Improving Lighting Efficiency in a Dairy Housing Facility

BREE 495
Engineering Design 3

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19 April 2013
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Executive Summary

Fluorescent lighting is the most commonly used system in dairy housing facilities, but it is not the most efficient lighting option. The goal of this project was to design and test a light-emitting diode (LED) lighting system for the dairy housing facility at the Macdonald Campus Farm ("the barn"), a research facility operated by McGill University. The efficiency of maintenance was considered in the design, particularly the ability to clean the lights regularly.

Previous testing of the fluorescent tube lighting system at the barn revealed that the illuminance was significantly lower than the recommended ASABE Standard (2005). The main objective of this project is to design an LED lighting and fixture system for use in the dairy housing facility of the Macdonald Campus Farm, which meets the following key requirements: utilizes maximum available energy efficiency; restricts illuminance to a minimum of 200 lux at a 1 m plane above the ground; and minimizes maintenance through a long bulb life and pressure-washable fixtures. The goal of the design is to meet the stated requirements using a retrofit of the current fixture layout installed at the facility.

While the initial design of the prototype features LED tube lights, silver laminate reflectors, and a watertight and insect-proof seal, the final prototype was optimized through the removal of the reflectors. Due to the directional nature of LED lights, which became apparent during prototype testing, the reflectors were unecessary. The prototype was tested to determine its generated intensity values (in lux), and a 2D computer-simulated lighting model was developed to represent the full installation of the prototype in the barn. These results were compared with the initial illuminance testing of the current fluorescent lighting system. This allowed for the validation of the model, and furthermore demonstrated a 33% increase in luminosity when the prototype installation was simulated.

The results show that the prototype came very close to satisfying the ASABE Standards (2005), which require 200 lux or higher, providing a barn area with 87.1% of light intensity values exceeding this standard. If installed at the barn, this design has the potential to significantly improve human working conditions. The total cost of implementation was estimated to be $7421.40, implying a payback period of 13.9 years for agricultural use. Due to increased popularity of green technologies, subsidies are available to aid in the retrofit. An extended testing period of several years would be required to prove that it could achieve these design objectives under operating conditions.

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1.0 Introduction and Objectives

Currently, fluorescent lighting is the most commonly used lighting system in dairy production facilities, but it is not the most efficient option. The goal of this project is to design and test a light-emitting diode (LED) lighting system for the dairy housing facility at the Macdonald Campus Farm ("the barn"), a research facility operated by McGill University. LED lighting is a new technology that is not widely used yet on the market, and minimal research has been done on its performance in a dairy housing environment (Clark, 2006).

LEDs were selected for this design for numerous reasons. According to the United States Department of Energy (2012), LED lighting systems release 80% less energy as heat and last up to 5 times longer than fluorescent tube lights. They are highly directional in the emission of light, making them especially efficient at "down lighting" when oriented towards the floor. This allows for less light intensity loss to the sides, making diffusers and reflectors unnecessary. The efficiency of maintenance will also be considered in the design, especially the ability to clean the lights regularly. With no reflectors, this becomes much easier. Overall, LED lighting could potentially increase maintenance efficiency and energy efficiency if implemented in a dairy house facility.

The barn currently comprises a 4-row, tie-stall layout to house dairy cattle, and initial testing was previously done on the current lighting system to find the depreciation factor. The light intensity was measured throughout the barn, and the results showed that the illuminance ranged from 30-293 lux. Under ideal conditions, including clean light fixtures and new fluorescent tube lights, the illuminance ranged from 113-316 lux. According to the ASABE Standards (2005), the recommended minimum illuminance level is 200 lux. Therefore, with the fluorescent lighting, certain areas in the facility were significantly below the illuminance standard.

The main objective of this project is to design an LED lighting and fixture system for use in the dairy housing facility of the Macdonald Campus Farm, which meets the following key requirements: utilizes maximum available energy efficiency; restricts illuminance to a minimum of 200 lux at a 1 m plane above the ground; and minimizes maintenance through a long bulb life and pressure-washable fixtures. The goal of the design is to meet the stated requirements using a retrofit of the current fixture layout installed at the facility.

To meet these design objectives, a prototype incorporating the key design aspects will be created, based on an LED retrofit of the current T8 and T12 fluorescent tube lighting in the barn. Through an extensive evaluation conducted previously, it was determined that this would be the most efficient choice, with respect to bulb efficacy (150 lumens/Watt), lifetime (100 000 hrs), and colour rendering index - CRI (100). The initial design of the LED features silver laminate reflectors and a watertight and insect-proof seal. This system is advantageous, in that it is made economically feasible by retrofitting the LEDs to fit fluorescent tube ballasts currently installed at the barn. The compact design and waterproof seal will also increases the ease of maintenance.

Testing will be conducted with the prototype, with the aim to simulate the lighting in the barn. The data collected will then be used to generate a 2D computer-simulated lighting model of the full installation of the prototype in the barn. These results will be compared with the initial illuminance testing of the current fluorescent lighting system. In this way, the computer-simulated lighting model will be validated, and it will be possible to analyze the success of the prototype at meeting the design objectives. A cost analysis will also be presented to determine the payback period.

2.0 Analysis and Specifications

2.1 Design Constraints

In designing the prototype, it was determined for simplicity and for the attractiveness of the product to potential consumers that the existing lighting infrastructure would remain intact. The existing infrastructure consists of the fluorescent fixtures and their positioning, as well as the electrical wiring of the barn. The largest design constraint was the ability to use an LED light within a fluorescent fixture. Through the analysis of the lighting systems it was proven that the current fluorescent fixtures could be rewired to accommodate LED tube lights (IG, 2013) by simply bypassing the fluorescent ballasts. This method is a simple solution to the first design constraint.

The positioning of the light fixtures was a secondary restraint that correlated to the maintaining of the electrical wiring. Since the fixtures could not be moved, it was important to consider the distribution of the light to ensure maximum coverage of the barn. When LED lights were chosen as the best option for the final design, the concern of acquiring proper light distribution was enhanced. Fluorescent lights generally distribute light in all directions whereas LEDs are very directional; in this case downwards (Heffernan et al., 2007). The positioning of some of the fixtures were rather spread apart and therefore low light areas were a concern and needed to be solved through other aspects of the design, such as proper reflection within the fixture.

The design constraints posed some challenges and influenced decisions made in the overall design process. The final product however was capable of overcoming the existing infrastructure constraints by incorporating the current fixtures and properly distributing the LED light to meet ASABE and industry standards.

2.2 Analysis of LED Component

When choosing a light, it is essential to evaluate certain key aspects such as cost, safety, quality of light, and reliability. According to Peck et al. (2011), movement towards more efficient lighting and reduced power consumption is essential. Through extensive analysis, it was shown that LED lights are the most efficient lighting option for several reasons. The analysis was done by comparing different light types, based on efficacy (lumens per Watt), lifetime (hours), and CRI (colour rendering index). This research revealed that LEDs had the highest CRI (100), efficacy (up to 150 lumens per Watt), and lifetime (over 100 000 hours).

Furthermore, a study done by Heffernan et al. (2007), looked at the comparison between fluorescent with LED lighting. Although results showed that fluorescent lighting had a higher radiant light power, the light waves of this type of light are spread out at a 360˚angle. Therefore, a large portion of this light is lost. LED lamps are made up of multiple "white" LEDs and thus result in multiple point sources. Areas directly underneath point sources are high in radiant light power. In terms of environmental waste, LEDs have zero impact on the environment.

2.3 Selection of Fixture and LED Lights

The central part to the prototype design was the light fixture. Westburne Electric was chosen as the supplier because of their close proximity to the Macdonald Campus and their large inventory collection. Unfortunately, the existing fixture, produced by Mid-day Lighting Inc. Model number: VAP240C86, were out of production and not available (Figure 1). The existing fixtures are rated for 32 Watts, 2 lamps, at 120 Volts on alternating current. They have a length of 127.0 cm (4'2") and a width of 17.8 cm (7"). The fixture has a depth of 7.6 cm (3") while the diffuser has a depth of 6.4 cm (2.5") giving a total depth of 14 cm (5.5") (MDL). The existing fixtures can utilize both T12 and T8 fluorescent lamps and can be mounted to a wall or ceiling. The desired fixture was as similar as possible to the current fixture.

