRR,15})$
IRR= 65%

To find the Present Worth Index (at i=10%) of LECO #3:

PWI= $PW_{i=10}$/(Implementation Costs) [5.4]
PWI= $21,861/$5,551
PWI= 3.94

If IRR is used incorrectly, it could indicate a different "best alternative" as compared to PW. To illustrate this phenomena, consider LECO #2 and LECO #6. Table 5.1 shows that at 10% interest, LECO #6 has a greater PW, but a smaller IRR than LECO #4. Although IRR for aggregate cash flow analysis is usually not used for determining the preferred LECO, this could confuse the facility manager, allowing him to choose the least economically attractive alternative.

For reasons stated above, and the ease of graphical analysis, the Data Analysis Section uses PWI for sensitivity analysis and evaluation.

## Sensitivity Analysis

A sensitivity analysis reveals the relative magnitude of change in LECO economic feasibility if one factor is altered. (White, 1989). The sensitivity analysis presented in this chapter shows the effects on a LECO's PWI when one factor was deviated from its original estimate while other factors were held constant. If PWI becomes negative, then the LECO becomes economically infeasible.

LECO #4 and LECO #6 from the OSU case study were chosen for sensitivity analysis because they had similar Simple Payback Periods, Internal Rates of Return and Present Worth Indexes. Because these two LECOs were different in technique, they collectively incorporated the most factors on the LECO Screening Tree. LECO #4 was to install occupancy sensors in classrooms. LECO #6 was to upgrade T-17 lighting systems to T-8 lighting systems.

Only the primary factors affecting costs and savings from LECOs were evaluated. Factors affecting lighting quality and performance were not included in the sensitivity analysis because these factors could not be consistently quantified in all types of LECOs. Each LECO had six factors which were deviated from baseline values for sensitivity analysis on PWI. Baseline values were established from average values measured during the case study. Table 5.2 shows the factors that were deviated to conduct sensitivity analysis of the PWI for each LECO.

**TABLE 5.2 FACTORS AFFECTING SENSITIVITY OF PWI FOR EACH LECO**

| Factors | LECO # 4 Installing Occupancy Sensors | LECO # 6 A Light Source Upgrade |
|---|---|---|
| 1 | Input Watts per Fixture | Watts Saved per Fixture |
| 2 | Annual Hours Saved | Annual Operation Hours |
| 3 | Energy Cost | Energy Cost |
| 4 | Total Material Cost | Total Material Cost |
| 5 | Total Labor Cost | Total Labor Cost |
| 6 | Interest Rate | Interest Rate |

Because the two LECOs are different, some corresponding factors appear different. In LECO #4, Annual Hours Saved is actually Annual Operating Hours multiplied by the percent time saved in a particular room. Input Watts per Fixture in an occupancy sensor application has exactly the same effect as Watts Saved per Fixture in a source upgrade LECO.

The sensitivity analysis was completed by deviating each factor from a baseline value, and observing the effect on the PWI for a particular LECO. In all calculations, one factor was deviated while all other factors remained constant at their original estimated values; the baseline values.

Tables 5.3 through 5.6 show the percent deviation for each factor and the impact on the PWI for each LECO. Tables A.1 and A.2 in the Appendix are the complete tables with actual baseline values, deviations and effects on PWI for LECOs #4 and #6 respectively.

# TABLE 5.3 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #4 (INSTALLING OCCUPANCY SENSORS)

| Factor % Deviation from Baseline | PWI (i=10%) | % Change in PWI from Baseline |
|---|---|---|
| | | |
| Baseline | | |
| 0 | 0.495 | 0% |
| | | |
| Input Watts | | |
| -0.4 | -0.103 | -121% |
| -0.3 | 0.047 | -91% |
| -0.2 | 0.196 | -60% |
| -0.1 | 0.346 | -30% |
| 0 | 0.495 | 0% |
| 0.1 | 0.645 | 30% |
| 0.2 | 0.794 | 60% |
| 0.3 | 0.944 | 91% |
| 0.4 | 1.093 | 121% |
| | | |
| Energy Cost | | |
| -0.4 | -0.103 | -121% |
| -0.3 | 0.047 | -91% |
| -0.2 | 0.196 | -60% |
| -0.1 | 0.346 | -30% |
| 0 | 0.495 | 0% |
| 0.1 | 0.645 | 30% |
| 0.2 | 0.794 | 60% |
| 0.3 | 0.944 | 91% |
| 0.4 | 1.093 | 121% |
| | | |
| Annual Hours Saved | | |
| -0.4 | -0.103 | -121% |
| -0.3 | 0.047 | -90% |
| -0.2 | 0.196 | -60% |
| -0.1 | 0.346 | -30% |
| 0 | 0.495 | 0% |
| 0.1 | 0.645 | 30% |
| 0.2 | 0.794 | 60% |
| 0.3 | 0.944 | 91% |
| 0.4 | 1.093 | 121% |

