UTILIZATION OF NATURAL LIGHT IN INDOOR APPLICATIONS: SIMULATION AND IMPLEMENTATION

by

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DEDICATION

I dedicate this thesis to both of my parents, ***Maria N. Estrada*** and ***Luis Estrada*** for their incredible support in my education. Also, to my brother and sister, *Luis Estrada Jr*. and *Victoria Estrada* who encouraged me every step of the way.

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ABSTRACT

The need for renewable energy has inspired the development of various methods that conserve or lessen the consumption of our nonrenewable natural resources. Alternative methods in conserving energy include technologies, such as utilizing natural light systems that can light buildings with the use of sunlight by receiving, distributing and delivering sunlight. Distribution of the delivered natural light is performed by positioning optical fibers (end glow and side glow) at certain heights and positions. While daylight systems utilize optical fibers to deliver natural light in buildings, this application has rarely been tested in an indoor environment for plant production. This research intends to test the application of optical fibers and end effector crystals in the transfer and distribution of natural light to an indoor environment and improve the application by identifying and optimizing the affecting factors. The adopted commercialized software, which is commonly used for architectural indoor lighting designs, is utilized in a nonconventional application. For this purpose, a mechanical, optical and electrical system was developed to hold, control, transfer, and distribute the light via the optical fibers system. The factor and its levels were identified using the full factorial design. Based on experiment results, the distance from the light source to the flat surface of the system revealed that the uniformity of the light distribution increased. The findings also showed distance increased the light intensity would fluctuate. Overall, the side glow had a better performance on light uniformity due to its consistency but the light was less intense while end glow had no uniformity but was distributing more intense light.

I.INTRODUCTION

One of the greatest consumers of energy is light which powers a great portion of the world. There are several of methods of powering light such as hydroelectricity, solar and wind energy, nuclear, and fossil fuels. According to Stanley Bull (2001), the cost of energy by conventional technologies can be expensive, which has bolstered the development of more economical renewable energy technologies. The world population has steadily grown over the years, so it is essential to provide the best source of energy to meet the global demand for energy services (Dincer, 2000). It is also important to provide alternate sources of energy (renewable energy sources and technologies) to impede possible energy shortages (Dincer, 2000). Buildings consume great amount of energy to provide lighting, heating, cooling and air conditioning (Abdeen Mustafa Omer, 2008). However, the efficiency of most renewable technologies is currently not sufficient for the full replacement of conventional energy.

Demand for Renewable Energy

Because of the typical provision of consumer goods and services, conventional technologies remain a better method of light production than most of the new technologies, but are known for higher percentages of emissions (Varun, Bhat & Prakash, 2009). While the use of solar panels can sometimes be an efficient source of energy, the loss found in these products and their high costs do not result in extensive use. Storing renewable resources such as wind, solar, tidal and wave require back-up storage to guarantee a reliable power source (based on the size of the grid), which makes it difficult to generalize their cost and potential (Sims, Rogner & Gregory, 2003). Research by A.

Evans, Strezov & T. J. Evans (2009) supports wind as the most sustainable form of energy, followed by hydropower, photovoltaics, and geothermal. According to Shehabi, et al., (2013), the lighting needed to power commercial buildings is a major consumer of electricity, and accounts for 10% of the electricity used in the United States.

Conservation projects are important for the preservation of renewable resources and further advancement of renewable energy. In fact, the EverGreen project (funded by the United States Department of Agriculture) has contributed to this research of an investigation of efficient soil free agricultural systems. Some of the important factors that contribute to this soil free agricultural system are the use of energy (light), water, and the environment (plants). These factors serve as important variables for the development of soil free agricultural systems that can function on renewable energy continuously.

Daylighting

Daylighting is a method of delivering light indoors with the use of windows, solar tubes, optical fibers, parabolic mirrors and other types of daylight technologies. Many industries have applied the use of daylighting as their source of lighting instead of artificial light because it utilizes renewable natural light in indoor spaces. Research by Bodart & Herde (2002) illustrates that daylighting systems can reduce artificial light consumption globally by 50-80%. Most of the commercial buildings in the U.S are lit by electrical lighting (e.g LED, fluorescent) systems (Leslie, Raghavan, Howlett, & Eaton, 2005). The high consumption of electricity has inspired research studies regarding the application and its efficiency of daylighting in indoor environments. Currently some daylighting technologies in the market are designed to infiltrate sunlight inside a building while containing the glare caused by the penetration of light (Leslie, Raghavan, Howlett, & Eaton, 2005). Potential energy savings from utilizing simple windows have been 77% of lighting energy and 14% of total energy in office buildings (Bodart & Herde, 2002). Daylight penetration in buildings varies based on the angle where the sun rays hit the building due to the design of most daylight technologies the incident angle is not always a driving independent variable. The use of most daylight technologies does not guarantee effective operation because daylight does not penetrate a building's interior uniformly (Leslie, Raghavan, Howlett, & Eaton, 2005). In fact, daylight technologies have to demonstrate their energy saving performance before they can be commercialized (Leslie, Raghavan, Howlett, & Eaton, 2005).

Sustainable development is the emphasis in daylighting, which seeks to decrease the depletion rate of natural resources by utilizing renewable resources. As mentioned by Ullah & Whang (2015), growth of lighting demand has increased the average of illuminance levels in buildings. In sustainable buildings, the consumption of energy can be reduced by using daylighting instead of artificial light to illuminate the interior. Based on research conducted by Ullah & Whang (2015), the use of fiber optic daylight systems have demonstrated promising and effectiveness in the transmission of sunlight in interior space, which have reduced the amount of energy consumption of electric lighting.

The Background of Light

The use of light is an everyday necessity; it forms the basis of human productivity. As described by Alexander Ryer (1998), light is just a portion of various electromagnetic waves that can move through any type of space. The electromagnetic spectrum covers radio waves, microwave waves, light waves, infrared waves, ultraviolet waves, X-ray and gamma rays (See Fig. 2). Electromagnetic waves (EM waves) have different wavelengths and can travel at different velocities. As mentioned by Beckers et al. (2016), the wavelength λ, is measured by the length of one period (See Fig 1.) and the frequency of the wave is equal to the number of wavelengths that move during a certain time range. The mathematical equation for frequency is:

$$f = \nu / \lambda \tag{1.1}$$

The expression signifies that the velocity of any wave relates to the frequency, f, and wavelength, λ (Beckers et al., 2016). As mentioned by Beckers et al. (2016), the shorter the wavelength the higher the frequency, or the longer the wavelength the lower the frequency. Since the velocity of the frequency changes due to the size of the wavelength is based on the distance to record can be used to determine the intensity of frequency

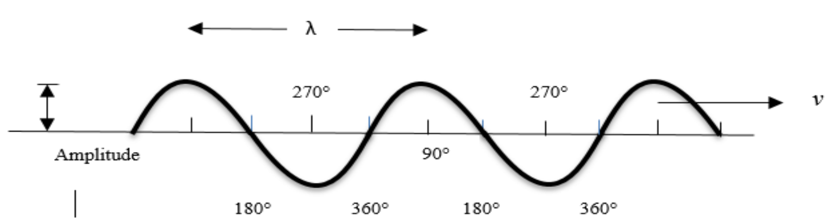


Figure 1. Wavelength frequency measurements. Adapted from “Introduction to Laser Technology” by C. Breck Hitz, J, Ewing, & Jeff Hecht.