Figure 1. The fixture currently used in the Macdonald barn (Mid-day Lighting, VAP240C86) is no longer available.

After consulting Westburne Electric, it was determined that the closest imitation fixture to the existing fixture was the Thomas & Betts Emergi-Lite IPE series: IP65 Linear Fluorescent Fixture. This fixture is rated for 32 Watts, 2 lamps at 120 volts on alternating current. It has a length of 129 cm (4' 2 ¾") and a width of 17 cm (6 ¾'). The fixture has a total depth of 10 cm (3

¾’). The chosen fixture can utilize both T12 and T8 fluorescent lamps (Thomas and Betts, 2013). Specifications of the chosen fixture and the price quote can be found in Appendix A.

Five suppliers on the Island of Montreal were investigated in order to source the LED lamps, and ultimately a private supplier was chosen based on pricing. The lamps are fabricated by Intertek Group, model number T8-2-L3HAPW288A2212. They are rated for 18 Watts and reduce the current to 180 mA. They are 1.2 m (4’) long, which is exactly the same length as the existing fluorescent tubes in the barn. Each lamp contains 288 LEDs and has a coating to ensure ‘pure white’ colour emission (IG, 2013).

2.4 Mathematics of Wall Reflectivity

The computer model discussed in detail in section 3.4 was required to account for the potential reflection of light off the barn walls. It is reasonable to assume that the smooth, white-painted metal walls of the barn will reflect a certain percentage of the incident light, since not all of the light is absorbed or transmitted through the surface. In fact, there are two types of reflectance factors: the directional reflectance factor, and the irradiance reflectance (Jupp, 1997). For this model, the directional reflectance factor was used.

In general, most of the light is diffused off the walls in all directions. The incoming light wave hits the wall at the angle of incidence to the normal, and leaves the wall at the angle of reflectance (Fellers and Davidson, 2004). According to Parker (2009), the average reflectivity of a white painted surface, similar to the barn wall, is 70%. Thus, in the simulated illuminance matrix, 70% of the illuminance at the wall surface is added to the adjacent data points. Palmer (n.d.) states that the average angle of reflectance of a light wave off of a white-painted surface is approximately 27˚. To obtain an average specular reflectivity, the light wave hitting the center of the wall was assumed to be representative of the main diffusion path. In the actual barn, the light would be diffused in all directions, depending on the wall’s roughness factor.

Given that the ceiling height of the barn is approximately 3 m, the incident light wave was estimated to contact the wall at a height of 1.5 m above the ground (see Figure 2). It was estimated that the incident ray contacted the wall at 45˚, and was reflected at 27˚ below the normal. Therefore, the 70% reflectivity of the wall would affect illuminance data points within approximately 0.98 m of the wall. Each data point was taken 0.75 m away from the wall, and 1 m above the ground. Therefore, due to these assumptions and calculations, each illuminance data point adjacent to the wall was increased by a factor of 0.70 (or 70%).

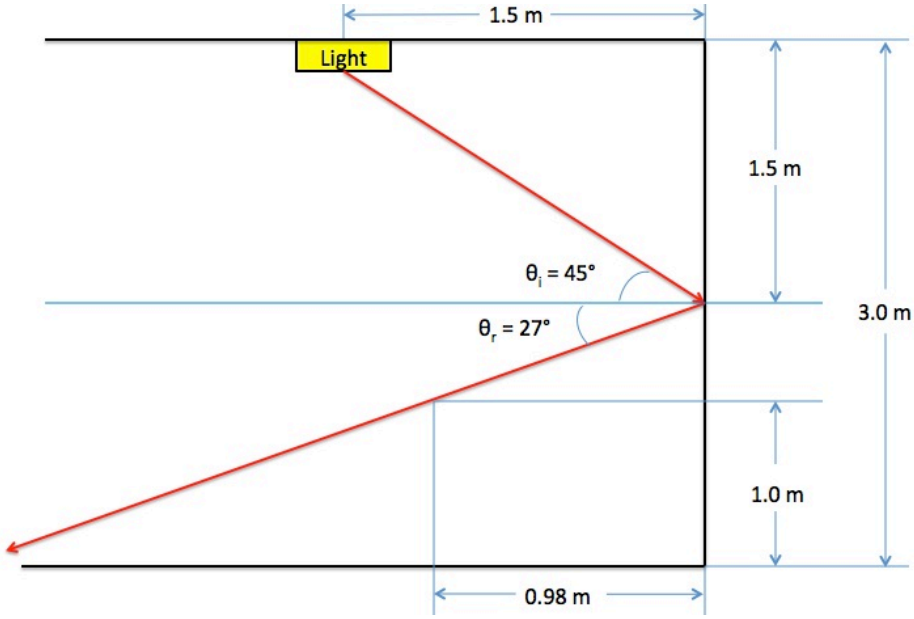


Figure 2. The reflectivity of the white-painted metal walls in the barn was accounted for in this mathematical approximation.

It is important to note that these assumptions were made within the context of the computer simulation of the barn lighting, and based on smooth, white-painted metal walls. In an actual dairy barn with cattle, many factors will influence the illuminance of the lighting system. Some of these factors include: dirt accumulation on walls, interference of nearby objects, and outdoor light penetration.

3.0 Prototyping, Testing, and Optimization

3.1 Construction of Prototype

The construction of the physical prototype involved three stages: 1) Research, 2) Procurement, and 3) Assembly. The topics of Research and Procurement are discussed in section 2.3, and now the Assembly will be discussed. This involved the construction of the prototype, which included the following parts acquired: 1- 4' tube fluorescent tube light fixture, reflective fixture surface, 2- LED tube lamps, waterproof seal and 1- diffuser with minimal surface area.

In order to create the waterproof seal, 100% silicone caulking was chosen to form a double gasket between the fixture and the diffuser. One ring of caulking was to be applied to the fixture while the other was applied to the diffuser (Figure 3). A double seal was chosen because of its low cost and decreased chance of failure. Silicone caulking provides an ideal material to form the gasket, because of its low cost, straightforward application method, and fast curing time. Silicone is also a very flexible material and will not degrade or crack as a result of temperature changes.

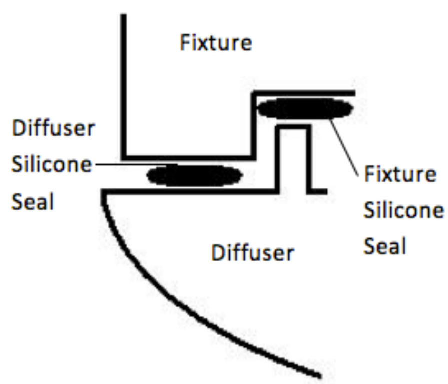


Figure 3. Side elevation cut of the double silicone gasket seal, showing the duel layer of silicone (not to scale).

The diffuser was chosen from a range of possible shapes available from Westburne Electric. The one selected was shaped as an elliptical prism with a smooth outer surface. This reduces the surface area of the diffuser compared to the existing rectangular prism design. It has a surface area of 0.177 m^2 (273.7 sq. in.), while the existing diffusers have a surface area of 0.25 m^2 (386 sq. in.). This represents a reduction of 30%. Reduced surface area ensures that less dirt collects on the projecting surface of the lamp, resulting in higher illuminance during operation.

3.2 LED Retrofitting Process

The individual components described in section 2.3 and 3.1 were then assembled to create the working prototype. A major step in assembly of the prototype was to rewire the fixture to be suitable for LED operation. While fluorescent tube lights utilize a ballast to regulate the current flowing through the low-resistance gas inside the tube lamps, this ballast is not necessary for LED lamp operation. Therefore the ballast must be removed from the wiring. Figure 4 shows a schematic of the existing fixture, and how the ballast is incorporated into the wiring.