## TABLE 5.4 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #4 (INSTALLING OCCUPANCY SENSORS)

| Factor % Deviation from Baseline | PWI (i=10%) | % Change in PWI from Baseline |
|---|---|---|
| Baseline | | |
| 0 | 0.495 | 0% |
| | | |
| Total Material Costs | | |
| -0.4 | 0.852 | 72% |
| -0.3 | 0.747 | 51% |
| -0.2 | 0.654 | 32% |
| -0.1 | 0.571 | 15% |
| 0 | 0.495 | 0% |
| 0.1 | 0.426 | -14% |
| 0.2 | 0.364 | -27% |
| 0.3 | 0.306 | -38% |
| 0.4 | 0.254 | -49% |
| | | |
| Total Labor Costs | | |
| -0.4 | 0.886 | 79% |
| -0.3 | 0.770 | 56% |
| -0.2 | 0.668 | 35% |
| -0.1 | 0.577 | 17% |
| 0 | 0.495 | 0% |
| 0.1 | 0.421 | -15% |
| 0.2 | 0.355 | -28% |
| 0.3 | 0.294 | -41% |
| 0.4 | 0.238 | -52% |
| | | |
| Interest Rate | | |
| -0.4 | 0.909 | 84% |
| -0.3 | 0.790 | 60% |
| -0.2 | 0.682 | 38% |
| -0.1 | 0.584 | 18% |
| 0 | 0.495 | 0% |
| 0.1 | 0.417 | -16% |
| 0.2 | 0.339 | -32% |
| 0.3 | 0.276 | -44% |
| 0.4 | 0.213 | -57% |

## TABLE 5.5 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #6 (A LIGHT SOURCE UPGRADE)

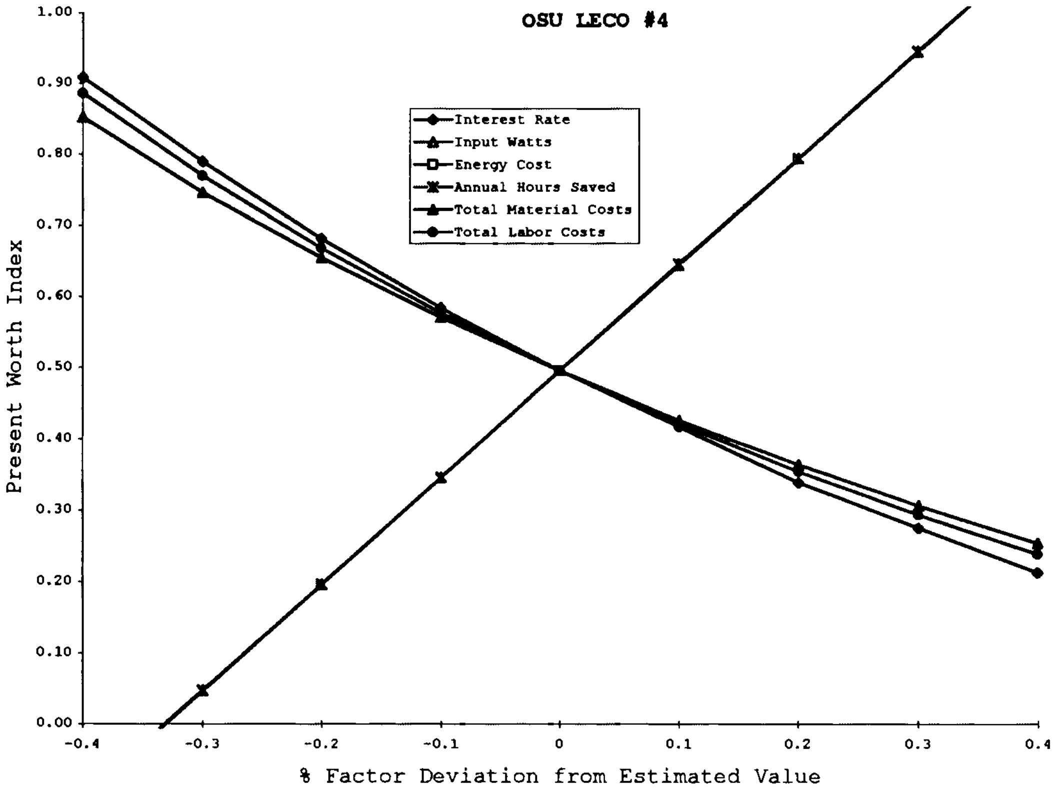
| Factor % Deviation from Baseline | PWI (i=10%) | % Change in PWI from Baseline |
|---|---:|---:|
| | | |
| Baseline | | |
| 0 | 0.306 | 0% |
| | | |
| Watts Saved per Fixture | 0.306 | 0% |
| -0.4 | 0.021 | -93% |
| -0.3 | 0.092 | -70% |
| -0.2 | 0.164 | -47% |
| -0.1 | 0.235 | -23% |
| 0 | 0.306 | 0% |
| 0.1 | 0.377 | 23% |
| 0.2 | 0.448 | 47% |
| 0.3 | 0.520 | 70% |
| 0.4 | 0.591 | 93% |
| | | |
| Energy Cost | | |
| -0.4 | 0.021 | -93% |
| -0.3 | 0.092 | -70% |
| -0.2 | 0.164 | -47% |
| -0.1 | 0.235 | -23% |
| 0 | 0.306 | 0% |
| 0.1 | 0.377 | 23% |
| 0.2 | 0.448 | 47% |
| 0.3 | 0.520 | 70% |
| 0.4 | 0.591 | 93% |
| | | |
| Annual Operating Hours | | |
| -0.4 | -0.432 | -241% |
| -0.3 | -0.361 | -218% |
| -0.2 | 0.073 | -76% |
| -0.1 | 0.189 | -38% |
| 0 | 0.306 | 0% |
| 0.1 | 0.423 | 38% |
| 0.2 | 0.539 | 76% |
| 0.3 | 0.656 | 114% |
| 0.4 | 0.772 | 152% |