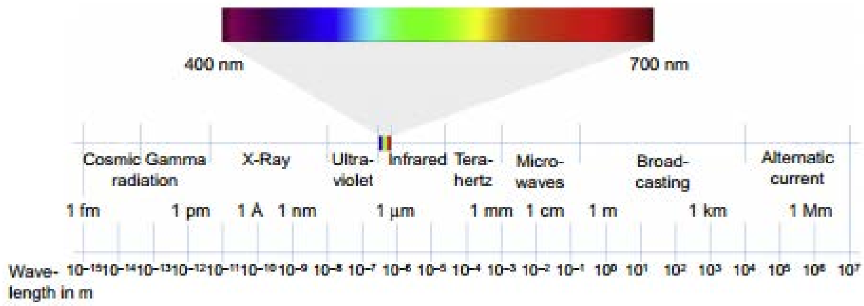


Figure 2. Frequency spectrum of electromagnetic waves. Adapted from “Basics of light guidance” by M. Beckers et al. (2016).

Because of sensitivity of the human eye, only a small fraction of wavelengths in the visible light spectrum are perceived by the human eye as light (Beckers et al., 2016). In the visible light spectrum, the wavelength colors seen are red, orange, yellow, green, blue, indigo, and violet (See Figure 3). According to Beckers et al. (2016), light is defined for wavelengths located between 300 and 2000 nm (nanometer) but the visible light perceived by the human eye is located at 450 and 700 nm. The power of light from a light source is luminous flux, measured in the unit of lumens (lm).

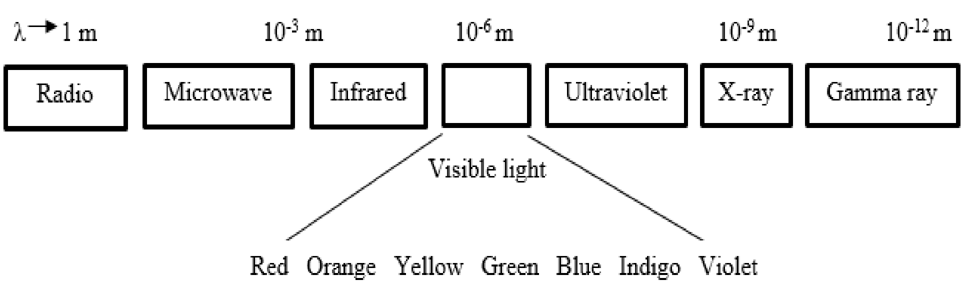


Figure 3. Visible light spectrum. Adapted from “Introduction to Laser Technology” by C. Breck Hitz, J, Ewing, & Jeff Hecht.

How Light Refraction, Reflection and Transmission Works

Light behaves based on the law of reflection, the equation $i = r$ where i the angle of incidence is equal to r the angle of reflection (See Figure. 4). Light is reflected of objects (e.g. mirrors, glass, or solid surfaces) because the waves change direction after hitting the surface. Even a transparent glass can reflect a small amount of light. The refraction of light (Snell's Law) occurs when waves pass between two different objects, the rays are bent and the velocity changes (Ryer, 1998). As explained by Ryer (1998), the refraction depends on the incident angle, θ, and its refractive index, n of the material, as seen in Snell's equation:

$$n \sin(\theta) = n' \sin(\theta') \qquad (1.2)$$

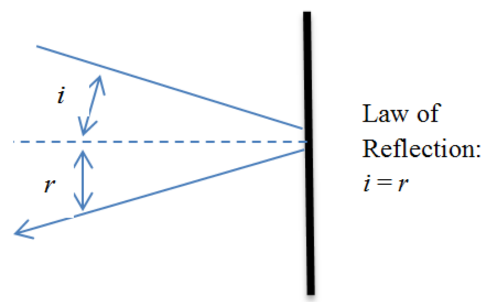


Figure 4. Law of reflection. Adapted from "Light Measurement Book" by Alexander D. Ryer.

An example of the refraction can be seen in Figure6 with two dissimilar objects, air and water where a source (fish) is refracted based on the incident angle and its refractive index. The refractive-index profile of an optical fiber can change based on the type of fiber and its radius (Bunge, Beckers, & Lustermann, 2017). Determining the refractive-index profile of an optical fiber is calculated by the refractive-index between the core (ncore) and the cladding (ncladding) of the optical fiber and is calculated by, Δ = n2core – n2cladding / 2n2core (Bunge, Beckers, & Lustermann, 2017). The power-law profile is calculated with this equation (Figure 5):

$$n(r) = \begin{cases} n_{\text{core}} \sqrt{1 - 2\Delta \left(\frac{r}{a}\right)^{g}} & \forall r \leq a \\ n_{\text{core}} \sqrt{1 - 2\Delta} & \forall r > a. \end{cases}$$

Figure 5. Power-law profile equation. Adapted from “Basic principles of optical fibers” by C. A. Bunge, M. Beckers, & B. Lustermann (2017).

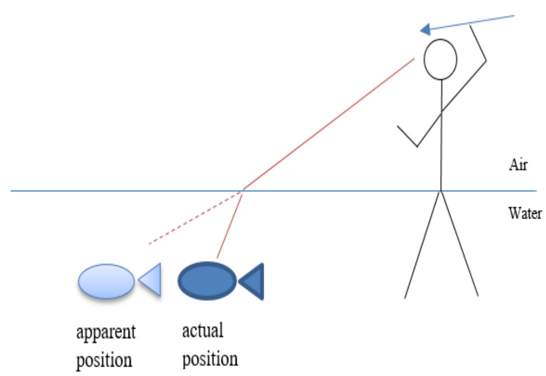


Figure 6. Reflection of light. Illustration shows how reflection works. Adapted from Refraction Virtual Lab by Mrs. Munn.

The transmission of light occurs when electromagnetic waves (visible light waves) are transmitted through the material (e.g. optical fiber). Light can be diffused either by transmission or reflection (Ryer, 1998). According to Ryer (1998), diffuse transmission can be transmitted through roughed quartz, flashed opal, or polytetrafluoroethylene (PTFE). The transmission of light between two materials that have different diffractive indices can produce reflection losses. The reflection loss can be quantified by the Fresnel’s Law:

$$r_\lambda = (n_\lambda - 1)^2/(n_\lambda + 1)^2 \quad (1.3)$$

Where:

r_λ= the reflection loss, at normal incidence between two middle elements with different refractive indexes

n_λ = n/n, the ratio of indices

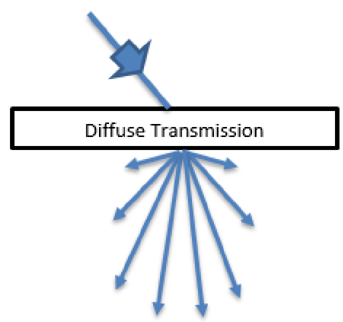


Figure 7. Diffuse transmission of light. Adapted from "Light Measurement Book" by Alexander D. Ryer.

In this research, a viable method to transfer light inside an indoor environment will be tested to find its effectiveness of light distribution for plants to create a more uniform growth pattern. While light pattern can be the affecting factor to the uniformity of plant growth, it is important to conduct further studies of the implication of light in plant growth in order to make a more viable design of experiments.

II.STATE OF THE ART OF THE NATURAL LIGHT IN INDOOR APPLICATIONS

Natural Light Applications in Indoor Environments

A possible way to reduce the dependency on nonrenewable energy is the substitution and integration of artificial lighting by natural daylighting in buildings (Scartezzini & Courret, 2002). Daylighting can provide more than just potential cost savings; research has found that it is beneficial for human health (Molteni, Courret, Michel & Scartezzini, 2001). The use of natural light in indoor applications has demonstrated to have a positive effect for those exposed to it when at work or at home. Daylighting technologies are introduced as commercialized or prototyped products. A few of the innovative daylight technologies have been successful enough to be developed into commercialized products (Mayhoub, 2014). The following applications are active technologies that can collect and deliver natural light in indoor environments. The products/inventions mentioned are considerable for this research and the use of patents as viable design ideas that are needed to formulate our own design for a daylight system to be usable in an indoor environment.