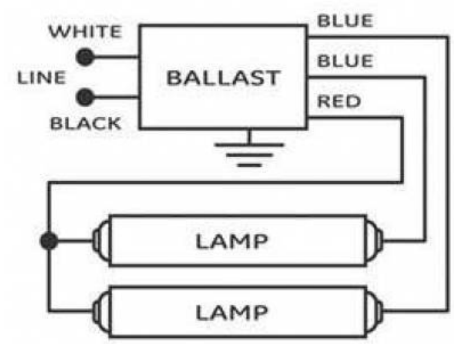


Figure 4. The "black" line indicates the positive wire entering the ballast from the outlet, and the "white" line indicates the negative wire returning to the outlet. The ground wire comes off the fixture and is connected to the outlet. The "blue" lines indicate the positive charge entering the lamp from the ballast. Finally, the "red" line indicates the negative charge returning to the ballast. Adapted from Thomas and Betts (2013): 'Installation Instructions'.

In order to modify the circuit for LED operation, the ballast was removed from the circuit. The final circuit is shown in Figure 5, with the lamps wired in parallel to ensure that only burnt out lamps go out.

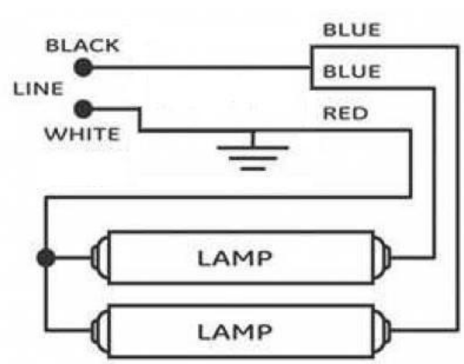


Figure 5. The "black" line indicates the positive wire entering the ballast from the outlet. The "white" line indicates the negative wire returning to the outlet. The ground wire comes off the fixture and is connected to the outlet. The "blue" lines indicate the positive charge entering the lamp. The "red" line indicates the negative charge returning to the outlet. Adapted from Thomas and Betts (2013): 'Installation Instructions'.

In order to properly rewire the circuit, the power must be completely disconnected. The existing diffuser and fluorescent tubes are removed, followed by the fixture panel behind the diffuse. The wires can then be cut leading into and out of the ballast, and the ballast can be removed from the fixture. The “black” input wire is crimped to the “blue” lamp input wires, while the “red” output wire is crimped to the white output wire. The ground is wired from the fixture to the outlet ground. The new fixture was wired to a three-prong outlet plug to act as the wiring input for the existing fixtures. It is important to properly dispose of the ballast after removal at an electronics recycling facility. After this process, the LED tube lights simply needed to be installed in the light in the same way as the old fluorescent tube lights. This process was estimated to take 20 minutes of a professional electrician’s time per fixture.

The reflective coating (aluminum tape) was then installed on the fixture panel before it was reinstalled on the fixture. Once the panel was in place, the new tube LED lights were installed on the fixture in the same manner as typical fluorescent tube lights. The silicone caulking can then be installed using a caulk gun in the indicated place on the fixture, forming the first waterproof seal. The second silicone gasket is installed onto the reduced-area diffuser. Once the caulk has cured, the diffuser can be clipped onto the fixture and the power turned back on.

3.3 Testing Methodology

In order to test the illuminance of the prototype, a testing methodology was developed. The testing site chosen was inside a dark, empty hayloft and was conducted at nighttime to minimize light pollution and interference with data sampling. In order to keep the model as accurate as possible, the illuminance was measured using a 6 m by 6 m grid. Each square of the grid was 0.75 m by 0.75 m, creating a 9 by 9 square grid with 81 data points (Figure 6). It was determined that a grid this size would accurately capture the entire footprint of the lamp. This was validated during the testing, as a result of the negligible levels of illuminance observed around the perimeter of the grid. See Appendix B for the data obtained through prototype testing.

The fixture was hung 3.0 m (10 ft) above the ground level to simulate the dairy housing facility environment. The power supply cord was hung above the light fixture to ensure it did not have an effect on the illuminance. The illuminance was then measured using a Reed Precision Instrument LM-81LX Light Meter in lux (RPI, 2008). This was the same unit used to obtain the brightness of the existing lighting system. The illuminance was measured on a 1 m plane above the ground level, at each of the 81 points on the grid. This testing procedure was repeated 3 times in order to reduce the chance of error in measurement.

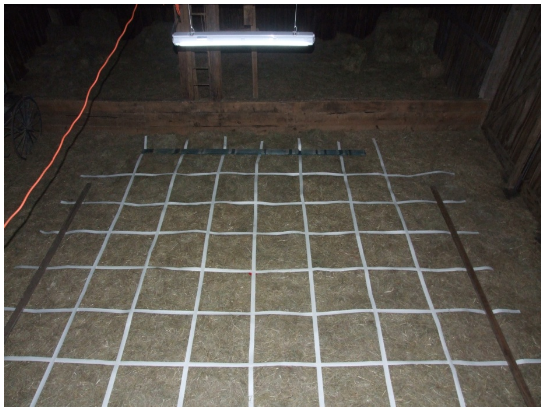


Figure 6. The testing grid developed for the prototype consisted of 81 data points, and covered a total area of 6 m by 6 m.

3.4 Computer Simulation of Prototype

The stated objective was to use data collected from testing the prototype to generate a 2D computer simulated model of the lighting at the dairy housing facility. This model was intended to represent the improvement in light intensity in the barn with the installation of the prototype, as compared to the current lighting system. The main challenge of this simulation was to determine an efficient way to model the installation of the prototype at the barn. In order to do this, the model was required to position the prototype lights at the same locations where fluorescent tube lights are currently installed. The location of the current light fixtures may be clearly seen in Figure 7, where they are represented by purple bars.

Firstly, the grid point data from the three different prototype tests was entered into an Excel file. The arithmetic average of the three tests was taken, and this worksheet was saved as a "comma separated value" (.csv) file. This file was then imported into Matlab and translated to a matrix of 9x9 elements. From this matrix of intensity values, a light intensity-position curve could be generated to represent a single prototype light source. This is further discussed in the Results (section 4.2).

The aim was for Matlab to be used to generate a 2D contour plot, which would represent the overall light intensity in the barn with the installation of prototypes. It was proposed to accomplish this by fitting a polynomial surface to the 9x9 intensity matrix. Coefficients could then be generated using Matlab to create a specific, representative intensity equation describing a single prototype. Then, Matlab could be used to position each light source within a large, empty "barn" matrix according to shifts in the x- and y-coordinates of the intensity equation. The final stage of this proposed method was to sum each matrix containing a carefully positioned light value, to generate a final product representative of the full lighting scheme in the barn.