## TABLE 5.6 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #6 (A LIGHT SOURCE UPGRADE)

| Factor % Deviation from Baseline | PWI (i=10%) | % Change in PWI from Baseline |
|---|---|---|
| | | |
| Baseline | | |
| 0 | 0.306 | 0% |
| | | |
| Total Material Costs | | |
| -0.4 | 0.805 | 163% |
| -0.3 | 0.648 | 112% |
| -0.2 | 0.516 | 69% |
| -0.1 | 0.403 | 32% |
| 0 | 0.306 | 0% |
| 0.1 | 0.222 | -27% |
| 0.2 | 0.147 | -52% |
| 0.3 | 0.082 | -73% |
| 0.4 | 0.023 | -92% |
| | | |
| Total Labor Costs | | |
| -0.4 | 0.490 | 60% |
| -0.3 | 0.439 | 44% |
| -0.2 | 0.392 | 28% |
| -0.1 | 0.348 | 14% |
| 0 | 0.306 | 0% |
| 0.1 | 0.267 | -13% |
| 0.2 | 0.230 | -25% |
| 0.3 | 0.195 | -36% |
| 0.4 | 0.162 | -47% |
| | | |
| Interest Rate | | |
| -0.4 | 0.668 | 118% |
| -0.3 | 0.564 | 84% |
| -0.2 | 0.470 | 54% |
| -0.1 | 0.384 | 26% |
| 0 | 0.306 | 0% |
| 0.1 | 0.238 | -22% |
| 0.2 | 0.169 | -45% |
| 0.3 | 0.114 | -63% |
| 0.4 | 0.059 | -81% |

Figures 5.1 and 5.2 are graphical representations of Tables 5.3 through 5.6. Each figure shows the sensitivity of the PWI to various deviations of factors from their original estimated values. The slope of the line indicates its relative effect on sensitivity. Steep sloping lines indicate factors that have a large impact on PWI.

**Figure 5.1 Sensitivity of Present Worth Index to Individual Factor Deviations for Installing Occupancy Sensors**
**OSU LECO #4**