Solar pipe/Solar tube

According to Mayhoub (2014), the solar pipe is the most commercially available daylighting system. As explained by Solatube (2014), the solar pipe, also known as a solar tube, works by capturing the sun rays using patented optical technologies and then delivering the light through a pipe or tube inside the building (See Figure 8). The use of these daylight systems is incorporated in buildings and homes for indoor lighting.

According to Solatube (2014), their tubular daylighting devices (TDD), also referred to as light tubes, sun pipes, and tubular skylights, utilize a daylight-capturing dome lens (acrylic or polycarbonate made), which redirect low angle sunlight to a reflector increasing the light input and transfer the light through a tube made from a reflective material (aluminum substrate) that delivers 99.7% of its reflective sunlight and then utilizes a diffuser (unique lenses) to diffuse the light into a room. The use of solar tubes or light pipes is not a potential effective daylight system due to the installation process of this technology that can result in energy loss.

Figure 8. Solatube 160 DS Daylight System. The sunlight is captured by a round dome containing optical components that transfer the light via a tube and delivered inside the building with a diffuser. Adapted from Solatube, LLC.

Parans system

Other commercially available products are the Parans system and Himawari. A Swedish company developed the Prans system in 2004 and has now developed three generations of this system, all of them composed of an array of small Fresnel lenses that can concurrently track and concentrate daylight (Mayhoub, 2014). The Parans system

SP3 collects light by using a tracking system and then concentrates the light with Fresnel lenses to transfer the light spectrum with fiber optics (Parans Solar Light System, 2016; See Figure 9). The use of fiber optics in this daylight system can transfer the light into the building due to their flexibility and ability to deliver large amount of light. The SP3 Parans system is made from the following materials: aluminum, tempered glass, Zinic/nickel steel, and acrylic (Parans, 2016). The Parans system is able to transmit natural light by reflecting ultraviolet (UV) and near-infrared (NIR) with the use of a reflective filter (Mayhoub, 2014).

Figure 9. Parans system SP3. This system can collect sunlight at all sun hours (by sun tracking) and can deliver the light with the use of thin fiber cables. Adapted from “Parans Solar Lighting System” by Wasco Skylights.

<u>Himawari</u>

The Himawari system was commercialized since the 1970s; it uses multiple Feresel lenses that act as collectors which can track and collect sunlight to transport via optical fibers and distribute it indoors with the use of luminaire devices (Mayhoub, 2014). The XD-1002/36AS (See Figure 10), a small Himawari model contains 12 lenses and is equipped with two optical fiber cables (1mm of core diamater) that are required in order to illuminate at least 10m of area (“Solar Lighting System Himawari”. La Foret Engineering Co., Ltd, 2006). The light is emitted by the optical fiber with an illumination angle of 58°, which at approximately 2.2m can illuminate approximately 500 lux on average ("Solar Lighting System Himawari". La Foret Engineering Co., Ltd, 2006). According to La Foret Engineering Co., Ltd (2006), the optical fiber cable used to transport light for the Himawari system is composed of large quartz glass fibers which are specially manufactured for sunlight transmission. This use of this daylighting system has shown effectiveness in energy saving. When compared with other lamps the Himawari system was consuming 0.5 Watts of energy. While the utilization and implementation of the Himawari can be difficult, the Himawari distributors advise its customers to attend training in order to better understand and install the system effectively. This application can be installed in a wide variety of places such as houses, offices, factories, and public spaces.

Figure 10. XD-100S/36AS known as the Himawari System. Adapted from "Specification of The Himawari/Solar Lighting System" by La Foret Engineering Co., Ltd.

Heliostat

The Heliostat from eSolar consists of a large mirror reflector that, with the use of a sun tracking system and a computer system, can concentrate sunlight (eSolar, 2007-

2016). The design composition of this system includes the use of a concentrators (e.g. mirrors or lenses) and reflectors to be able to direct the natural light in most indoor application. Furthermore, the design of the Heliostat depends on its ability to deliver natural light; methods of delivery include via vertical voids and via liquid (fiber optics) guides used as a prototype demonstrated by University of Athens in 2002 (Mayhoub, 2014). The Universal Fiber Optic (UFO) project (a prototype) was composed of a heliostat (Frensel lenses captured sunlight), an artificial light source, fiber optic cables (connected directly to the emitter), a flat emitter, and a control system (Tsangrassoulis, et al., 2013).

While many of these systems can utilize sun-tracking features, others do not possess such characteristics but can direct and distribute sunlight with the use of stationary concentrators. As explained by Light Manufacturing, the H1 Heliostat (See Figure 11) can be controlled by web browser due to its integral Wi-Fi networking capability, has an 85% reflective mirror, an integral microprocessor tracking system, and contains shatterproof reflectors (flat or parabolic focus mirrors). The downfall of this daylight system is that any mechanism failure can leave an indoor facility with no light. Also, heliostat systems are not often installed with the intention of reducing energy use; their main use is to improve the feeling of wellbeing and aesthetic effects (Mayhoub, 2014). While the use of daylight systems like the heliostat can have possible energy-saving potential, it is still hard to conclude if the system will be efficient in the future applications.

Figure 11. H1-Heliostat. Adapted from “High-performance Heliostat with Wireless Remote Control” by LightManufacturing.

Sundolier

The Sundolier Daylight Harvester (See Figure 12) system utilizes a dual-axis digital sun tracking system where specialized mirrors capture the collimated beam of sunlight into the interior of the building (Sundolier, Inc. 2015). According to Sundolier, Inc. (2015) this system can harvest approximately 100,000 lumens and can withstand various weather conditions. Most conventional daylighting systems can operate to their peak but do not have the necessary technology to deliver the light without creating glare, reflections, and hot spots. The Sundolier has the necessary components to introduce light with no glare and hot spots without the use of blinds or shades in the buildings (Sundolier, Inc., 2015). This is a high-cost product, but it can be a cost-efficient system that can save energy relative for indoor applications (e.g., blinds, shades) (Mayhoub, 2014). According to Mayhoub (2014), the Sundolier system is a daylight technology with the capability to track and concentrate sunlight with the use of mirrors to then deliver the captured light through a duct.

Figure 12. Sundolier. Adapted from “Delivering on the Promise of Daylighting” by Sundolier, Inc.

Patents/Prototypes

Although plants can receive sunlight through greenhouse applications in a potentially systematic way, it is hard to control the temperature, and atmosphere them. The use of a daylight system in a controlled indoor environment can potentially increase and optimize the growth patterns for the plants. The solar-illuminated energy conserving greenhouse describes the design of a solar illuminator that is placed in a greenhouse. With the use of shuttered lenses, a solar collector, and a diffuser, light is directed and dispersed through the interior of the greenhouse (Power, 1980). The natural-light illumination enhancement assembly describes the design of a louvre-type reflector. The reflector is composed of an array of reflecting louvres in which two adjacent louvres. One reflecting louvres inclined downwardly-facing concave and another reflecting louvre positioned lower, less-steeply inclined downwardly-facing concave both utilized for enhancing greenhouse or factory illumination using natural light (Critten, 1987). While these brilliant ideas have been put to the test, there are other more efficient tools that can be used to transfer natural light to plants in a more efficient way such as the use of daylight systems.