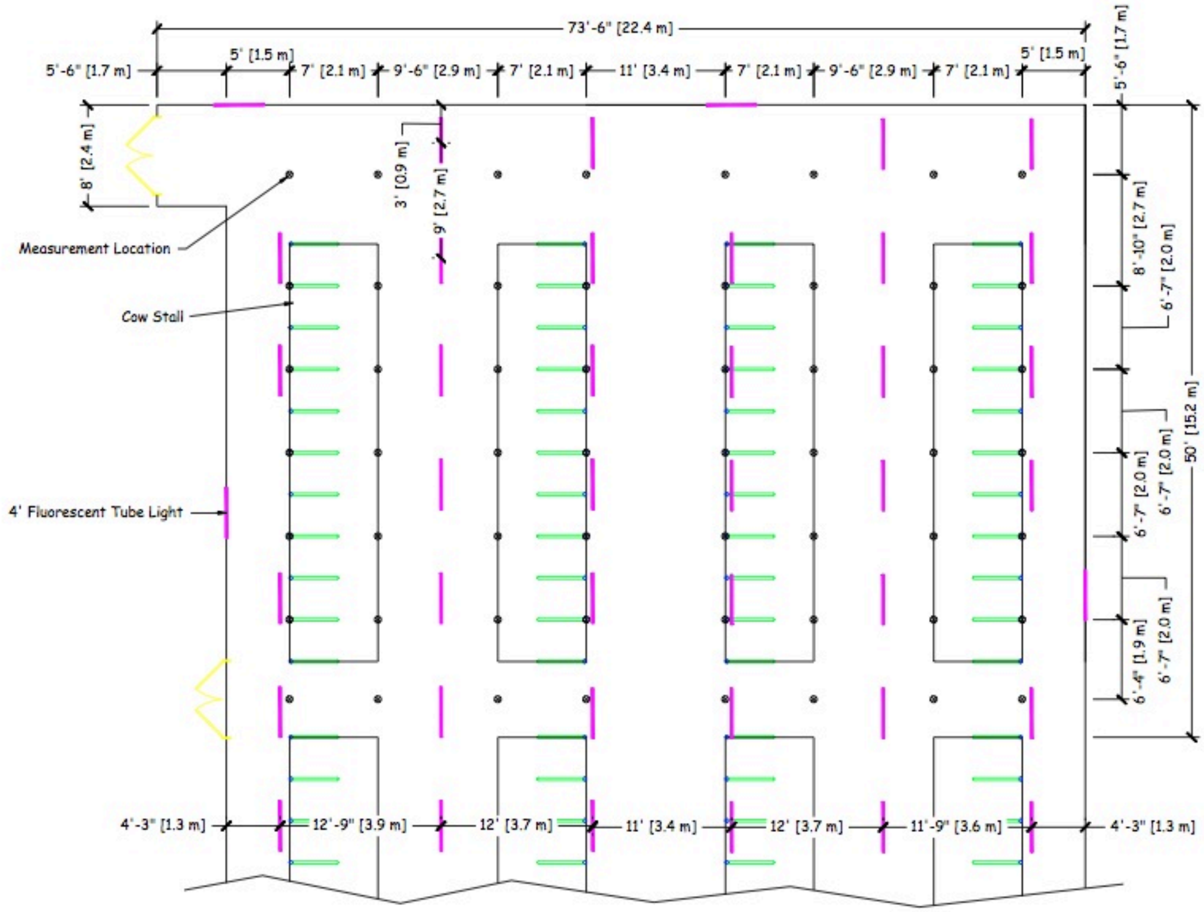


Figure 7. The location of the existing fluorescent tube lights in the Macdonald Dairy Farm are represented as purple bars. While most of the lights are mounted on the ceiling, there are four wall-mounted lights in the testing area.

Through extensive research, trial, and error, it was decided to use an alternative approach to modeling multiple light placements. Microsoft Excel was used instead of Matlab to overlay the 9x9 matrix of illuminance data into a 29x22 matrix (see Appendix C). This method was chosen because it was a more time-efficient alternative to the polynomial surface fitting in Matlab. The resulting matrix had the same dimensions as the barn, where each cell in the matrix represents a 0.75 m by 0.75 m area.

The center point of the average illuminance data was placed at the location of each existing light fixture in the barn, so as to simulate the average illuminance across the entire barn area. In places where the 9x9 intensity matrices overlapped, the data for those cells were summed. This Excel worksheet was then imported to Matlab as a comma-separated value file.

Matlab was able to translate the cell values to a 22x29 matrix of intensity values, and plot the data as a 2D contour plot. Although this method is slightly different from the one initially proposed, the final objective of generating a 2D computer simulated model of light intensity was met.

An important stage to the computer simulation and modeling process was the validation of the final model. This was accomplished by comparing the 2D contour plot of the prototype implementation to the same plot of the current lighting system at the barn. By comparing the simulated data to the true data collected at the barn, it was possible to see how closely the simulated conditions matched the actual conditions. Although each plot is representative of different light systems (both "simulated" and "real"), the intensity values generated were within similar ranges, demonstrating the model to be relevant and representative. For a more detailed comparison of the two systems, see the Results (section 4.2).

Several simplifying assumptions were made in the development of this model. Firstly, the lights mounted on the walls were assumed to be mounted on the ceiling. They were also shifted horizontally by approximately 1.3 m, in order to be in line with the other lights. Although only one half of the barn was considered in this project, the effect of the lighting from the other half was also considered. In order to account for light placements along the north side of the facility, additional intensity values were summed into the matrix to represent the light diffusing from the other side of the barn. It was also assumed that the walls reflect uniformly in all directions, with no interruptions caused by windows or doorways, and that the angle of incident light on the wall is consistent. It was also assumed that the reflected light waves would increase the illuminance of data points adjacent to the wall (see section 2.4). It is important to note that the model does not take into account the effect of objects that may interfere with the diffusion of light, such as beams, stalls, and cattle.

3.5 Revisions and Optimization

Through the research and the testing process, the prototype was optimized to enhance efficiency and cost, and to remove unnecessary components. As previously mentioned, LEDs have on average straight down directional light waves. Therefore, it was proven through testing that reflectors on the fixture had a negligible effect on the enhancement of radiant light. Furthermore, it was decided that for the prototype, it would be more efficient to use aluminum tape instead of silver laminate due to cost reasons. Aluminum tape is much less expensive, easy to find, and simple to incorporate into the prototype. Although silver laminate does have a higher specular reflectance (92-98%) and lower diffuse reflectance (1-2%), enhanced aluminum tape has very similar results of 85-91% and 5-10% respectively (Kloczkowski and Stolshek, 1989). Therefore, the difference in radiant light results can be termed negligible.

3.6 Failure Modes and Risk Analysis

Three areas were identified as potential areas for failure if this system was implemented on a large scale. The first is inadequate illuminance, the second being electrical failure, and the third being materials insecurely fixed to the ceiling.

If the model is invalid due to unforeseen circumstances, it is possible that the illuminance in the bar could be inadequate. This could be a result of a poor estimated reflectivity of the walls, greater than estimated effect of obstacles and obstructions, or a large amount of dirt getting deposited on the diffuser surface. This risk could be reduced by retrofitting a fixed number of fixtures in a specific location of the facility, and testing their effectiveness at installation after one month. The illuminance of these results could then be used to validate or dismiss the current model.

Faulty wiring, a short circuit, or failure of the waterproof seal during washing could all lead to an electrical failure. This could cause lighting failure and the potential replacement of a burnt out fixture. Using a licensed electrician to remove the ballast would mitigate this risk. It would also be mitigated through the ground wiring and the breaker box. If the fixtures are pulling large amounts of power from the source, the breakers switch the system off. This would shut down all the lights on the same breaker and create darkness in the barn. This effect is reduced by the presence of an emergency lighting system inside the barn. By having a double gasket seal between the diffuser and the fixture, and ensuring that the seals are protected by a plastic lip on the diffuser, the risk of water entering the fixture would be greatly reduced.

Finally there is a risk of parts falling from their fixed point in the ceiling. This risk is reduced by ensuring there are 10 clips holding the diffuser on, instead of the minimum 4 clips (one on each corner).

3.7 Economic Evaluation

The final design requires many components to function properly. The cost of each piece was analyzed in this section, in order to determine the feasibility of retrofitting a barn from the current fluorescent fixtures to the new LED design. An overall payback period is shown, as well as potential subsidies that are available.

Retrofitting the facility requires labour for altering the exterior sections such as the addition of aluminum tape for reflectivity and the addition of the water proof and bug proof double seal. Assuming that each fixture requires 20 minutes and the rate for the labour is $15/hour, one fixture will require $5 of labour. As well as the labour of constructing the light, an electrician is required. According to Stats Canada, the rate for an electrician in Quebec is $32.54/hour. Assuming once again that the fixture would require 20 minutes of electrical labour, it would cost $10.85 per fixture.

Each aspect of the final design pertaining to pieces required to build the product are listed in Table 1, as well as the cost of labour and electrical services. The overall cost for one fixture consisting of two LED tube lights, a new cover/diffuser, 24 linear feet of caulking, 300 in^2 of aluminum tape is $88.35.

Table 1. The components of the prototype and the associated costs of construction.

Item	**Cost ($)**
LED Tube Light (2)	60.00
New Cover (1)	4.50
Caulking (24 linear feet)	1.00
Aluminum Tape (300 in^2)	7.00
Electrician	10.85
Labour	5.00
TOTAL	**88.35**

Continuing to use the Macdonald Campus Dairy Housing Facility as the basis of this design, a payback period can be calculated. The barn has 84 fixtures overall and therefore a total cost of $7421.40 is required to retrofit to the new fixtures. To determine the payback period, the difference in Watts from the fluorescent bulbs to the LED bulbs was calculated to be 14 W. Currently, the Quebec rate for electricity for agricultural use is 7.78 cents/kWh according to Hydro-Quebec (2013). Utilizing these numbers the payback period is calculated to be 13.9 years (Equation 1).