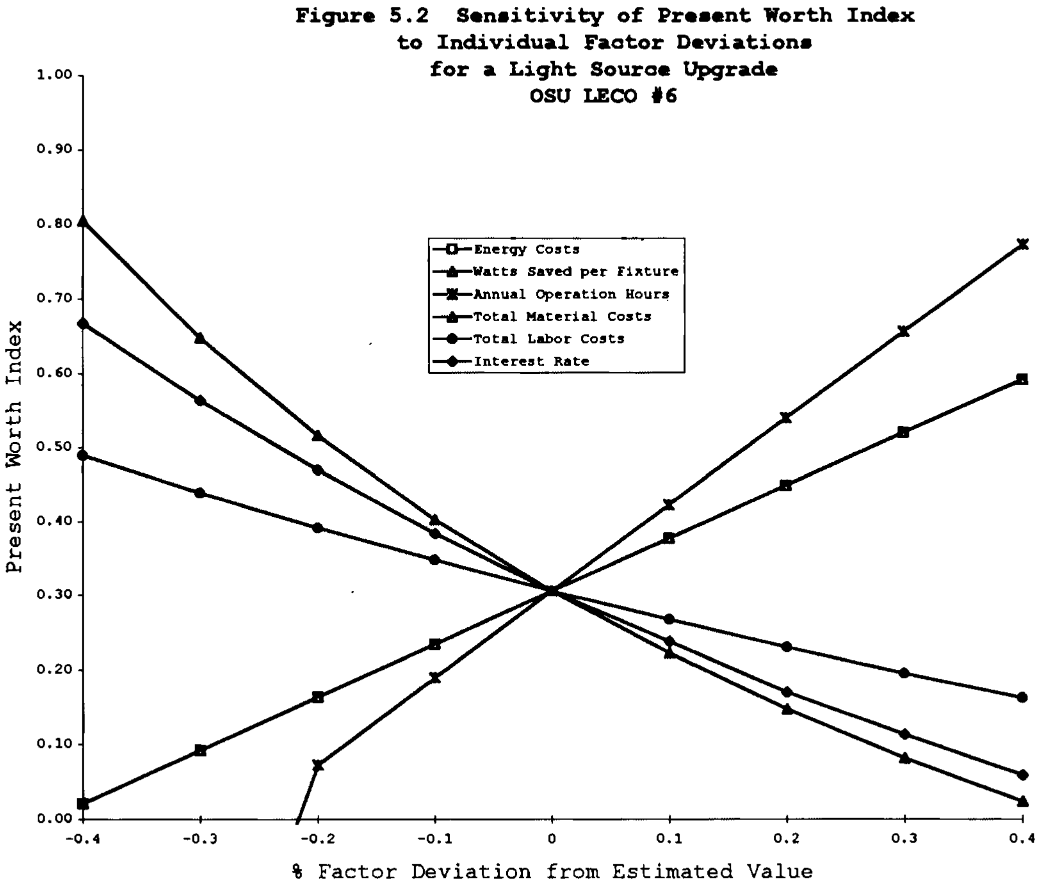


Figure 5.2 Sensitivity of Present Worth Index
to Individual Factor Deviations
for a Light Source Upgrade
OSU LECO #6

## Effect on LECOs

The PWI is considered to be sensitive to factors that have a large influence (on PWI) if such factors are changed. For example, with LECO #4, if energy costs decrease from their original estimates by 40%, the PWI decreases by 121%. In comparison, if total material costs increase by 40%, PWI decreases by only 49%. Therefore, in this comparison, the PWI is more sensitive to fluctuations in energy costs.

Each LECO has its own set of factors that have the most dramatic effect on PWI. In LECO #6, if annual operating hours decrease by 40%, the PWI drops by 241%. In comparison, increasing labor costs by 40% only decreases the PWI by 47%.

Because significant differences in sensitivity exist, it is important to identify which factors have the greatest impact on each LECO. However, even when some factors are varied independently, the same effect on PWI sensitivity may result. Table 5.3 and Figure 5.1 show that for LECO #4, sensitivity is common for independent deviations of three different factors: Annual Hours Saved, Energy Cost and Input Watts per Fixture. Therefore, if any of these factors are deviated by a certain percentage, the PWI changes by the same amount. This occurrence is due to the fact that those three factors are multiplied together to yield Energy Cost Savings. The same sensitivity results occur, regardless of which factor is deviated by a certain percentage. Therefore, the combined result (the line labeled "Annual Hours Saved") in Figure 5.1 is actually an expression of PWI sensitivity to variations in Energy Cost Savings.

Table 5.5 and Figure 5.2 show that LECO #6 also had two factors which influenced PWI sensitivity identically. These two factors were: Energy Cost and Watts Saved per Fixture. This phenomena was the same as in LECO #4, except that the Annual Operating Hours factor didn't share the same effect on PWI sensitivity. Annual Operating Hour deviation produced a different PWI sensitivity because other factors, such as maintenance re-lamping savings and ongoing labor costs, were incorporated into the energy cost savings. Due to the particular constraints of LECO #4, maintenance re-lamping savings and ongoing labor costs, which affect annual energy cost savings, were not included in the LECO calculations.

Sensitivity Rank

The preceding sections have demonstrated the need to determine which factors that have the greatest impact on LECO feasibility. By observing Figures 5.1 and 5.2 along with Tables 5.3 through 5.6, a ranking order of factors can be determined for each LECO. Table 5.7 shows the order of sensitivity for factors affecting each type of LECO.

TABLE 5.7 RANK OF SENSITIVITY FOR FACTORS AFFECTING LECOS

| Rank | LECO # 4<br>Installing Occupancy Sensors | Rank | LECO # 6<br>A Light Source Upgrade |
|---|---|---|---|
| 1 | Input Watts per Fixture | 1 | Annual Operation Hours |
| 1 | Annual Hours Saved | 2 | Total Material Cost |
| 1 | Energy Cost | 2 | Energy Cost |
| 4 | Interest Rate | 4 | Watts Saved per Fixture |
| 5 | Total Labor Costs | 5 | Interest Rate |
| 6 | Total Material Costs | 6 | Total Labor Cost |

As previously discussed, some factors when deviated independently, had similar effects on the PWI sensitivity. Thus there were some factors that are equally ranked. However, the factors consistently appearing at the "top" of the rank are the most important. From sensitivity analysis of the OSU LECOs it is clear that the Annual Operating Hours was the factor that consistently had the greatest impact on LECO feasibility.

After Annual Operating Hours, Energy Cost and Input Watts per fixture were the next most important. Following these factors were Material Costs, Interest Rate and Labor Costs.

Because Annual Operating Hours of a lighting system is the factor that has the largest influence on the feasibility of LECOs, it should be incorporated into the LECO Screening Tree as one of the first factors to consider.

