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Improving the Lighting Efficacy by Upgrading the Lighting of a Commercial Building

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Areas of Interests: - Zonal modeling approach, - Integration zonal models/building energy simulation models, - Zero Net Energy (ZNE) building, - Airflow in Multizone Buildings & Smoke Control, - Thermal Comfort & Indoor Air Quality, - Predictive modeling and forecasting: Support Vector Machine (SVM) tools, - Energy, HVAC, Plumbing & Fire Protection Systems Design, - Computational Fluid Dynamic (CFD) Application in Building, - BIM & REVIT: application to HVAC and Electrical/Lighting Design systems.

Improving the Lighting Efficacy by Upgrading the Lighting of a Commercial Building

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Only few years ago, the lighting design is mostly focusing on the lighting aspects, such as illuminance, color rendering, and color temperature. With the first edition of IECC was published in 1998, the electrical part of the lighting starts to control the design aspect, the use of daylighting, fixture selection and the project cost, in order to improve the efficacy. The Efficacy is the ratio of light output from a lamp to the electric power it consumes and is measured in lumens per watt (LPW). The successive versions of the code push further toward more sustainable design using lighting control, daylighting, harvesting lighting and new type of more economic fixtures.

This paper describes the upgrade of an industrial lighting system from T12 and T8 to T5 or LED fixtures, to fulfil the Department of Energy's objective by removing less efficient fluorescent systems from the market, and thus being more ecological friendly and increase lighting energy efficiency for commercial applications. This paper describes the design and economical aspects of the project, by including all the aspects, such as labor of replacing the fixture and the ballast, maintenance, and depreciation. This work has been performed within a capstone design course.

Most importantly, project methodology will be discussed. Both direct and indirect assessments have been performed. The self-assessment section generates indirect assessment data, which complements the traditional direct assessment data.

We discuss the capstone design program from students' point of view, and the experience earned in design, integration, and also in written and oral communication skills. Methodology used to evaluate the effectiveness of the capstone design program in term of learning outcomes is also described.

Introduction:

Only few years ago, the lighting design is mostly focusing on the lighting aspects, such as illuminance, color rendering, and color temperature. With the first edition of IECC was published in 1998, the electrical part of the lighting starts to control the design aspect, the use of daylighting, fixture selection and the project cost, in order to improve the efficacy. The Efficacy is the ratio of light output from a lamp to the electric power it consumes and is measured in lumens per watt (LPW). The successive versions of the code push further toward more sustainable design using lighting control, daylighting, harvesting lighting and new type of more economic fixtures.

The U.S. Department of Energy's fluorescent lighting mandate is official. As of July 1, 2010 magnetic ballasts most commonly used for the operation of T12 lamps will no longer be produced for commercial and industrial applications. Also, many T12 lamps will be phased out of production starting July 2012.

Due to the phase-out of the fluorescent bulb T12 and magnetic ballasts combined with companies' need to find new ways to cut costs, many are reviewing their current lighting arrangements in search of easily replaceable and money-saving opportunities. Fortunately, more advanced lighting technologies become commercially available every year providing numerous options for companies looking to upgrade their office and manufacturing sites with resilient, low-wattage lighting. Often, a lower power light source is able to provide more illumination at a less expensive operating cost. The most common forms of upgrades in industrial facilities include fluorescent T8 to T5, T5HO, LED, and high-bay lighting change-outs. This paper describes the design and economical aspects of the project, by including all the aspects, such as labor of replacing the fixture and the ballast, maintenance, and depreciation.

Lighting Literature:

There is extensive technical literature on lighting (ECW webpage). The most relevant is associated with the Illuminating Engineering Society of North America (IESNA). The IES Lighting Handbook related to fundamentals and very informative of the lighting practice in different type of buildings, including commercial. The Lighting Handbook does provide information that helps the designers to perform design.