Equation 1. Payback Period

$$\frac{Cost\ of\ retrofit}{Rate(\Delta Watts)(Hour\ of\ operation\ per\ day)\left(365\frac{days}{year}\right)(\#\ of\ fixtures)(\frac{1}{1000})}$$

It is noted that 13.9 years is a long payback period, and this is discouraging in hopes of a retrofit. However, with the demand for new green energies there are many subsidies available. A current program that is in place by Hydro-Quebec targets agricultural facilities. It encourages the use of more efficient lighting systems, specifically LEDs and new fluorescents. Due to provincial and federal subsidies and grants, this allows the retrofit design to become much more feasible by reducing the payback period.

4.0 Results and Discussion

4.1 Final Prototype

The final design of the prototype incorporates the existing infrastructure of the dairy housing facility. This component is mandatory for the proper execution of the design, since it simplifies the process of switching over to more energy efficient lights. The LEDs used were chosen for their ability to fit simplistically into the existing fixture. The design uses aluminum foil tape within the fixture to help disperse the given light properly. The area of the light cover was reduced by 30%, in comparison to the existing cover, and also helps in light distribution and prevention of dust build-up. This was accomplished by locating a newer cover that was rounded and smaller. For simplified cleaning, the fixture also incorporated a double water/bug proof seal made of caulking, to allow the consumer to pressure wash the lights without risk of damage. The final prototype may be seen in Figure 8.

Figure 8. The final prototype consists of an IP65 Linear Fluorescent Fixture (Thomas & Betts, 2013), 2 x 18 Watt LED lamps (Intertek Group, 2013), a dual layer silicone caulking seal, a reduced surface area hard plastic cover, and a retrofitted wiring system.

The design may be examined and understood in a more technical manner through AutoCAD drawings of the section (Figure 9), elevation (Figure 10), and plan view (Figure 11).

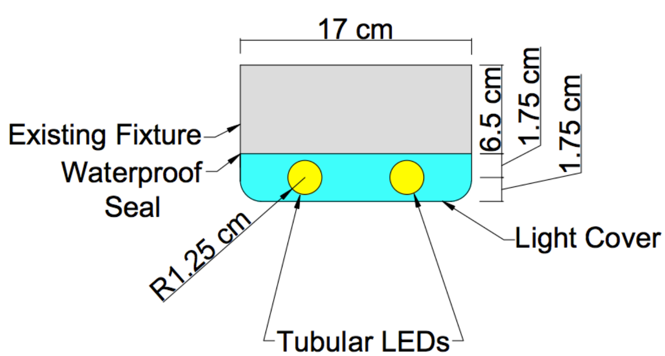


Figure 9. This dimensioned and labeled plan view of the final prototype demonstrated shows the reduced surface area of the light cover, as well as the location of the waterproof seal.

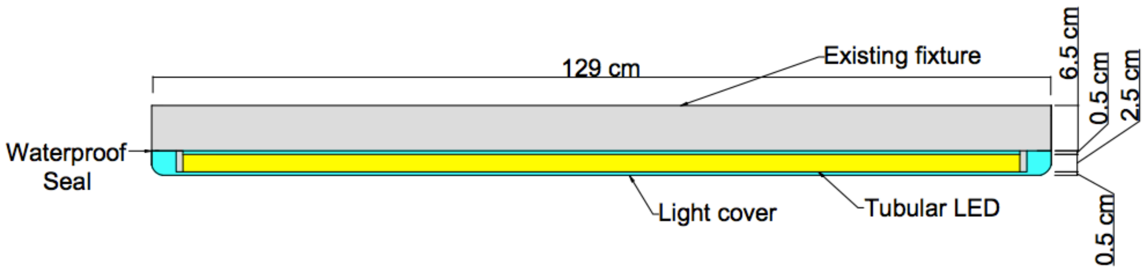


Figure 10. The dimensioned and labeled elevation of the final prototype shows the reduced surface area of the light cover, and the closely fitting LED tube lights. It may be seen that the design incorporates the exiting fixtures from the barn.

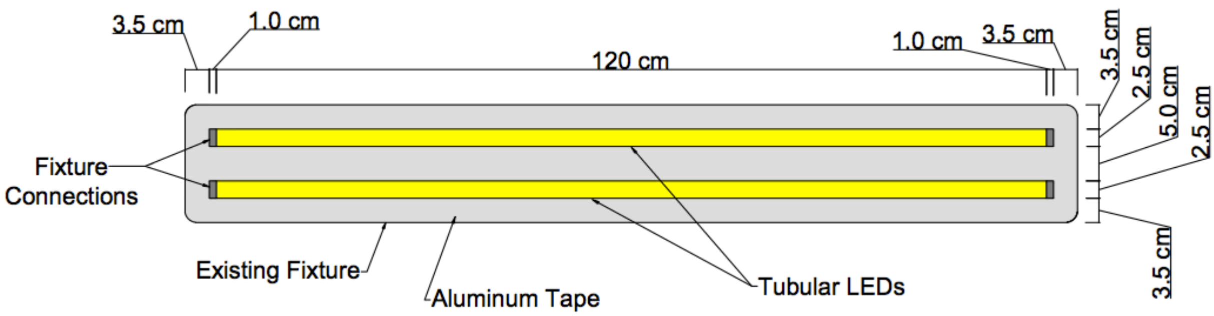


Figure 11. The dimensioned and labeled plan view of the final prototype shows the reflective, aluminum interior, as well as the spacing of the LED tube lights.

The specific design objective of a low maintenance prototype, with a long bulb life and pressure-washable fixtures was achieved in theory. However, without the ability to fully install the prototype and collect data over an extended period of time, it is not possible to prove that our design meets this objective in reality. In order to demonstrate the maintenance efficiency and long-lasting bulb life of the final prototype, it would have to be installed in the barn and monitored over a period of several years.

4.2 Results from Computer Simulation

Matlab was used to perform a computer simulation of the prototype and its installation in the barn, and two important results were obtained: an intensity-position curve for the prototype, and a 2D contour plot representing the prototype fully installed in the barn (Appendix D). Firstly, the intensity-position curve was generated using the 81 intensity data points collected during testing of the prototype. This plot represents the level of light intensity (lux) as a function of the proximity the light (m), and may be seen in Figure 12. It can be seen that the maximum value of intensity (212 lux) occurs directly below the prototype light source, at a location of x = 3 m. The light intensity diffuses towards the edges of the sampling grid, reaching minimum values of 12 lux at x = 6 m and 18 lux at x = 0.

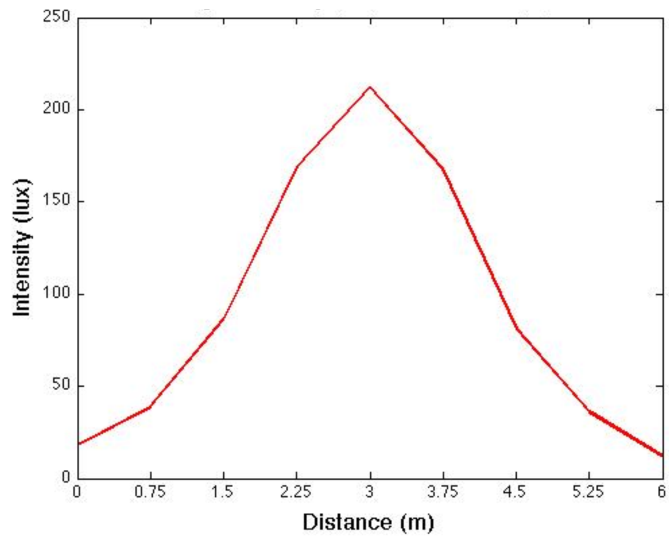


Figure 12. Plot of Light Intensity (lux) as a function of Distance (m) with respect to the prototype light source.