The overall effect of the passive daylight system is to arrange its reflectors in a vertical and horizontal array above a lightwell. In such a system, test results show an increase of interior light levels with substantially reduced heat absorption (Terrill, 1989). The method and apparatus for a tubular skylight system patent is a solar tube designed includes an with an outer dome constructed with an aluminum ring around the base that contains a circular channel and holes which provide increased heat dissipation and condensation removal. This design is useful where daylight system limitations of delivering sunlight can be caused by heat dissipation or condensation (Grubb, 1999). Skylights composed of roof windows can provide lighting in buildings (Brett Martin, n.d.). Many of the daylight systems described have shown potential to benefit the purpose of this research. Admittedly, daylight systems do not have to be technological; non-conventional methods can be as simple as plastic bottles with water and bleach on roof ceilings (Zobel, 2013).

Table 1. Summary of Natural Light Collector Technologies.

System	**Type**	**Technology Description**	**Status**
Solar pipe/Sun tube	Commercial product	Polycarbonate or mirror made dome with reflective film that delivers light through the tube duct	Sales most countries (e.g. USA, Korea, UK), Easily accessible
Parans	Commercial product	Sun Tracking lens transfers light through fiber optics	Sales with minimum order (e.g. $50K) in UK

Table 1. Summary of Natural Light Collector Technologies (continued).

Himawari	Commercial product	Fresnel lenses concentrate sunlight, transfers light via fiber optics, diffuses the light with luminaries	Sales in certain country (e.g. not in US), training suggested for efficient use
Heliostat	Commercial product	Flat or parabolic mirrors, tracking system, transfers light via vertical voids	Sales in most countries (e.g. USA, Korea, UK), Various design compositions
Sundolier	Commercial product	Mirrors track and concentrate sunlight and then delivers it through a light duct	Sales in most countries (e.g. USA, Korea, UK)
Solar illuminated energy conserving greenhouse	Patent	Shuttered lenses, a solar collector, and a diffuser, light; direct and disperse light through the interior of the greenhouse	Not commercialized
Natural-Light illumination enhancement assembly	Patent	Two adjacent louvred reflectors; one inclined downwardly-facing concave and the other less steeply inclined lower; both reflect light to produce uniform light	Not commercialized
Method and apparatus for a tubular skylight system	Patent	Outer dome made with an aluminum ring around the base that contains a circular channel and holes; increased heat dissipation and condensation removal	Not commercialized/ Commercialized
Passive daylighting system	Patent	Reflectors above a lightwell and distribution lens at lower end	Not commercialized

Plant Growth in Indoor Applications

The factors that affect plant growth are light, temperature, humidity, water, nutrition and soil. Occasionally light is an important factor that can affect plant growth, and is critical in indoor environments. The common use of applications to grow plants in indoor environments has demonstrated that there is a limit to the light availability. Obtaining optimal indoor light levels in all seasons can be challenging without artificial sources; and artificial lighting using non-renewable energy creates drawbacks, including farming practices that contribute to climate change. The wavelength spectrum that activates the photosynthesis process in plants is the photosynthetically active radiation (PAR) which is between 400-700nm (Kittas, Baille, & Giaglaras, 1999). Plants that require high light intensity and long duration of light are more difficult to grow indoors (e.g. flowering plants and cacti). Greenhouses allow transmission of light from the sun to the plant canopy, and typically enable light transmission of 300 to 3000nm (Kittas et al., 1999). According to the study conducted by Kittas, Baille, & Giaglaras (1999), greenhouses designed with fiber glass (FBG) had a high total results in outdoor flux integrals, indoor flux integrals, and greenhouse transmission. The use of greenhouses to harvest plants is considered an important application because they are capable of maintaining a controlled environment; however, with new lighting technology, plant production efficiency can be improved.

III.FIBER OPTICS TECHNOLOGIES

Fiber Optics for Natural Light Transfer

The primary use of fiber optic technologies is considered for this research. Optical daylight technology depends mainly on sunlight as its direct source of light and is used mainly on interior buildings where sunlight is difficult to reach (J.T. Kim & G. Kim, 2010). According to Vu & Shin (2016), optical fiber technologies consist of using large optical components that collect sunlight and transfer it to the interior with optical fibers. Where the use of fiber-based systems is most suitable, there are two common approaches: parabolic reflectors and Fresnel lenses, which are considered as potential concentrators used to direct the sunlight into the fiber optics (Ulla & Shin, 2014). Based on research by Vu & Shin (2016), the Fresnel lenses have a high concentration, making these suitable for optical fiber technologies. As mentioned earlier, the Himawari system serves as a tracking and concentrator system that with the use of Fresnel lenses can transfer the light collected through the optic fiber cables (Ullah & Whang, 2015). Research performed by Feuermann, Gordon, & Huleihil (2002), states that optical fiber cables can cause light leakage depending on the incidence angle, the core and cladding properties of the fiber optics, and the fiber length. According to Koike (2015), propagation of light through the fiber is referred to as modes, patterns of electromagnetic field distributions (p. 3).

The Types of Optical Fibers

Optical fibers are classified into two types: single-mode fibers (SMFs) and multi-mode fibers (MOFs) (See Figure13). Both are divided into two classes: step-index (SI) and graded-index (GI) fibers (Koike, 2015; p. 3). In step-index (SI) fibers the entire core has a constant refractive index and graded –index (GI) fibers have a parabolic refractive-index distribution (Koike, 2015; p. 3). According to Koike (2015), the only difference between these fibers is modal dispersion. Single-mode fibers (SMFs) are used to conduct this experiment because they have the potential to deliver longer light duration than MMFs.

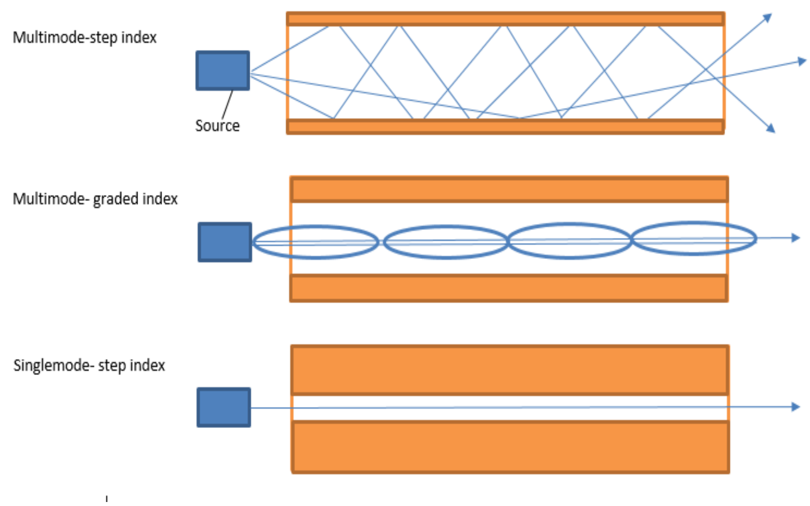


Figure 13. Light propagation in multimode and singlemode. Adapted from "The fundamentals of optical light sources and transmission" by Valerie Maguire (2010).

There are two types of optical fibers used in their associated technologies: plastic optical fibers (POFs) and glass optical fibers (GOFs). Both contain the same design characteristics, in the form of coaxial layers: a core (located in the central part of the inside diameter) and cladding (the peripheral form that surrounds the core). The core is what directs the light propagation while the cladding only acts as a protective layer (See Figure 14). The core has a higher refractive index than the cladding. The cladding protects the core surface from any imperfections and changes that can occur in the refractive index while keeping the light signals inside the core (Koike, 2015). POFs were first developed in the late 1960s and this past century has been highly used due to their technological capabilities, and applications (Bunge, Beckers, & Gries, 2017). GOFs were also developed in the 1960s; these were composed of ultra-thin glass optics with diameters as below as 1mm (Bunge, Beckers, & Gries, 2017). The use of POFs is more suitable for this experiment because they are more flexible than GOFs, which break easily. However, most POFs cannot withstand high temperatures, so it is essential to use filters in the concentrator to reduce the amount of heat transferred (Xue, Zheng, Su, & Kang, 2011). Based on the design of experimentsit will be more efficient to use polymer optical fibers (POFs) for this study due to their low cost, material components, mechanical and optical properties. This was the only material available because of the cable size.