The existing literature does examine the lighting from different aspects:

(1) Lighting design: Lighting controls in commercial buildings.
(2) Study of office worker performance and indoor environment.
(3) Articles come from scholarly research and concentrate on daylighting and integration daylighting and building energy analysis; as well integration between daylighting and design of net zero energy buildings, daylighting and productivity, dynamic daylighting, while the second category of research is financed or directly published by lighting companies.

In this paper, we will focus on the most significant literature, where energy saving was the objective. Williams et al., (2012) conduct a comprehensive study of available research on the energy savings associated with lighting controls. A total of 88 papers (40 of the papers were published in peer-reviewed journals or presented at conferences, while the remaining 48 papers were self-published reports or case studies) discuss the savings estimates of 4 controls strategies; daylighting, occupancy sensors, personal tuning and institutional tuning. Daylighting is defined as the automatic adjustment of light levels in response to daylight. *On average, the lighting energy savings were summarized to be 28% for daylighting, 24% for occupancy controls, 31% for personal tuning, and 36% for institutional tuning. Combining multiple approaches resulted in average lighting energy savings of 38%.* The study also showed that simulation typically over-predicts energy savings. In particular, simulation over-estimated daylighting energy savings by at least 10%. Taken together, this report indicates that these lighting control strategies result in significant energy savings.

Two studies (Heschong Mahone Group, Inc., October 2003) tracked the performance of 100 and 201 workers consecutively and found that workers with a view of a large window tended to have decreased times than their counterparts with no view. The study also found that the absolute level of light, whether from daylight or an electric source, had no significant effect. Similarly, the effect of partition height was small. Having a view again increased performance, while those workers with a view reported less fatigue and overall better health. It was also reported that the quality of the view, such as having sky and trees, was important. Alternatively, those workers experiencing glare tended to have decreased performance. However, the impact of both of these variables was small. In conclusions daylight can have both a positive or negative effect on worker productivity, depending on the way in which it is introduced.

Multiple lighting projects regarding library, middle school, healthcare and hospitality center, to demonstrate the characteristics of the design, the daylight savings, the level of lighting in different locations, and the lessons learned (Lighting Research Center web page).

Galasiu et al. (2001) evaluates the performance of photosensor-controlled electric lighting under different configurations of office spaces. Four offices spaces were studied. Each have a high visible transmittance view window and a low visible transmittance clerestory window along with 2 two lamp, 32 W, T8 fluorescent lamps. This equates to a lighting power density of 9 W/m^2 (0.84 W/ft^2). The electric lights were controlled to a work plane illuminance of 570 lux (57 fc). Two of the offices had electronic dimming ballasts, while the other two had on/off controls. One of the "dimming" offices and one of the "on/off" offices had motorized blinds tied to the photosensors. The results did show that adding static blinds increased the electric lighting usage by between 40 and 45% for the "on/off" system and between 30 and 35% for the "dimming" system. Further, controlling the blind angles via the photosensors showed only a 10% increase in electrical usage.

Daylight modeling and energy modeling tools have been evolved in this study. Specifically, daylight modeling was utilized to analyze the impact of different window head heights, widow-to-wall ratios, glazing transmittance, and interior finishes had on daylight illuminance levels (Guglielmetti et al., 2010). Light Louver's Daylight System was also analyzed, showing daylight penetration of up to 60' from the south-facing clerestories. A technique was also developed to integrate Radiance modeling in SPOT with DOE-2 to create a more robust daylight model inside of the energy model. This model showed an overall building EUI of 34 $kBTU/ft^2/yr$. A portion of this low energy usage was attributable to the aggressive daylight harvesting.

Vaidya et al., (2004) summarize eight cases studies of various projects (College Dining Hall, College Classroom Building, three Office Buildings, College Classroom Building, and Recreation Center) that employed daylighting controls. Each project encountered issues and the authors analyze the failure mechanism and how the users coped with them. A method of failure analysis is developed and four typical failure modes are identified. Finally, a template for resolving each kind of failure is developed. The case studies covered a wide range of space types and daylighting control systems.