Matlab was also used to plot the matrix of intensity values obtained from Excel, when 42 prototype lights were positioned in the barn matrix with their light intensities overlaid. This was representative of the 42 lights currently installed at the barn, and was specifically chosen to meet the design requirements. The 2D contour plot of light intensity may be seen in Figure 13, and translated the 638 intensity data points into a colour map. In this plot, the intensity value ranges from just over 170 lux to 250 lux. It is important to note that the ASABE Standards require dairy barns to be lit at 200 lux or above, while the industry-accepted lighting standards are any intensity greater than 170 lux.

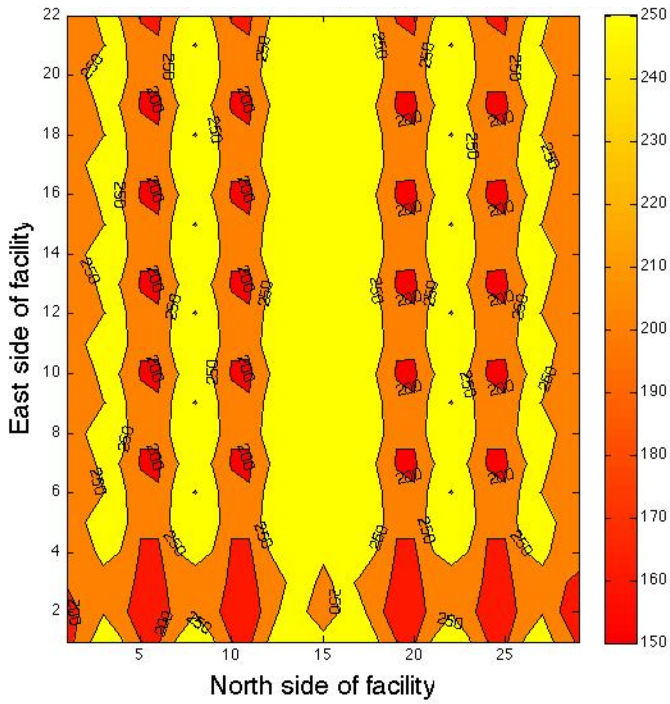


Figure 13. The 2D contour plot generated with Matlab shows the effect of installing 42 prototypes at existing light locations in the Macdonald Campus dairy barn. The plot represents light intensity (lux) as a function of position in the barn.

This plot can be compared directly with a similar 2D contour plot representing the newly replaced, fully cleaned fluorescent tube lighting currently installed in the barn (Figure 14). There are some significant differences between these two plots. Firstly, it can be seen that the installation of the prototype (14. b) has significantly decreased the areas represented in red and orange. These areas have intensities ranging from 150 lux to 200 lux, which are undesirable from the standpoint of the ASABE Standards. Since a greater area of yellow is indicative of intensity values above 200 lux, it is notable that this increase can be directly observed with the installation of the prototype.

In Figure 14. (b), there are several small areas of red and orange, which are very distinct as compared to the larger, more widespread red and orange areas in Figure 14. (a). This was attributed to the directional nature of LED lights, which do not diffuse in the same manner as fluorescent lights. The light orange areas along the east and west walls of the facility (Figure 14. b) are also observed to be quite uniform as compared to Figure 14. (a), which is due to the effect of the wall reflectivity assumptions. In the model, the effect of doors and windows along the walls was not taken into account, despite how in reality that would affect the reflectivity. This can be observed in the actual data collection in Figure 14. (a).

Figure 14. (a)

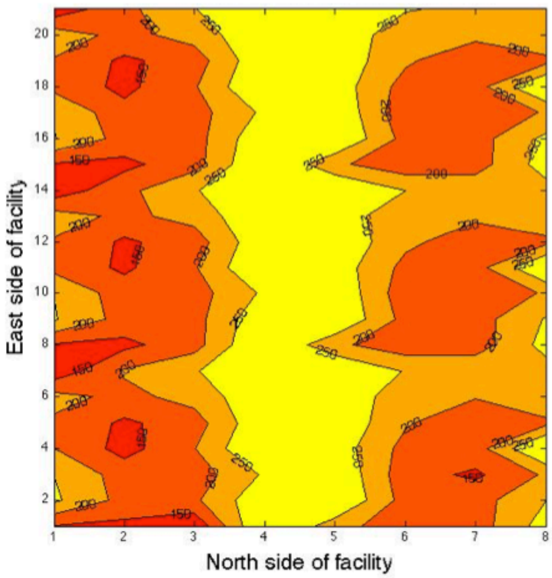


Figure 14. (b)

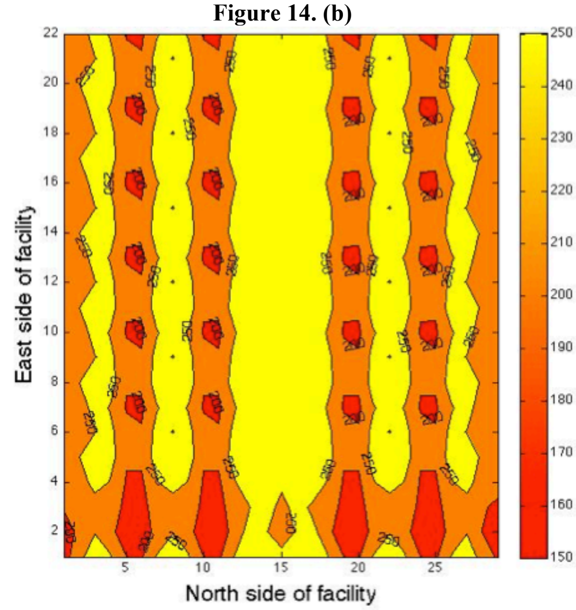


Figure 14. The current fluorescent tube lighting system (14.a) can be compared to the simulated installation of the prototype at the barn (14.b). On the far right, a colour scale indicates the light intensity levels, measured in lux.

The performance of the computer simulated prototype installation was compared to and validated against the actual data collected in Figure 14. (a). Examination of the intensity values in the matrices for each plot allowed for the generation of performance statistics. In order to determine the percent area that met the ASABE Standards, the ratio of accepted intensity values to unacceptable ones was formed. It was found that the prototype performed very well, with 87.1% of the barn area reaching intensities greater than 200 lux. This is compared to the current fluorescent system, which only achieved 54.2% of the barn area meeting this standard. As previously mentioned, the industry standard is 170 lux or greater. In this regard, the prototype allowed for 98.7% of the barn to meet this lighting requirement, while the current system only achieves 79.5%.

In general, the prototype is capable of improving lighting efficiency by up to 33% based on the assumptions made in the model. In reality, these assumptions likely improve the performance of the model, and are not fully representative of the true conditions in the barn. It is acknowledged that slightly lower results should be expected if the prototype was actually installed in the Macdonald dairy barn. Finally, it is important to note that in the generation of these statistics, there were 638 data points for the prototype plot and 168 for the current system.

5.0 Conclusion

The final prototype performed well in meeting the required design objectives. This LED retrofitted design offers outstanding luminous efficacies of 150 lumens/Watt, a long bulb lifetime of approximately 100 000 hours, and provides a good CRI of 100. The computer simulation of the installation of the prototype at the barn demonstrated that this design is capable of improving lighting conditions by up to 33%. The results of the simulation show that it comes very close to satisfying the ASABE Standards (2005) requiring 200 lux or higher, providing a barn area with 87.1% of light measurements exceeding this standard. When evaluated based on industry-accepted luminous standards, it was found that the prototype is capable of providing a well-lit barn area, with 98.7% of the area meeting the requirement of 170 lux or higher.

If installed at the barn, this design has the potential to significantly improve human working conditions. This is especially true when compared to the current fluorescent system, which only provides an area of 54.2% that meets the ASABE Standards. The total cost of implementation was estimated to be $7421.40, implying a payback period of 13.9 years at current electricity prices for agricultural use. The prototype was constructed to facilitate ease of maintenance with its waterproof and insect-proof seal, as well as to diminish dirt build up with its reduced-surface area cover. An extended testing period of several years would be required to prove that it could achieve these design objectives under operating conditions.