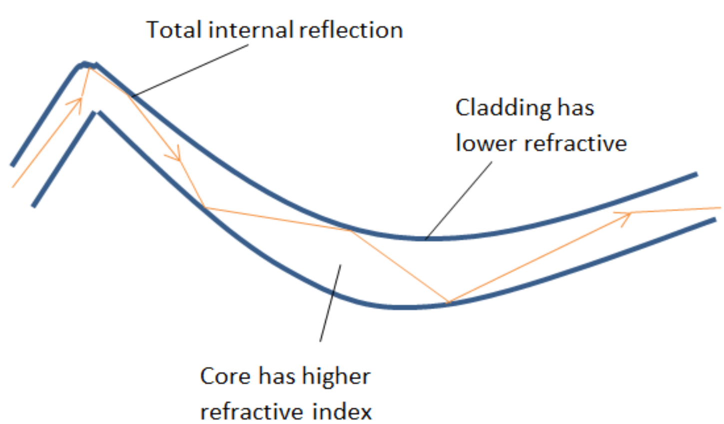


Figure 14. Fiber optic refractive index. Explains the process of reflection inside a fiber optic cable. Adapted from Fiber Optics by Chris Woodford (2016).

The Use of PMMA in Optical Fibers

POFs can consist of different types of core material, one of them being polymer. Polymer core made optical fibers have a larger core diameter than silica-based optical fibers which contain higher flexibility (Koike, 2015). The most common types of optical fibers are the polymer optical fibers (POFs) these are composed of high resistant polymers. The compound poly (methyl methacrylate) PMMA often known as acrylic glass or acrylic is polymer based optical fiber. The exterior core of the optical fiber cable is black PVC, which is used to contain the light to deliver the light to the end-point of use. According to Koike (2015), PMMA material is shatter proof when ruptured, has a high scratch resistance and can transmit 93-94% of visible light and reflect the remainder. Ali et al. (2015) stated that the PMMA material has a high resistance to sunshine exposure, good thermal stability, glass transition temperature of 100 °C to 130° C. Many POFs can be efficient within short distance applications but most are generally made from materials with low absorption at short wavelengths such as red light estimated at 650nm (Hayes, 2010). As described by Zaremba & Evert (2017), PMMA contains three loss windows where light transmission is favored at 570, 650, and 780 nm.

The information provided by manufacturer `Jiangsu TX Plastic Optical Fibers Co., Ltd of the fiber optic cables contained information about the chemical properties of the cable; the core of the material was made of poly (methyl methacrylate) and the mechanical properties showed that the minimum bending radius of cables was 6 times the diameter (16mm) from an 18mm optic fiber cable. Also, based on further information provided by `Jiangsu TX Plastic Optical Fibers Co., Ltd, PMMA polymer optical fibers (POFs) have an estimated wavelength of 400-700nm. The materials used in the manufacturing process of the side glow optical fiber were tested by Shenzhen BCTC Technology Co., Ltd, which conducted a screen report on 169 substances of very high concerns (SVHC). The results, based on the submitted sample, showed the concentration of the 169 SVHC substances was less than 0.1 % (1000mg/kg) (w/w).

Attachment/bonding of PMMA

The use of side glow optical fibers in this study demands extensive research of the primary material used in the inner core of the optical fiber. Use of poly (methyl methacrylate) (PMMA), the material of the inner core of the end glow and side glow optical fibers, is an important factor to consider when viable methods of attachment and bonding of PMMA are applied to the design. A research study analyzed different PMMA-PMMA bonding while creating a new method of bonding. The different types of bonding are: thermal bonding, intermediate adhesive layer-based bonding, solvent-assisted bonding, and microwave welding (Tran, Wu, & Lee, 2013). The study conducted by Tran, Wu & Lee (2013), proposed an instantaneous strategy to bond PMMA-PMMA substrates based on surface dissolution via ethanol treatment followed by UV radiation. After testing these materials, they concluded that using 90% ethanol solution to coat one side of PMMA plate for 30 seconds of UV irradiation exposure at a temperature of 77°C, can bond PMMA. This experiment is essential in this research because it is important to consider methods to prolong the usability of the material so that such material and methods can be efficient incorporating the optical fiber in the indoor experiment of the hydroponic system. The use of extension parts are a viable consideration in this research, these will connect to the optical fibers so that the material is not affected by attachment methods such as bonding.

Light Transmitting with End-fittings/Effectors

Common reasons for using end-fittings are decorative purposes, which can disperse light more uniformly. According to Vu & Shin (2016), incorporating end-fittings, such as a ball lens, for POFs is a great cost effective choice that can also uniformly increase the distribution of light. In order to manipulate the light dispersed to the plant canopy, efficient transmission methods, such as through the use of end-fittings and reflectors, is necessary. Based on the shape of the end-fitting attached to the optical fiber, this experiment will test the uniformity levels of light distribution.

Potential Losses in the Transmission of Light in Plastic Optical Fibers

With the transmission of light through optical fibers, it is possible to experience loss. The transmission loss can limit the distance of a signal that propagates in the fiber before the optical fiber which can then become weak making it harder to detect the source (Koike, 2015). According to Koike (2015), the amount of light lost between input and output; is the sum of all losses. The equation is defined as (expressed in decibels)

$$\text{dB} = -10 \log_{10} \left(\frac{P_{out}}{P_{in}}\right) \tag{2.1}$$

There are two different types of losses: extrinsic and intrinsic losses (See Figure 15).

<u>Extrinsic losses</u>

Within these losses, there are other forms of losses, which can occur due to stress and usage over time such as bending and aging of the optical fiber. Bending losses are those that occur when fibers are bent, which causes modes to be misguided. These fiber modes distribute the light through the fiber optic and depending on the bending radius; these can lead to large losses (Bunge, Beckers, & Lustermann, 2017). In addition, fiber optic cables used in stress-related applications can cause extrinsic losses. Stress-related loses are similar to the bending losses, when bent the loss increases but stress is also applied to the fiber (Bunge, Beckers, & Lustermann, 2017). Additionally, age increases the attenuation of the optical fiber. Some polymers have the tendency of yellowing over time due to exposure of ultra-violet light (Bunge, Beckers, & Lustermann, 2017). PMMA-based fibers have high increase of attenuation due to temperature and humidity.

<u>Intrinsic losses</u>

According to Bunge, Beckers, & Lustermann (2017), the intrinsic losses are caused by basic-fiber material properties which can be overcome by changing the materials or components of the optical fibers. According to Koike (2015), electron transition absorption and molecular vibration absorption are the main causes of absorption losses. The absorption of light depends on the frequency or wavelength of the optical fiber, the material found in the optical fibers can fluctuate the absorption transition due to the different energy levels involved (Koike, 2015). The ultraviolet wavelengths are the cause of electronic transition absorption because the absorption tails the influence of transmission losses in plastic optical fibers (Koike, 2015). According to Koike (2015), the molecular vibration absorption can be found in infrared wavelengths, which are the resonance frequencies for molecular vibrations.

Scattering loss found in polymers can be caused by the microscopic variations found in the material density of the optical fiber (Koike, 2015). The scattering loss have no energy transfer but the direction of the propagation of light changes. Scattering occurs when any local changes are made to the refractive-index, the refractive index variations result in refraction, reflection and scattering (Bunge, Beckers, & Lustermann, 2017). According to Bunge, Beckers, & Lustermann, (2017), based on the scattering centers if these are smaller than the wavelength are referred to as Rayleight scattering and if larger than the wavelength are characterized by Mie scattering. Because all materials consist of molecules, Rayleight scattering molecules have small variation structures usually smaller than the wavelength of the light (Bunge, Beckers, & Lustermann, 2017).