## Summary of the Data Analysis

For this thesis, sensitivity analysis was used to evaluate the logic of the LECO Screening Tree. If the economic impact of a LECO was sensitive to a particular factor, then that factor should be located at the beginning of the LECO Screening Tree.

Sensitivity analysis of the OSU LECOs showed that in both types of lighting retrofits Annual Operating Hours and Energy Cost were the most sensitive factors analyzed. Therefore, these two factors had the greatest impact on economic feasibility of LECOs.

The LECO Screening Tree developed in this thesis did incorporate Annual Operating Hours as the first survey-based factor. The LECO Screening Tree also incorporated all major factors into the first level of decisions. Therefore, the LECO Screening Tree is a logically ordered screening system. It was effective because the factors having the greatest impact on economic feasibility were incorporated into the LECO evaluation early in the decision process.

# CHAPTER VI

# CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

## Conclusion

The purpose of this thesis was to develop an on-site LECO screening procedure for surveyors. This objective was accomplished with the development of the LECO Screening Tree. The LECO Screening Tree is not a complete survey and evaluation manual. However, it can improve the cost-effectiveness at which lighting surveys are conducted.

The LECO Screening Tree is different from standardized survey and evaluation methods because it helps the surveyor evaluate LECOs during the survey. Because economically infeasible LECOs are identified and eliminated during the survey, less data collection and evaluation is necessary. Surveyors using the LECO Screening Tree can spend the majority of their time on the LECOs with the most economic worth.

The LECO Screening Tree influences the surveyor to think in an evaluative mode, rather than the "data recording" mode common with most standardized survey instructions. Thus, after using the tree a few times the surveyor will better understand the complete survey and evaluation process, and surveyor skills will improve. Because the surveyors are focused on the survey, instead of post-survey analysis, factors affecting the lighting quality, retrofit costs and savings are more accurately incorporated into LECO analysis.

The tree incorporates multi-disciplinary factors which affect the feasibility of each LECO. These factors are prioritized according to their importance. Important factors have a large influence on LECO feasibility and are located at the beginning of the tree. However, the tree is flexible and factors can easily be added or re-arranged.

The LECO Screening Tree was tested and analyzed in a case study at Oklahoma State University (OSU). The tree was a benefit because it helped the surveyor identify the most cost-effective LECOs quickly, and eliminate economically infeasible LECOs with minimal time investment.

An analysis of the data collected at OSU verified the factors that have the greatest influence on the economic feasibility of LECOs. Because the LECO Screening Tree located and prioritized these factors within the early stages of the tree, economically infeasible LECOs were identified quickly. Therefore, the tree's structure was logical, allowing elimination of economically infeasible LECOs with minimal effort.

The LECO Screening Tree is most applicable at facilities with low potential for identifying cost-effective LECOs. At these facilities, standardized lighting surveys may appear too burdensome to initiate. The LECO Screening Tree offers a "middle ground" between doing nothing and conducting a time-intensive standardized survey.

## Recommendations for Further Research

The development of the LECO Screening Tree produced numerous thoughts on needs for further research. The following topics are recommended for further research:

1. Test the LECO Screening Tree in other case studies to determine which factors consistently have the greatest influence on LECO feasibility.
2. Verify the accuracy of quick survey estimates. Compare estimates of Annual Operation Hours and Percent Vacancy Time with actual measurements using occupancy meters.
3. From additional case studies, determine which factors are most likely to deviate from survey estimates.
4. Test ballasts in actual applications to determine if Input Watts per Fixture increases as a function of time. In addition, lamp lumen depreciation as a function of time needs to be measured in an actual application.

5. Quantify the increased performance from improved lighting quality when source upgrades are completed. Variables to be improved could be the Color Rendering Index, Coordinated Color Temperature and Visual Comfort Probability.
6. Incorporate into the LECO Screening Tree a more quantified value for savings from lighting quality improvements.