Acknowledgments

This design project would not have been possible without the help of our mentor, Yves Choinière. Yves has offered us guidance and direction since September 2012, and contributed many resources so that this project could be accomplished. We offer our sincere thanks to Yves for the assistance he has given us, and the time he dedicated in mentoring our team.

Thank you to Paul Meldrum and all the staff at the MacDonald Campus Dairy Facility for allowing us to conduct our research at the barn. We were grateful to have the opportunity to expand our knowledge in fluorescent lighting systems, as well as obtaining critical research data.

We would also like to acknowledge Dr. Mark Lefsrud, who was helpful in guiding us through the more complex lighting theory. Thank you for your time, and for lending us light testing instruments for our data collection.

Finally, we would like to thank Dr. Grant Clark for his guidance throughout this project. As a teacher and mentor of the Engineering Design 2 and 3 courses, he gave us the opportunity to develop and understand the concepts needed to carry out the capstone Design project. We would like to thank him for his time, expertise, and enthusiasm, which contributed to a memorable experience in Engineering Design.

References

ASABE Standards. 2005. EP344.3: Lighting Systems for Agricultural Facilities. St. Joseph, Mich.: ASABE.

Chen, N., and S. Chung. 2011. A Driving Technology for Retrofit LED Lamp for Fluorescent Lighting Fixtures With Electronic Ballasts. *IEEE Transactions on Power Electronics* 26: 588-601.

Clark, Steve. 2006. Energy Efficient Dairy Lighting. Ontario Ministry of Agriculture, Food, and Rural Affairs. Available at: http://www.omafra.gov.on.ca/english/engineer/facts/06-007.htm#3. Accessed 3 Feb. 2013.

Fellers, T. J. and Davidson, M. W. 2004. Reflection of light. *Molecular Expressions: Optical Microscopy Primer.* Available at: http://micro.magnet.fsu.edu/primer/lightandcolor/reflectionintro.html. Accessed 19 April 2013.

IG. 2013. Intertek Group. Model number: T8-2-L3HAPW288A2212.

Jupp, D. L. B. 1997. Issues in Reflectance Measurement. *CSIRO Earth Observation Centre* 1-17. Available at: http://www.eoc.csiro.au/millwshop/ref_cal.pdf. Accessed 19 April 2013.

Kloczkowski, R., and J. Stolshek. 1989. Lighting Design Considerations of Reflectorized Luminaires. In IEEE Industry Applications Society Annual Meeting 1989, 2: 2343-2349. San Diego, CA, USA.

Heffernan, B., L. Frater, and N. Watson. 2007. LED Replacement for Fluorescent Tube Lighting. In *Australian Universities Power Engineering Conference* (AUPEC).

MDL. Year unknown. Mid-day Electric. Model number: VAP240C86.

Palmer, J.M. (n.d.). The Measurement of Transmission, Absorption, Emission, and Reflection. *Optical Sciences Center, University of Arizona*. Available at: http://photonics.intec.ugent.be/education/IVPV/res_handbook/v2ch25.pdf. Accessed 19 April 2013.

Parker, D. 2009. Reflective Walls. *Home Energy* 24-26. Available at: http://www.ba-pirc.org/media/pdf/ReflectiveWalls_DParker.pdf. Accessed 19 April 2013.

Peck, J., G. Ashburner, and M. Schratz. 2011. Solid state LED lighting technology for hazardous environments: lowering total cost of ownership while improving safety, quality of light, and reliability. In Petroleum and Chemical Industry Conference Europe Conference Proceedings (PCIC EUROPE), 1-8.

RPI. 2008. Reed Precision Instrument. Model number: LM-81LX.

Thomas and Betts. 2013. Emergi-Lite IPE series. Model number: IP65 Linear Fluorescent Fixture.

USDE. 2012. Types of Lighting. US Department of Energy. Washington, DC. Available at: http://energy.gov/energysaver/articles/types-lighting. Accessed 3 Feb. 2013.

Appendices

Appendix A – Specs for Light Fixture

IPE Series

IP65 Linear Fluorescent Fixtures

Project/Location:

Contractor:

Date:

Prepared by:

Features

- IP65 rated for wet and damp locations
- Polycarbonate enclosure and lens, vandal resistant and UV stabilized
- Rust proof hardware
- Ceiling, surface or pendant mounting
- Low profile, less than 4" deep
- Ultra efficient specular reflector with optimized shape
- 32W T8 or 54W T5HO
- 90 minutes of emergency operation when installed with our FPSI or FPSU inverters
- Emergency operation from external DC low voltage power source when installed with our 48 Series inverters
- Suitable for wet locations

Typical Specification

Supply and install Emergi-Lite **IPE Series** of fluorescent fixtures as specified. The luminaire shall operate from 120Vac to 277Vac or 347Vac and use high quality instant start or 3-step programmed rapid start high efficiency electronic ballasts.

The body and lens shall be constructed of UV stabilized industrial grade vandal resistant polycarbonate. A durable formed gasket shall be provided between the enclosure and the lens and shall be designed specifically for hostile environments. The reflector shall be made of highly specular material and formed to maximize light output efficiency. All parts shall be corrosion resistant. A metal plate used to retain the ballast and reflector also serves to dissipate heat, therefore lengthening ballast life.

Lamps shall be as specified, either T8 or T5 HO linear fluorescent lamps, 32W or 54W. The lamps shall not be supplied with the luminaire. Models with an inverter from the FPSI/FPSU series and illuminate one or two lamps during emergency operation for at least 90 minutes upon AC failure. During power outage, dual voltage source (AC/DC) models with an inverter from the 48 Series, shall illuminate one lamp while the DC voltage is present.

The fixture shall be CSA approved and meet IP65 designation requirements.

The inverters of Series 48 shall be CSA approved.

The inverters of the FSPI series shall be CSA or cUL approved.

The fixture shall be Emergi-Lite model: ____________________

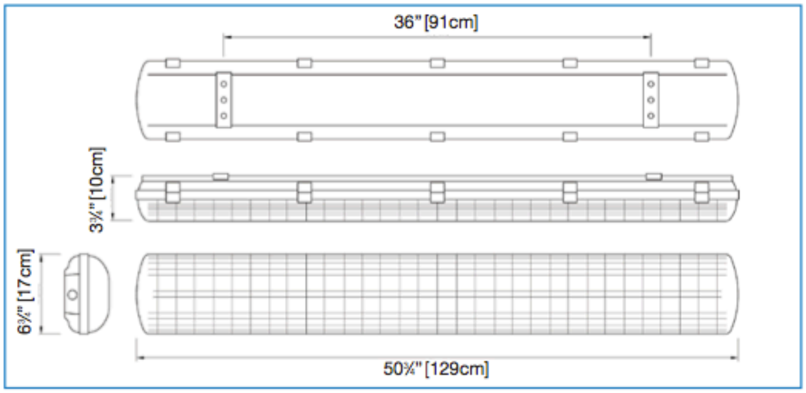
Continued…

Appendix A – Specs for Light Fixture

Wire Guards

460.0105-E	Wall or Ceiling Mount

Dimensions



Power Consumption

Ordering Code	AC Specs		
IPE8	120/277Vac	0.54 / 0.23 Amp	PF > 0.9
IPE83	347Vac	0.19 Amp	PF > 0.9
IPE5	120/277Vac	1.03 / 0.143 Amp	PF > 0.9
IPE53	347Vac	0.35 Amp	PF > 0.9

Ordering Information

Series	Lamp type*	Voltage	Accessories
IPE= 48" (122cm) linier fluorescent	**8**= 2x lamps 32 watts T8 **5**= 2x lamps 54 watts T5HO *Lamps not included. Consult factory for DC operation	**Blank**= AC only 120/277Vca **3**= A.C. only 347Vca	**SELF-POWERED, ONE LAMP EMERGENCY** **FPSI-32**= inverter for IPE8 (complete code = IPE8FPSI-32) **FPSIU-3**= inverter for IPE8-3 (complete code = IPE8-3FPSIU-3) **FPSIU**= inverter for IPE5 (complete code= IPE5FPSIU) **SELF-POWERED, TWO LAMPS EMERGENCY** **FPSU-28**= inverter for IPE8 (complete code= IPE8FPSu-28) **FPSIU-3**= inverter for IPE8-3 (complete code= IPE8-3FPSIU-3) *Two lamp model not available for T5 bulb (IPE5)* **AC/DC OPTION, USING A REMOTE BATTERY, ONE LAMP ONLY IN EMERGENCY MODE:** **4806100**= 6 volts, 120Vac **4806100-3**= 6 volts, 347Vac **4812100**= 12 volts, 120Vac **4812100-3**= 12 volts, 347Vac **4824100**= 24 volts, 120Vac **4824100-3**= 24 volts, 347Vac **4832100**= 32 volts, 120Vac **4832100-3**= 32 volts, 347Vac **4848100**= 48 volts, 120Vac **4848100-3**= 48 volts, 347Vac **48120100**= 120 volts, 120Vac **48120100-3**= 120 volts, 347Vac **081282-E**= Stainless Steel Clips Kit (10) For more information on the 48 Series, please refer to Options & Accessories in your Emergi-Lite catalogue.