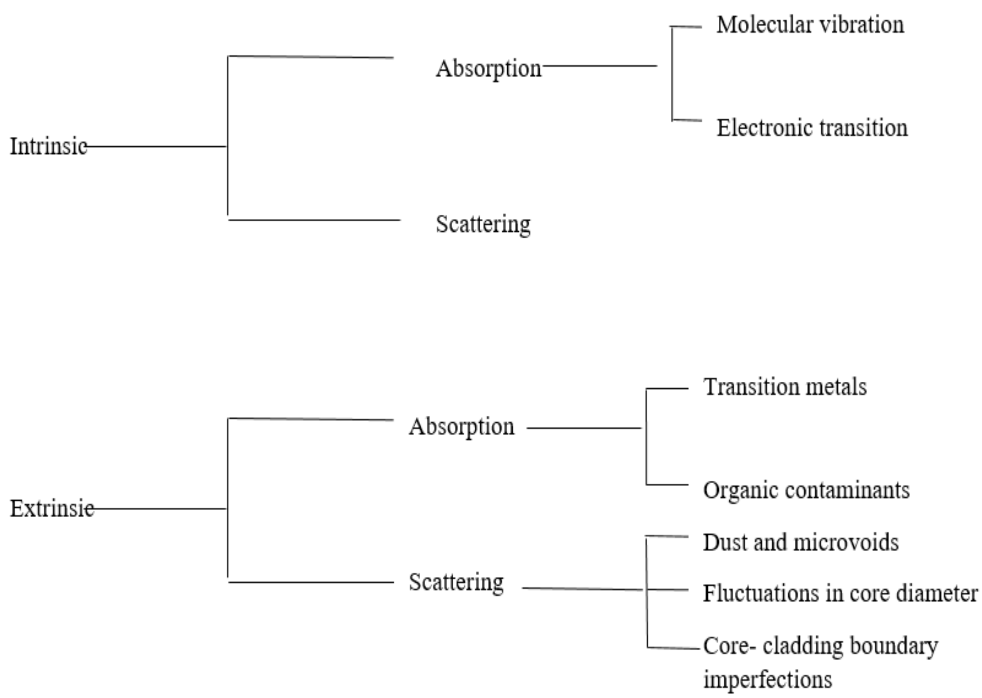


Figure 15. Overview on intrinsic and extrinsic loss effects. Adapted from Fundamentals of Plastic Optical Fibers: *Transmission loss* (2016) by Y. Koike.

Based on the information given by the supplier (Jiangsu TX Plastic Optical Fibers Co., Ltd) about the optical fibers used in this experiment, they have a bending radius of 6 times the diameter (20mm). This information is useful in order to consider the amount of bending that the fiber optics can withstand while also considering the amount of loss that occurs when bending. Further information about optical fiber parameters can found in Table 2 and the supplier's website (http://www.txpof.com).

Table 2. Product Parameters of Optical Fibers.

Item		Unit	Index
Structural parameters	Core diameter	mm	16± 0.2mm
	Cladding diameter	mm	18± 0.4mm
	Cladding non-cicularity	%	≤ 6
	Numerical Apertures	/	0.65
	Length	m/roll	100
Optical properties	Attenuation @ 650nm	dB/km	≤ 780
Mecahnical properties	Repeated bending (200times)	dB	Loss added ≤ 2
	Tensile strength	N	70
	Twisting (5times)	dB	Loss added ≤ 2
	Impacting (0.4N/meter)	dB	Loss added ≤ 2

The following information is based on the product structure of TX-SFL-6000-1W (side glow fiber optic). Adapted by Jiangsu TX Plastic Optical Fibers Co.,Ltd.

IV. RESEARCH METHODOLOGY

Introduction

Since the study of using plastic optical fibers to deliver natural light began, there has been considerable effort and progress on the development on the project of completing a working plant growth system. With the help of the lighting system to deliver the natural or artificial light through fiber optic cables, a working system can be developed that will ensure uniform plant growth. Because of the different integral activities that are used to develop this system, it can be difficult to separate the system's development into well-defined categories. These activities are categorized in four groups: computer simulation (modeling) research, analytical research, experimental research, and developmental research (See Figure16).

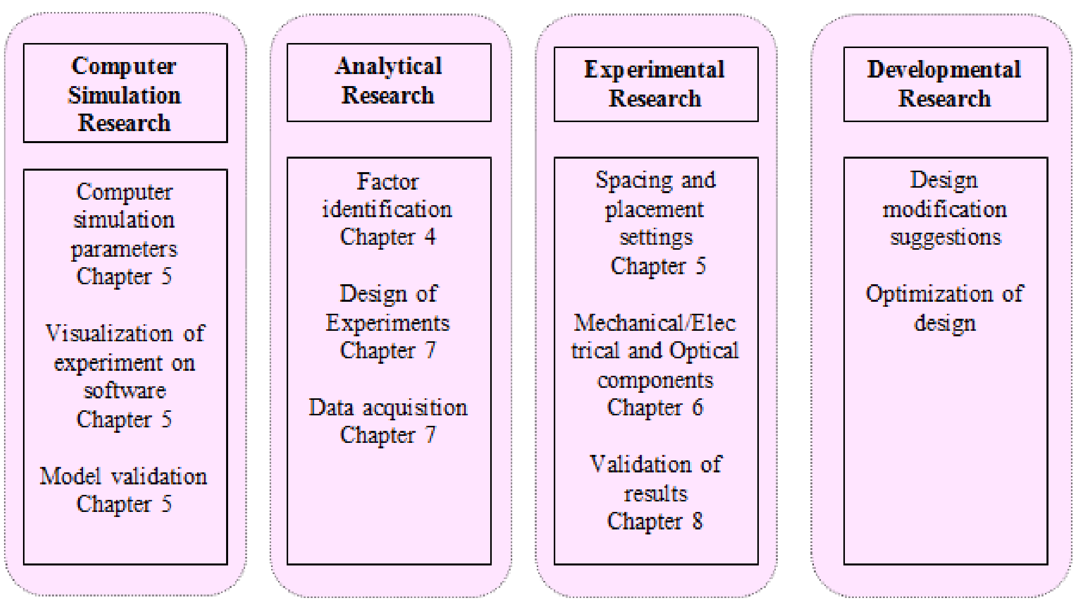


Figure 16. Research methodology.

Computer Simulation (Modeling) research

The design and visualization of the experiment can be done by using computer modeling or simulation software. In order to design an effective structured system that will enable the potential use of the experiment it must first be design and tested in simulation programs to avoid potential loss in time and cost. While there is variety of software that can be helpful for the development of mostly any experiment, it is always important to consider what software program will be effective for the study. In this research, the software utilized for the design and testing of the design is mention further in Chapter 5. After the computer program provides promising results then the model validation is determined for testing.

Analytical Research

To design the analytical research, there are a couple of goals that must be achieved. The primary goal is to achieve uniformity of light through a flat surface from a certain distance. Other important goals are to understand and control process variables affecting light transfer, light distribution, and light uniformity. Because of the limited number of sources on this research, these goals were developed for the objective of designing a working system to distribute and deliver light effectively. The sources are analyzed and based on our data acquisition they are compared to ensure the cause and effect relationship is present.

Experimental Research

In the experimental research, various components are acquired for the set-up and structure of the system. The experiment is then conducted considering the spacing and placement settings selected previously from earlier process. Also, various experiments have been designed but only some were implemented in order to improve previous designs. These include experiments that measured light at different heights and light uniformity produced by various designs.