Guglielmetti et al. (2011) discuss the daylighting design process associated with the Research Support Facility, a 220,000 ft^2 office building, where the project had a goal of low energy use, setting out to be approximately 50% below ASHRAE 90.1-2004. Daylighting was chosen early as an integral part of the project's energy efficiency strategy, requiring daylighting in all perimeter occupied zones, glare mitigation strategies, automatic, continuous dimming, and commissioning. Advanced controls strategies are also considered. This collaborative environment was realized through coupled daylight and energy simulation, using simulating representative spaces in the Sensor Placement Optimization Tool (SPOT), a Radiance based software. Several design variations were considered and an optimum set was settled upon.

A light louver system was added to the daylight glazing to bounce the light up the ceiling and even deeper into the building's interior. Further, light reflectances were chosen for the interior surfaces. When coupled with low partition heights, this minimized the amount of daylight that was absorbed and obstructed, thereby allowing a more even and deep penetration of daylight. The lighting design incorporated a task-ambient approach, utilizing direct/indirect, pendant-mounted fixture with 25 watt fluorescent T8 lamps and compact fluorescent downlights for the ambient illumination and LED downlights for task illumination. A target open office illuminance of 25 footcandles was set along with an additional 20 to 30 footcandle contribution from the task lighting. This design led to an average lighting power density of 0.62 watts per square foot.

Oakley et al. (2001) develop a testing method for measuring the amount of natural daylight and passive ventilation a light pipe introduces into a test chamber. Photosensors measure the illuminance levels both internal and external to the chamber, while a tracer-gas method was employed to measure the ventilation flow rate. The results showed a ratio of internal to external illuminance of approximately 16%. The highest natural light penetration was during periods of time that the sun was overhead. However, the addition of a Laser Cut Panel to the top of the light pipe enhanced daylight penetration during periods of low angle sunlight. The natural ventilation averaged 8 air changes per hour of the 1.3 m x 1.3 m x 1.3 m test chamber during the study, with little to no effect from wind speed or direction.

In this paper, Gagne and Anderson (2010) develop a genetic algorithm for determining the set of facade parameters (window-to-wall ratio, glazing transmissivity, overhang depth, among others) that, for a given massing model, maximizes the space's illuminance within a specified range, while minimizing the space's glare potential. Their approach uses the Lightsolve Viewer coupled with an approximation of the Daylighting Glare Probability. The approach was applied to multiple spaces and validated against a known test case.

Building Audit:

The first step to determine exactly how to reduce energy consumption from lighting energy costs is to conduct an audit of your facilities' energy use. An energy audit will help you to identify the type of fixtures used, the level of maintenance, as well as actual level and quality of lighting available.

There are two types of energy audits. A Walk-Through Audit is the place to start because it deals with basic information and actions that are generally low cost or no cost. After the visit of the building, implementations of recommended actions, the students use computer program to verify the outcomes of their decision and study the economic aspects of their decision, as well as compare multiple solutions. An Analysis Audit identifies more comprehensive, capital-intensive energy-saving improvements.

The process started by visiting the industrial building. The walk through was very essential to discover the building, the construction types, as well as the color of walls, roof, and floor. The students use binoculars to identify high bay lights. The amount of light "available" at a particular location is measured in foot-candles by a hand held light meter.

Luminaires:

The most common forms of upgrades in industrial facilities include fluorescent T8 to T5, T5HO, LED, and high-bay lighting change-outs.

High bay lighting and low bay lighting fixtures are located at different height and they have different purpose. High bays and low bays are industry standard terms for commercial and industrial types of light fitting.

High bays are designed to be used in very high areas (approximately 5m and greater) to provide well distributed and uniform light for open areas. Common applications include warehouses, manufacturing areas, gymnasiums, barns, and storage spaces. The key element of the fitting which will help guarantee the correct light output is the reflectors and optics used by the fitting. In our industrial application (testing building), a particular consideration for use with a high bay is to illuminate the floor (not the working plane) between cells, the top of the cells, as well as the crane levels. Lighting of verticals is not important (as the case with warehouses where items are required to be picked from a shelf). Correct lighting for such spaces is crucial to workplace safety and productivity. For our project, the high bay lighting fixtures are located at about 45 feet height.