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# APPENDIX

## TABLE A.1 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #4 (INSTALLING OCCUPANCY SENSORS)

| Factor % Deviation from Baseline | x | Input watts per fixture (watts/fix | Total Annual Hours | kWh Cost ($/kWh) | TOTAL ANNUAL DOLLAR SAVINGS ($/yr) | Annual Hours Saved | Total Material Cost | Total Labor Cost | TOTAL IMPL. COST ($) | SIMPLE PAYBACK (years) | Present Worth | PWI (i=10%) | % Change in PWI from Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | | | | | | | | | | | | | |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| **Input Watts** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| -0.4 | \ | 46.8 | 2700 | 0.045 | $32 | 945 | 130 | 140 | $270 | 8.48 | -28 | -0.10 | -1.21 |
| -0.3 | \ | 54.6 | 2700 | 0.045 | $37 | 945 | 130 | 140 | $270 | 7.27 | 13 | 0.05 | -0.91 |
| -0.2 | \ | 62.4 | 2700 | 0.045 | $42 | 945 | 130 | 140 | $270 | 6.36 | 53 | 0.20 | -0.60 |
| -0.1 | \ | 70.2 | 2700 | 0.045 | $48 | 945 | 130 | 140 | $270 | 5.65 | 93 | 0.35 | -0.30 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| 0.1 | \ | 85.8 | 2700 | 0.045 | $58 | 945 | 130 | 140 | $270 | 4.63 | 174 | 0.64 | 0.30 |
| 0.2 | \ | 93.6 | 2700 | 0.045 | $64 | 945 | 130 | 140 | $270 | 4.24 | 214 | 0.79 | 0.60 |
| 0.3 | \ | 101.4 | 2700 | 0.045 | $69 | 945 | 130 | 140 | $270 | 3.91 | 255 | 0.94 | 0.91 |
| 0.4 | \ | 109.2 | 2700 | 0.045 | $74 | 945 | 130 | 140 | $270 | 3.63 | 295 | 1.09 | 1.21 |
| **Energy Cost** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.495 | 0.00 |
| -0.4 | \ | 78 | 2700 | 0.027 | $32 | 945 | 130 | 140 | $270 | 8.48 | -28 | -0.103 | -1.21 |
| -0.3 | \ | 78 | 2700 | 0.032 | $37 | 945 | 130 | 140 | $270 | 7.27 | 13 | 0.047 | -0.91 |
| -0.2 | \ | 78 | 2700 | 0.036 | $42 | 945 | 130 | 140 | $270 | 6.36 | 53 | 0.196 | -0.60 |
| -0.1 | \ | 78 | 2700 | 0.041 | $48 | 945 | 130 | 140 | $270 | 5.65 | 93 | 0.346 | -0.30 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.495 | 0.00 |
| 0.1 | \ | 78 | 2700 | 0.050 | $58 | 945 | 130 | 140 | $270 | 4.63 | 174 | 0.645 | 0.30 |
| 0.2 | \ | 78 | 2700 | 0.054 | $64 | 945 | 130 | 140 | $270 | 4.24 | 214 | 0.794 | 0.60 |
| 0.3 | \ | 78 | 2700 | 0.059 | $69 | 945 | 130 | 140 | $270 | 3.91 | 255 | 0.944 | 0.91 |
| 0.4 | \ | 78 | 2700 | 0.063 | $74 | 945 | 130 | 140 | $270 | 3.63 | 295 | 1.093 | 1.21 |
| **Annual Hours Saved** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| -0.4 | \ | 78 | 2700 | 0.045 | $32 | 563 | 130 | 140 | $270 | 8.54 | -30 | -0.10 | -1.21 |
| -0.3 | \ | 78 | 2700 | 0.045 | $37 | 662 | 130 | 140 | $270 | 7.26 | 13 | 0.05 | -0.90 |
| -0.2 | \ | 78 | 2700 | 0.045 | $42 | 756 | 130 | 140 | $270 | 6.36 | 53 | 0.20 | -0.60 |
| -0.1 | \ | 78 | 2700 | 0.045 | $48 | 851 | 130 | 140 | $270 | 5.65 | 94 | 0.35 | -0.30 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| 0.1 | \ | 78 | 2700 | 0.045 | $58 | 1040 | 130 | 140 | $270 | 4.62 | 174 | 0.65 | 0.30 |
| 0.2 | \ | 78 | 2700 | 0.045 | $64 | 1134 | 130 | 140 | $270 | 4.24 | 214 | 0.79 | 0.60 |
| 0.3 | \ | 78 | 2700 | 0.045 | $69 | 1229 | 130 | 140 | $270 | 3.91 | 255 | 0.94 | 0.91 |
| 0.4 | \ | 78 | 2700 | 0.045 | $74 | 1326 | 130 | 140 | $270 | 3.63 | 296 | 1.09 | 1.21 |
| **Total Material Costs** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| -0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 78 | 140 | $218 | 4.11 | 186 | 0.85 | 0.72 |
| -0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 91 | 140 | $231 | 4.35 | 173 | 0.75 | 0.51 |
| -0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 104 | 140 | $244 | 4.60 | 160 | 0.65 | 0.32 |
| -0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 117 | 140 | $257 | 4.84 | 147 | 0.57 | 0.15 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| 0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 143 | 140 | $283 | 5.33 | 121 | 0.43 | -0.14 |
| 0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 156 | 140 | $296 | 5.58 | 108 | 0.36 | -0.27 |
| 0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 169 | 140 | $309 | 5.82 | 95 | 0.31 | -0.38 |
| 0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 182 | 140 | $322 | 6.07 | 82 | 0.25 | -0.49 |
| **Total Labor Costs** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| -0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 84 | $214 | 4.03 | 190 | 0.89 | 0.79 |
| -0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 98 | $228 | 4.30 | 176 | 0.77 | 0.56 |
| -0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 112 | $242 | 4.56 | 162 | 0.67 | 0.35 |
| -0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 126 | $256 | 4.82 | 148 | 0.58 | 0.17 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| 0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 154 | $284 | 5.35 | 120 | 0.42 | -0.15 |
| 0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 168 | $298 | 5.62 | 106 | 0.35 | -0.28 |
| 0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 182 | $312 | 5.88 | 92 | 0.29 | -0.41 |
| 0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 196 | $326 | 6.14 | 78 | 0.24 | -0.52 |
| **Interest Rate** | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| -0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 245 | 0.91 | 0.84 |
| -0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 213 | 0.79 | 0.60 |
| -0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 184 | 0.68 | 0.38 |
| -0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 158 | 0.58 | 0.18 |
| 0 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 134 | 0.50 | 0.00 |
| 0.1 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 113 | 0.42 | -0.16 |
| 0.2 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 91 | 0.34 | -0.32 |
| 0.3 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 74 | 0.28 | -0.44 |
| 0.4 | \ | 78 | 2700 | 0.045 | $53 | 945 | 130 | 140 | $270 | 5.09 | 57 | 0.21 | -0.57 |