Developmental Research

In the developmental research, the experimental design is modified based on the results of the experimental and analytical research. Based on the results the changes are then applied to improve the design and overall results of the research. The optimization of the design is based on these changes made in order for the research to be effective. The mechanical, electrical, and optical components can also change based on the design optimization.

Factor Identification

The identification of factors and their levels is an important step to the research methodology. These factors have a significant impact on the response variables, which are the light intensity and light uniformity. The major factor in this experiment is the height at which light illumination is occurring. Constant factors include: cable size and length and curves, light source type, and spacing. A model of the typical process of these factors is applied with input, independent variables, controllable factors, nuisance factors, and output. In this experiment, the light illumination is the process. The input factor is the height level at which the fiber optics are placed. The controllable factors are the spacing, and level of cleanness of the fiber optics. The nuisance factors are the bending, aging, and yellowing of the fiber optics. And the output is the light uniformity and light intensity.

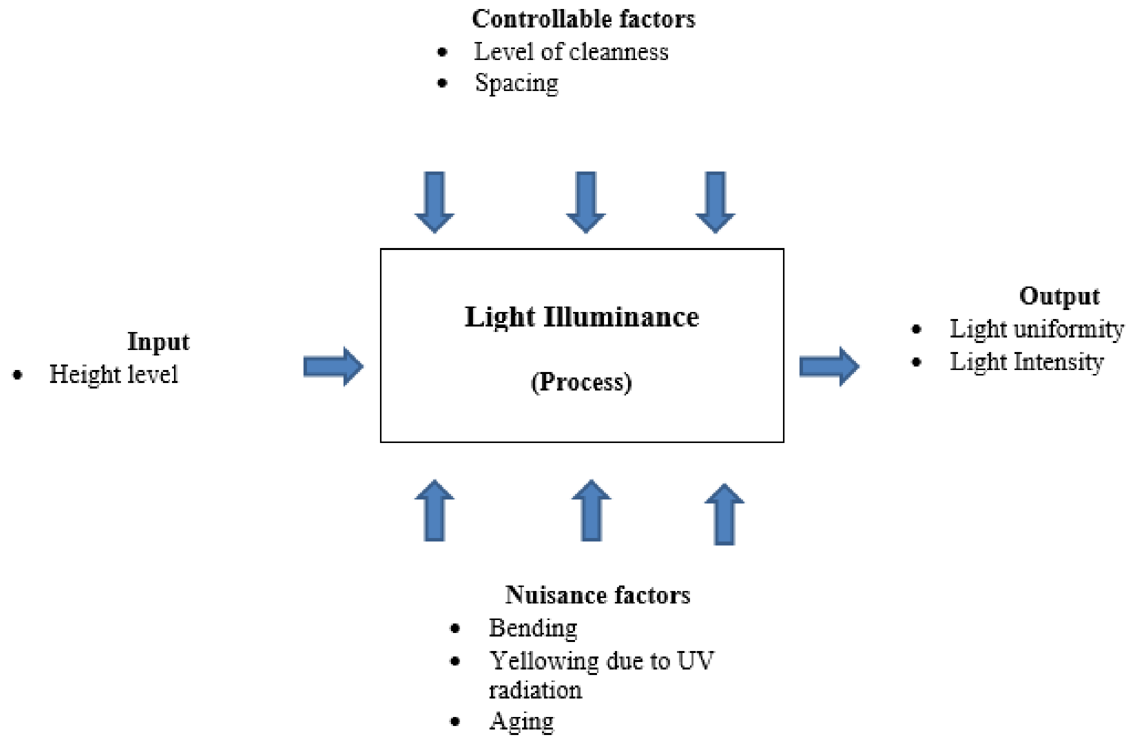


Figure 17. Experiment process diagram.

V.MODELING AND SIMULATION

Introduction

Natural light can be delivered to the most remote and hard to reach places in a building. The use of non-conventional energy methods such as using plastic bottles with water and a small amount of bleach to radiate the natural light, to illuminate small houses, (See Figure 18). Alfredo Moser, the inventor of the solar water bulbs developed an efficient source of energy where sunlight is transmitted through a plastic bottle containing water and bleach, which can deliver light rays faster due to its denser than air material (water) (Gibby Zobel, 2013). Methods such as these are used to utilize natural light in places where electricity cannot be reached or simply finding a better way to deliver light in places where sunlight is difficult to reach. As part of this research, the utilization of natural light is applied for plant growth in an indoor application where light is delivered through fiber optic cables.

Figure 18. Solar water bulb. A water bottle containing water and bleach to radiate light indoor. Adapted from “Alfredo Moser: Bottle light inventor proud to be poor” by Gibby Zobel (2013).

LED lighting for plant growth

In other studies which implemented LEDs to maximize the indoor growth of plants, LED colors used were red, blue, green, and yellow. In order for plants to undergo photosynthesis their wavelength spectrum should be at approximately 400-700 nm; red (600-700nm) and blue (400-450nm) colors fall into this spectrum category ("UCSB Science Line," 2015). In this research, the goal was to produce the overall energy needed for indoor plant growth.

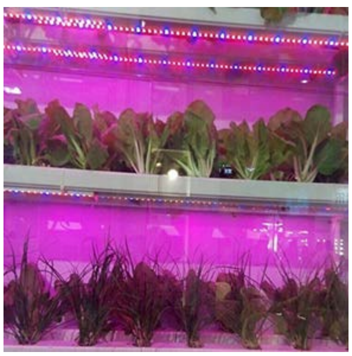


Figure 19. Plants under a full spectrum of LED grow lights. Adapted from "Why Use Full Spectrum LED Grow Lights".

In order to distribute sufficient natural light to the indoor environment, it is important to conduct a simulation of light distribution before physical implementation.

Method and Modeling

The distribution of the natural light is performed by positioning the end effectors in a certain height and position. In order to determine the overall energy needed for this indoor application and energy needed for plant growth, it is necessary to utilize software to determine the best light type (side glow or end glow). In this research, a light simulation software was adopted to find the optimum position of end effectors in a way that it produces uniform light distribution for the entire plant rack. The dimensions of the rack were 90 inches (in) x 24 inches (L x W). The different height levels (14in, 12, 10in, 8in, and 6in) were used in order to determine at what height light was distributed more uniformly. The light type used for side glow and end glow were based on the light measurement captured when measuring the light passing through the each of the optical fibers. It was then determined to use the same amount of light power to conduct the simulation. The light types (side glow and end glow) were simulated as follows:

Table 3. Light Design Details. Details of the light type, light pattern, and height of the experiment.

Lighting Type	Lighting Pattern	Height (Inches)
Side Glow (4,000 lux)	One bar, Two bar, Three bar, Four bar, Five bar, Six bar	14, 12, 10, 8, 6
End Glow (8,000 lux)	Center line (8 points), double line (16 points), Zig Zag (8 points)	14, 12, 10, 8, 6

In this research, the software utilized to run the simulation was AGI32. Illumination software such as AGI32 is commonly used for various types of applications including nontraditional use, a simulation tool for the optimization of a heater. According to Asiabanpour et al. (2007), the AGI32 software was used to evaluate the uniformity of the distributed heat that is generated from the heater. The different functions of AGI32 are a great tool for this experiment; it is designed to study the light intensity and distribution of indoor and outdoor applications. AGI32 can compute a numerical point-by-point calculation, where luminaries are placed on any surface to then evaluate its distribution in any simulated environment (AGI32, available at: www.agi32.com).

Illuminance is defined as the amount of light falling on a point on a surface and is calculated from the luminous intensity (with standard units of Candela) and the distance between the luminous source and the surface (Freivalds and Niebel, 2003). The following equation can be utilized to calculate the amount of light falling on a surface.