Low bays work in much the same way as a high bay, but will be best suited to lower mounting heights. The main differences will be in the lamp types selected and the types of reflectors and optics used.

When using the interior design tool (Lumen method) from visual, where only one type of fixture at the same height is used, we need to use the principal of superposition, where the illuminances of different category of fixtures are added at each point of the level of the work plane. Here, we need to be sure that students understand that they can add the levels of foot-candle at each point of the work plane (direct, indirect, reflected and from different fixtures), but not the luminous flux, which is provided by the manufacturer at the level of the fixture surface. This step is essential to predict the number of fixtures of each category to be used, using the average illuminance.

Case study:

The building that we are studying is an industrial building, for testing automobile equipment. The building has a steel structure. The dimensions of such building are 300 x 400 x 50 ft^3. Within such building, about 50 testing cells, equipped with independent HVAC system to maintain constant temperature and relative humidity conditions for testing.

The building is equipped with high bay metal halide fixtures and 8 feet fluorescent T12 fixtures. The T12 are used to light the three aisles. Regarding the aisle, our objective is to upgrade the existing T12 fixtures, using either T8, T5, T5HO, or LED. These types of fixtures are different in term of initial cost, energy consumption and can give you relatively the same quality of light (CRI and CT).

Upgrade from T12: The need to upgrade the fluorescent T12 luminaires is not only to save up to 40% of energy, but because of the legislation mandated the phase-out of the majority of T12 lamp production is effective since July 2012. Other benefits are to improve the lighting quality, improves light output and color quality, eliminates flickering and buzz that T12’s can cause, and makes your building look better/feel newer. All these lead to increase the productivity.

For energy considerations, and according to International Energy Conservation Code, the Lighting Power Density is selected to be around 0.41 W/ft^2 for the aisles area. Form IES recommendation, we selected the illuminance for different location of the building, to ensure safety and productivity.

Several quantitative and qualitative factors must be taken into consideration when choosing High Bay Lighting including: Illuminance, Color Rendering Index (CRI), and Efficacy and cost-effectiveness.

Type of fixtures:

- Metal Halide High Bay lights, with brilliant high-intensity output (41,000 lumens) and useful life of 20,000 hours.
- Fluorescent
- LED

Our objective is to compare three types of fixtures (three systems).

- TZL1N L96 (System 1)
- TZ154T5HO (System 2)
- TZ132 MV (System 3)

Assumptions:

- Recommended Illuminance (Foot-candle): IES requirements
- LLF ~ 0.65 (IES Recommendation)
- CU is calculated by the Visual Software
- Area (from company AUTOCAD drawings)
- Fixtures characteristics (from the manufacturer)