EXAMPLE: IPE8

Appendix B – Data from Prototype Testing

B.1. Testing Trial 1 *(Note: bolded number is center of grid, centered directly below prototype)*

5	8	13	17	19	15	12	7	5
9	20	22	31	32	30	19	13	6
10	23	43	72	82	70	40	24	7
13	29	62	119	143	115	68	30	10
15	39	86	169	**212**	168	81	36	11
17	86	77	148	182	140	65	35	12
12	24	49	79	109	87	51	21	12
18	17	29	39	48	42	29	12	9
5	8	16	24	23	26	16	12	6

B.2. Testing Trial 2

6	7	12	14	17	15	12	8	5
10	17	27	37	40	40	26	14	8
11	23	43	72	74	62	37	20	9
11	27	60	119	164	127	72	33	10
13	41	91	170	**210**	162	78	37	11
15	37	70	145	175	142	72	36	11
12	30	56	93	83	77	51	19	11
9	18	33	42	45	40	30	18	11
6	10	16	24	27	24	28	10	13

B.3. Testing Trial 3

5	7	12	17	20	16	15	9	5
8	14	25	35	36	32	20	13	8
9	21	40	60	68	64	40	22	8
10	34	71	119	155	112	65	28	8
15	38	89	172	**210**	166	88	37	11
20	36	82	150	87	146	73	33	10
15	24	63	86	106	86	53	31	9
11	16	27	49	47	39	25	14	9
5	7	18	22	27	21	18	13	8

Appendix C – Prototype Intensity Data for Barn

Units: lux (lumens/m^2)

Note: It was assumed that the white-painted metal walls have a reflectivity of 70%, and that 1.94 m from the wall is affected by the reflectivity.

184	230	294	255	202	196	254	294	255	202	196	254	322	290	269	295	318	255	202	196	254	294	255	202	196	254	294	227	195
193	205	247	223	160	163	223	247	223	160	163	223	270	256	217	255	265	223	160	163	223	247	223	160	163	223	247	199	177
201	216	223	235	184	175	235	223	235	184	175	235	250	283	227	272	242	235	184	175	235	223	235	184	175	235	223	208	185
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226
243	248	293	276	205	208	276	293	276	205	208	276	329	313	275	313	321	276	205	208	276	293	276	205	208	276	293	240	224
230	239	248	264	213	203	267	248	264	213	203	267	281	315	265	307	276	264	213	203	267	248	264	213	203	267	248	232	220
226	221	272	246	196	195	246	272	246	196	195	246	302	280	266	283	297	246	196	195	246	272	246	196	195	246	272	217	226

Appendix D – Matlab Code for Prototype Simulation

Contents

BREE495BarnLighting.m

```
% Brenda Moore BREE 495% McGill University Engineering Design 3

% This code is a component of the Engineering Design 3 Project, for the %
purpose of displaying light intensity data.
```

Importing .csv files

```
% Data collected at Macdonald Dairy Housing Facility, using the original %
lights with fluorescent tubes newly replaced and fixtures fully cleaned

original = csvread('BarnNewLights.csv');

% Data collected solely from Design 3 prototype, in dark empty space

onelight = csvread('OneLight.csv');

% Data collected using Design 3 prototype, constructed with new materials %
and LED tube lights

prototype = csvread('PrototypeBarn.csv'); prototype = fix(prototype);
```

Plotting light intensity vs. distance from source

```
% Brenda Moore BREE 495% McGill University Engineering Design 3

% This code is a component of the Engineering Design 3 Project, for the %
purpose of displaying light intensity data.

% Data collected at Macdonald Dairy Housing Facility, using the original %
lights with fluorescent tubes newly replaced and fixtures fully cleaned

original = csvread('BarnNewLights.csv');

% Data collected solely from Design 3 prototype, in dark empty space

onelight = csvread('OneLight.csv');

% Data collected using Design 3 prototype, constructed with new materials %
and LED tube lights

prototype = csvread('PrototypeBarn.csv'); prototype = fix(prototype);

figure(1)onelight_max = max(onelight);x = 1:9;p = plot(x,onelight_max);
set(gca,'XTickLabel',{'0','0.75','1.5','2.25','3','3.75','4.5','5.25', '6'})
```

```
set(p,'Color','red','LineWidth',2)title('Intensity Curve (lux) vs. Distance
(m) for Prototype', 'fontsize', 16); xlabel('Distance (m)', 'fontsize',
14);ylabel('Intensity (lux)', 'fontsize', 14);
```

Plotting 2D light intensity matrices

```
% Plotting intensity data from original lights% (i) Surface contour
plotfigure(2);c1 = 0:50:250; % Restricting intensity ranges for all plots
[C1,h1] = contourf(original,c1); % Creating a contour plot of old light data
clabel(C1,h1); % Labeling countour lines with intensities (lumen colormap
autumn; % Setting a red/orange/yellow color scheme

% Setting plot size and background color

set(gcf, 'position', [400,100,600,600], 'color', 'w');% Assigning title to
plottitle(' 2D Intensity Plot of Original Lights (lux)','fontsize', 16);
ylabel('East side of facility', 'fontsize', 16);xlabel('North side of
facility','fontsize',16);%colorbar

%(ii) Surface plot%figure(3)%surf(original);%title(' Intensity Surface Plot
of Original Lights (lux)','fontsize', 16); %ylabel('East side of facility',
'fontsize', 16);

%xlabel('North side of facility','fontsize',16); %zlabel('Light intensity
(lux)', 'fontsize', 16);

% Plotting intensity data from prototype

% (i) Surface contour plot

figure(4);c2 = 0:50:250;[C2,h2] =
contourf(prototype,c2);clabel(C2,h2);colormap autumn;set(gcf, 'position',
[400,100,600,600], 'color', 'w');title(' 2D Intensity Plot of Prototype
Lights (lumen/m ^2)','fo ylabel('East side of facility', 'fontsize',
16);xlabel('North side of facility','fontsize',16);colorbar

%(ii) Surface plot%figure(5)%surf(prototype);%title(' Intensity Surface Plot
of Prototype Lights (lux)','fontsize', 16); %ylabel('East side of facility',
'fontsize', 16);

%xlabel('North side of facility','fontsize',16); %zlabel('Light intensity
(lux)', 'fontsize', 16);
```

Calculating the performance of each, compared to published standards

```
% For the barn lit using prototype

best_prototype = find(prototype > 200);p = size(best_prototype);best_p =
p(1,1);perform_p = best_p/(22*29)*100; % 87.1% of barn is lit above 200 lux

good_prototype = find(prototype>170);p2 = size(good_prototype);good_p =
p2(1,1);perform2_p = good_p/(22*29)*100; % 98.7% of barn is lit above 170 lux
```

```
% For the barn lit using original system

best_original = find(original > 200); or = size(best_original);best_or =
or(1,1);

perform_or = best_or/(21*8)*100; % 54.2% of barn is lit above 200 lux

good_original = find(original > 170);or2 = size(good_original);good_or2 =
or2(1,1);perform2_or = good_or2/(22*8)*100; % 79.5% of barn is lit above 170
lux
```