## TABLE A.2 FACTOR DEVIATIONS AND PWI SENSITIVITY TO LECO #6 (A LIGHT SOURCE UPGRADE)

| Factor % Deviation from Baseline | Total Annual Hours | watts saved per fixture (watts/fix) | kWh Cost ($/kWh) | TOTAL ANNUAL DOLLAR SAVINGS ($/yr) | TOTAL IMPL. COST ($) | Total Material Cost | Total Labor Cost | SIMPLE PAYBACK (years) | Present Worth | PWI (i=10%) | % Change in PWI from Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Baseline** | | | | | | | | | | | |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| | | | | | | | | | | | |
| **Watts Saved per Fixture** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| -0.4 | 2,450 | 33 | 0.045 | 243.4 | $1,813.3 | $1,253.3 | $560.0 | 7.4 | 38 | 0.02 | -0.93 |
| -0.3 | 2,450 | 38.5 | 0.045 | 260.4 | $1,813.3 | $1,253.3 | $560.0 | 7.0 | 167 | 0.09 | -0.70 |
| -0.2 | 2,450 | 44 | 0.045 | 277.4 | $1,813.3 | $1,253.3 | $560.0 | 6.5 | 296 | 0.16 | -0.47 |
| -0.1 | 2,450 | 49.5 | 0.045 | 294.4 | $1,813.3 | $1,253.3 | $560.0 | 6.2 | 426 | 0.23 | -0.23 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| 0.1 | 2,450 | 60.5 | 0.045 | 328.3 | $1,813.3 | $1,253.3 | $560.0 | 5.5 | 684 | 0.38 | 0.23 |
| 0.2 | 2,450 | 66 | 0.045 | 345.3 | $1,813.3 | $1,253.3 | $560.0 | 5.3 | 813 | 0.45 | 0.47 |
| 0.3 | 2,450 | 71.5 | 0.045 | 362.3 | $1,813.3 | $1,253.3 | $560.0 | 5.0 | 942 | 0.52 | 0.70 |
| 0.4 | 2,450 | 77 | 0.045 | 379.2 | $1,813.3 | $1,253.3 | $560.0 | 4.8 | 1071 | 0.59 | 0.93 |
| | | | | | | | | | | | |
| **Energy Cost** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.306 | 0.00 |
| -0.4 | 2,450 | 55 | 0.027 | 243.4 | $1,813.3 | $1,253.3 | $560.0 | 7.4 | 38 | 0.021 | -0.93 |
| -0.3 | 2,450 | 55 | 0.032 | 260.4 | $1,813.3 | $1,253.3 | $560.0 | 7.0 | 167 | 0.092 | -0.70 |
| -0.2 | 2,450 | 55 | 0.036 | 277.4 | $1,813.3 | $1,253.3 | $560.0 | 6.5 | 296 | 0.164 | -0.47 |
| -0.1 | 2,450 | 55 | 0.041 | 294.4 | $1,813.3 | $1,253.3 | $560.0 | 6.2 | 426 | 0.235 | -0.23 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.306 | 0.00 |
| 0.1 | 2,450 | 55 | 0.050 | 328.3 | $1,813.3 | $1,253.3 | $560.0 | 5.5 | 684 | 0.377 | 0.23 |
| 0.2 | 2,450 | 55 | 0.054 | 345.3 | $1,813.3 | $1,253.3 | $560.0 | 5.3 | 813 | 0.448 | 0.47 |
| 0.3 | 2,450 | 55 | 0.059 | 362.3 | $1,813.3 | $1,253.3 | $560.0 | 5.0 | 942 | 0.520 | 0.70 |
| 0.4 | 2,450 | 55 | 0.063 | 379.2 | $1,813.3 | $1,253.3 | $560.0 | 4.8 | 1071 | 0.591 | 0.93 |
| | | | | | | | | | | | |
| **Annual Operating Hours** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| -0.4 | 1,470 | 55 | 0.045 | 135.3 | $1,813.3 | $1,253.3 | $560.0 | 13.4 | -784 | -0.43 | -2.41 |
| -0.3 | 1,715 | 55 | 0.045 | 152.3 | $1,813.3 | $1,253.3 | $560.0 | 11.9 | -655 | -0.36 | -2.16 |
| -0.2 | 1,960 | 55 | 0.045 | 255.8 | $1,813.3 | $1,253.3 | $560.0 | 7.1 | 132 | 0.07 | -0.76 |
| -0.1 | 2,205 | 55 | 0.045 | 283.5 | $1,813.3 | $1,253.3 | $560.0 | 6.4 | 343 | 0.19 | -0.38 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| 0.1 | 2,695 | 55 | 0.045 | 339.1 | $1,813.3 | $1,253.3 | $560.0 | 5.3 | 766 | 0.42 | 0.38 |