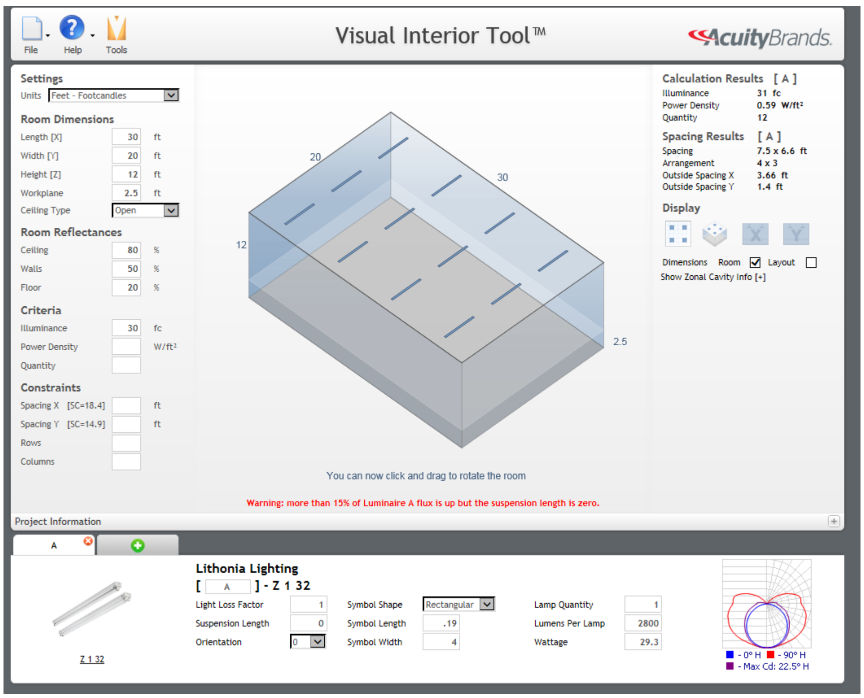

Figure 1: Visual Indoor Tool

Testing Cell Calculation:

- Cell Dimensions: variable
- Illuminance (Foot candle) recommendation from IES: 20 fc
- LLF (lighting lose factor): 0.65
- Reflectance: Ceiling: 70%, Wall: 50 %, Floor: 20 %

Table 1: The size of the cells and the number of rooms.

Area (SF)	Number of Rooms
Less than 100 SF	1
Between 100 to 200	18
Between 200 to 300	2
Between 300 to 400	13
Between 400 to 500	27
Between 500 to 600	7
Between 600 to 700	12
Between 700 to 800	4
Between 800 to 900	1
Over 1000 SF	6

Whole Building Calculations:

Assumptions

- Ceiling Height of Testing Cells: 12'
- Ceiling Reflectance: 70%
- Wall Reflectance: 50%
- Floor Reflectance: 20%
- Light Loss Factor: 0.65

Economic Analysis and Life Cycle Cost Analysis:

Visual economical tool allows for life cycle cost estimation. This means that the estimation includes not only the initial cost (purchase luminaires, lamps, controls), but energy cost, maintenance cost (lamps and ballasts replacement, and cleaning), disposal cost (lamps and ballasts recycling), controls savings (energy use reduction), and the additional HVAC cost (to remove heat produced by lighting) due to lighting.

The students have to compare multiple alternatives that are similar in term of lighting quality, and select the best and the most appropriate solution in term of cost.

Life cycle cost analysis take into account the time value, which can be illustrated by the fact that you could do more with the money now than you could if you wait for a year. Consequently, more money in the future has less value in comparison to present value. The discount rate, also called opportunity rate or interest rate is a value that is used to discount the future cash flows to put them in terms of the present value. Discount between 3 and 12% is a good starting value if no information is available to make a better estimate. Usually, the students need to test a range of rates. Higher discount rate places more emphasis on initial cost, where lower discount rate has a relatively greater impact on future events. The higher the discount rates decrease the life cycle cots present value, and the difference in cost between systems.

Maintenance cost is an aspect of cycle cost estimation. They are often overlooked by simple estimation methods. Labor rates directly contribute to the total maintenance costs and easily underestimated. Common maintenance estimation in locations such as high bays and pole mounts require special equipment such as scissor lifts or cherry picker tracks. The owner may have to pay the rent for these equipment.

The hourly cost lamp replacement need to be taken in consideration. Labor cost is different from system upgrade (upgrading the fixtures that use T12 lamps to hold T8 or T5 lamps) to system replacement (where the whole fixtures are replaced by new fixtures, such as LED fixtures). To increase or decrease the labor cost for a particular system, the service time in the maintenance section may be changed.

Each system may have up to four separate controls included. Each control can reduce the energy system uses, or the amount of time lighting systems is turned on. For effectively control to be calculated a type must be selected and the quantity must be also decided. The quantity here refers to the total quantity of the control type and is not a preliminary quantity. When you select a control, reduction factors are automatically identified by the program. The students (designers) need to confirm these reductions are appropriate for their project. There are case studies showing the actual energy saved by using controls (http://gaia.lbl.gov/btech/papers).

Your total reduction factors are calculated and displayed. Some control types may affect the life of the lamps. This can be accounted for by entering a reduction of apply factor. The students, under the supervision of the instructor, need to estimate the decrease or increase in the life.

The students have the possibility to use a control that is not already in the drop-down list, by selecting other time reduction to control and reduce hours of operation or other energy reduction if the control will reduce energy use while the luminaire is turn down. If daylighting control system includes dimming and shut off, the students need to include a separate time reducing control in addition to the standard daylight energy reduction.

By selecting an HVAC type changes in the operation and size of heating and cooling units due to heat generated by lighting equipment will be considered. Use the new HVAC system type if the HVAC system has been designed yet or will be resized in a renovation. Use the existing HVAC type if the HVAC is already in place. Adding an HVAC to your system will likely increase the life cycle cost, but it will typically not change which system has a lowest life cycle cost. Cooling hours can be displayed by the computer program; by selecting a cooling zone from the drop down (USA is divided to 5 cooling zones). Cooling hours are the hours the cooling system will be turned on. Cooling in our information is available only for the United States. If the project is outside USA, the students need to estimate the cooling hours using their HVAC knowledge. When selecting a cooling zone, the heating hours will be automatically calculated using the equation a simplified equation: Heating Hours = [0.85*(lighting hours) – cooling hours]

The initial maintenance and operating costs factors for the HVAC section are based on the recommendation values provide by designers. The students are warned that the analysis is not completed if they just enter on all the values and look at the answer. They need to experiment with changing the discount rate, electricity rate and labor rate until they have a good understanding of how changing these values affect your life system costs. They need to perform a parametric study. By experimenting with these values, they will develop an understanding of how sensitive their life system costs to different parameters.

If the system is particularly sensitive to labor rates, they need to make sure that they can defend their selection of a particular labor day. They are advised that the resulting outputs are only as good as the inputs.

Visualization of the illuminance over the work plane (point by point method) is a necessary step, where the students have an idea about the distribution of illuminance over the work plane, to detect the dark spots and the spots where an excessive. This step is necessary to check the finale design.

Economic Analysis:

- Same Value for all System
  - Ballast Cost
  - Disposal Cost
  - Replacement Cost
  - Cleaning Time
  - Lift Cost
- Initial Cost
- Annual Utility Savings
- Payback

Comparison between the fixtures

Data related to fixtures from table 2.

Table 2: input of the three systems analyzed

Fixture Data					
Fixture Type		Wattage	Fixture Lumens	Fixture Count	Total Wattage
System 1	TZL1N L96	82	7874	303	24846
System 2	Z 1 32	29.3	2800	1017	29798.1
System 3	Z 1 54T5HO	56.6	4450	638	36110.8

Table 3: results of the economic analysis

	System 1	System 2	System 3
Fixture Cost ($/Fixture)	255.7	69.45	43.6
Fixture Quantity	303	638	1017
Ballast Cost ($)	12	12	12
Disposal Cost ($)	50	50	50
Replacement Cost ($)	75	75	75
Cleaning Time (Minutes)	45	45	45
Lift Cost	500	500	500
Initial Cost	116,713	119,243	161,914
Energy Cost	132,438	192,483	158,834
kWh Savings (Annually)	217651	316331	261031
Annual Operating Cost	27852	70426	65479
Annual Utility Savings ($/fixture)	65479	42201	64683
Payback (Years)	8.9	4.1	5.7

Indirect Assessment Results

Using the indirect course evaluation form, students were asked, anonymously, to self-assess their ability in specific areas identified by the instructors in connection with the course learning objectives related to ABET. The compilation of the results of the student self-assessment of course learning objectives questions for AREN 485 are presented in Table 4. The student responses of "A" through "E" were converted to a 4.0 GPA scale in the standard way, with an "E" being considered equivalent to an "F". In this way, an equivalent class GPA was obtained for each question. The results of the students' assessment show that for all the questions, students generally feel like they are able to perform the task requested. The next step is to check if the assignments performed by the students will show the same positive answers.