| 0.2 | 2,940 | 55 | 0.045 | 366.9 | $1,813.3 | $1,253.3 | $560.0 | 4.9 | 977 | 0.54 | 0.76 |
| 0.3 | 3,185 | 55 | 0.045 | 394.7 | $1,813.3 | $1,253.3 | $560.0 | 4.6 | 1189 | 0.66 | 1.14 |
| 0.4 | 3,430 | 55 | 0.045 | 422.5 | $1,813.3 | $1,253.3 | $560.0 | 4.3 | 1400 | 0.77 | 1.52 |
| | | | | | | | | | | | |
| **Total Material Costs** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| -0.4 | 2,450 | 55 | 0.045 | 311.3 | $1,312.0 | $752.0 | $560.0 | 4.2 | 1056 | 0.80 | 1.63 |
| -0.3 | 2,450 | 55 | 0.045 | 311.3 | $1,437.0 | $877.0 | $560.0 | 4.6 | 931 | 0.65 | 1.12 |
| -0.2 | 2,450 | 55 | 0.045 | 311.3 | $1,562.0 | $1,002.0 | $560.0 | 5.0 | 806 | 0.52 | 0.69 |
| -0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,688.0 | $1,128.0 | $560.0 | 5.4 | 680 | 0.40 | 0.32 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| 0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,938.0 | $1,378.0 | $560.0 | 6.2 | 430 | 0.22 | -0.27 |
| 0.2 | 2,450 | 55 | 0.045 | 311.3 | $2,064.0 | $1,504.0 | $560.0 | 6.6 | 304 | 0.15 | -0.52 |
| 0.3 | 2,450 | 55 | 0.045 | 311.3 | $2,189.0 | $1,629.0 | $560.0 | 7.0 | 179 | 0.08 | -0.73 |
| 0.4 | 2,450 | 55 | 0.045 | 311.3 | $2,314.0 | $1,754.0 | $560.0 | 7.4 | 54 | 0.02 | -0.92 |
| | | | | | | | | | | | |
| **Total Labor Costs** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| -0.4 | 2,450 | 55 | 0.045 | 311.3 | $1,589.3 | $1,253.3 | $336.0 | 5.1 | 779 | 0.49 | 0.60 |
| -0.3 | 2,450 | 55 | 0.045 | 311.3 | $1,645.3 | $1,253.3 | $392.0 | 5.3 | 723 | 0.44 | 0.44 |
| -0.2 | 2,450 | 55 | 0.045 | 311.3 | $1,701.3 | $1,253.3 | $448.0 | 5.5 | 667 | 0.39 | 0.28 |
| -0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,757.3 | $1,253.3 | $504.0 | 5.6 | 611 | 0.35 | 0.14 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| 0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,869.3 | $1,253.3 | $616.0 | 6.0 | 499 | 0.27 | -0.13 |
| 0.2 | 2,450 | 55 | 0.045 | 311.3 | $1,925.3 | $1,253.3 | $672.0 | 6.2 | 443 | 0.23 | -0.25 |
| 0.3 | 2,450 | 55 | 0.045 | 311.3 | $1,981.3 | $1,253.3 | $728.0 | 6.4 | 387 | 0.20 | -0.36 |
| 0.4 | 2,450 | 55 | 0.045 | 311.3 | $2,037.3 | $1,253.3 | $784.0 | 6.5 | 331 | 0.16 | -0.47 |
| | | | | | | | | | | | |
| **Interest Rate** | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| -0.4 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 1210 | 0.67 | 1.18 |
| -0.3 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 1022 | 0.56 | 0.84 |
| -0.2 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 852 | 0.47 | 0.54 |
| -0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 696 | 0.38 | 0.26 |
| 0 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 555 | 0.31 | 0.00 |
| 0.1 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 431 | 0.24 | -0.22 |
| 0.2 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 307 | 0.17 | -0.45 |
| 0.3 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 207 | 0.11 | -0.63 |
| 0.4 | 2,450 | 55 | 0.045 | 311.3 | $1,813.3 | $1,253.3 | $560.0 | 5.8 | 107 | 0.06 | -0.81 |

# VITA

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