Direct Assessment Results

The five course learning objectives were measured using exam questions and home works. The average grading of such exams and home works are shown in figure x. One or multiple exam questions were associated with each learning objective, permitting that learning objective to be measured by direct assessment. The points scored per question were converted to a percentage scale and then to an "A" through "F" scale, using the traditional grade assignments. Table 5 shows the breakdown of letter grades received for each exam question. The equivalent class GPA is shown for each question, based on a 4.0 scale.

Direct assessment provides the most accurate measure of a student's knowledge in a given course. In this course, about 50% of students were able to have a grade of "A". The other 50% are subdivided between "B" and "C". Some students were not able to answer the questions successfully, obtaining grades of "F".

The direct assessment of the five learning objectives is relatively acceptable, but need improvement. However, the students received better grades in their other assignments. The assignments used for this assessment are relatively hard.

A more rigorous process in assessing the learning outcomes of this capstone course will be implemented, which are in parallel with the program outcomes. The following outlines process will be used for this capstone course assessment.

- Individual instructor evaluation of the degree of learning achievement of individual students on a capstone team, which includes consideration of the collective achievements of the team.
- Peer evaluation (optional by instructor).
- Grading of deliverables by the instructors (project plan, mid-term review, final report, exhibit (and abstract), oral presentation, team minutes, web site if applicable).
- Teamwork survey.
- Self-assessment.
- Senior Design Symposium judging (with evaluation criteria explicitly indexed to the learning objectives and articulated via rubrics for all measures).

Table 4: Results of Indirect Assessment for AREN 485 (twenty students in the course)

Indirect Assessment						
Student Self-Assessment of Course Learning Objectives	**Number of A's**	**Number of B's**	**Number of C's**	**Number of D's**	**Number of E's**	**Equivalent GPA (4 to 0 scale)**
Capable of performing building assessment: lighting measurement	12	5	2	0	1	3.35
Capable of performing evaluation and analysis of Actual measurement vs. computer prediction	12	5	2	0	1	3.35
Capable of making the best Lighting fixtures selection	14	6	0	0	0	3.7
Capable of performing Economic Analysis and LCCA	10	7	2	0	1	3.25
Capable of understanding the difference between fundamentals: illuminance, luminance, luminous flux, and so on.	10	7	2	0	1	3.25

Table 5. Results of Direct Assessment for AREN 485 (twenty students)

Direct Assessment						
Course Learning Objectives	**Number of A's**	**Number of B's**	**Number of C's**	**Number of D's**	**Number of E's**	**Equivalent GPA (4 to 0 scale)**
Capable of perfoming building assessment: lighting measurement	10	5	3	1	1	3.1
Capable of performing evaluation and analysis of Actual measurement vs. computer prediction	11	4	2	0	2	3.0
Capable of making the best Lighting fixtures selection	10	5	3	1	1	3.1
Capable of performing Economic Analysis and LCCA	10	3	5	0	2	2.95
Capable of understanding the difference between fundamentals: illuminance, luminance, luminous flux, and so on.	10	5	3	1	1	3.1

Conclusions:

Teaching a design courses for undergraduate students is challenging and require real applications, where students need to perform real engineering application. The main objective is to familiarize them with the Life Cycle Cost Analysis (LCCA). For that a comparative study is performed between three types of fixtures: T12, T5HO, and LED fixtures.

LCCA is very sensitive to the quality of the input that students need to collect regarding the efficiency and finance of several systems. Displaying total cost, operating costs, as well as the average percent of lamp life over time have a significant effect on the final decision.

Both direct and indirect assessments revealed that students had an exaggerated view of their own capabilities. More work is necessary including changes in the design courses and the lighting labs at junior level, where an emphasis on equipment, measurement, as well as fundamentals is necessary. As well, an emphasis on LCCA is decided at the junior level.

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