Amount of light falling on surface = Illuminance = Source intensity/ Distance2

Simulations and calculations were performed for all patterns along with the critical test heights. End effector patterns were performed through testing correlation variation in different scenarios.

Results and Discussion

AGI32 can generate the output in different formats as desired by the user. The following are the graphical patterns of the simulation conducted for the indoor application with the end effectors (See Figures 20, 21, 22, 23, 24, 25, 26, 27, & 28). The graphical illuminance distribution illustrates the nine different patterns at five different height levels with their corresponding CV values. In Figure 20, the simulation was conducted by using the pattern of End glow (end part of the optical fiber that is not covered by PVC) and setting eight luminaries in the center of the room (symbolizing the plant racks) at 5 different heights (14in, 12in, 10in, 8in, and 6in). The similar concept was done for Figure 21, the amount of the luminaries was double (16 luminaries) than the amount of Figure 20 and where placed evenly at the center of the room. In Figure 22, the simulation was conducted with a zig zag pattern (eight luminaries) spread evenly across the room but the light distribution was not uniform.

Side glow design (optical fiber cable with no PVC) was also conducted using the simulation for the possibility of a more uniform distribution. The similar concept was done for side glow by setting 5 different height levels and then using 1, 2, 3, 4, 5, & 6 bars as different light patterns. In Figure 23, the side glow pattern containing 1 bar was placed on the center of the room at the same height as the previous patterns (for end glow). The similar side glow concept was used for Figure 24 and 25, 2 bars and 3 bars where the number of luminaries placed on the room. The more amount of lights placed increased grater illumination when adding 4, 5,& 6 bars these demonstrated higher CV values than those of the end glow patterns (See Figures 26, 27, & 28). The side glow concept was determined to have a more uniform light distribution.

The graphical illuminance distribution illustrates the nine different patterns at five different height levels. The correlation variation (CV) measures the repeatability and reproducibility within the data; it can be calculated by CV = (Standard Deviation (σ) / Mean (μ)) (5.1) and multiplying the resultant value by 100. The lower the CV, the greater light distribution is portrayed uniformly. By using this statistical parameter, we can determine the correlation variation of illuminance for the nine different patterns. In Figure 25, 26, 27, & 28, the Side glow patterns with 3, 4, 5, & 6 bars at the 4 different heights (14in, 12in, 10in, 8in, and 6in) have low variation when placed at 14 in and 10 in height. The objective of the simulation was not to pick the pattern with the highest light illumination but the one displaying uniformity within these 9 patterns. The illuminance needed to cover the rack uniformly so that it can assure that the plant growth will be consistent. The coefficients of variation for the lighting scenarios were graphed (See Chart 1). This chart shows more clearly that Side glow 5 bar and 6 bars are relatively close to each other, meaning that both patterns approve the uniformity claim.

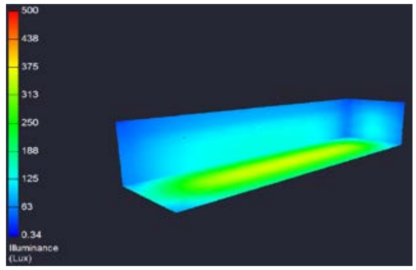
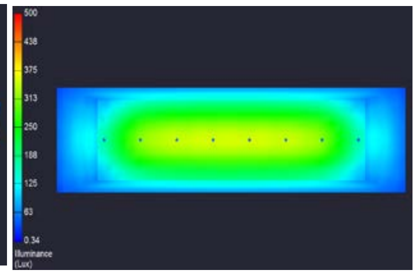
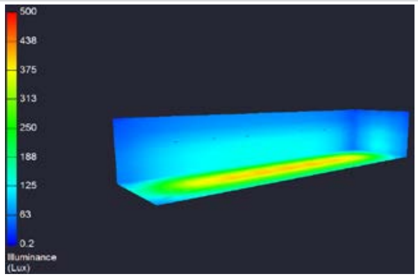
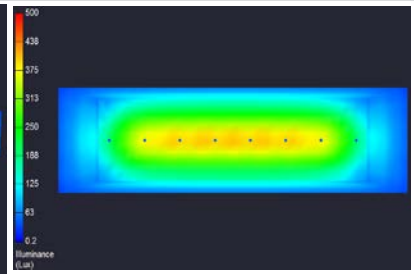
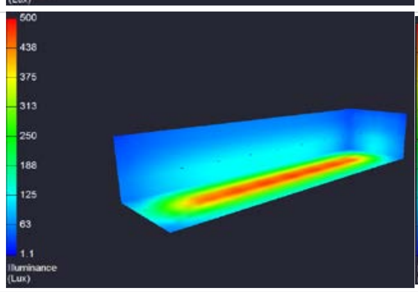
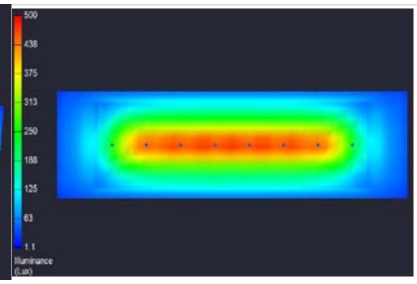
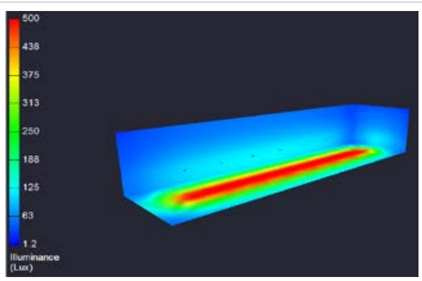
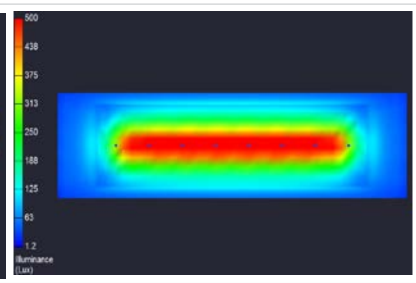
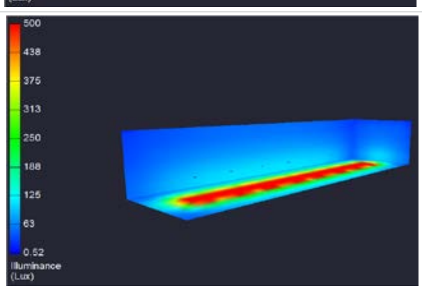
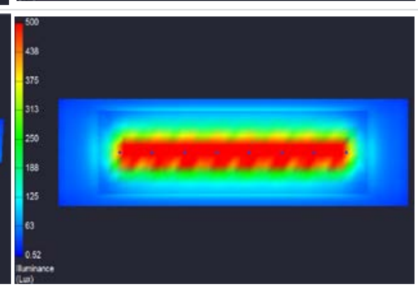
Pattern	Graphical illuminace distribution	
End glow Center 14in **CV=0.314%**		
End glow Center 12in **CV=0.384%**		
End glow Center 10in **CV= 0.483%**		
End glow Center 8in **CV=0.622 %**		
End glow Center 6in **CV= 0.868%**		

Figure 20. End glow (1 line) experiment conducted at 5 different heights with their corresponding CV values.

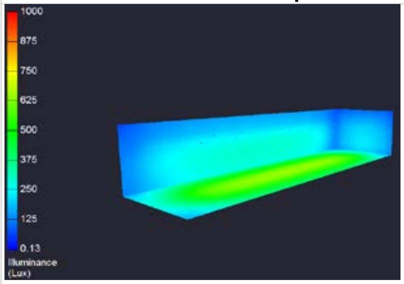
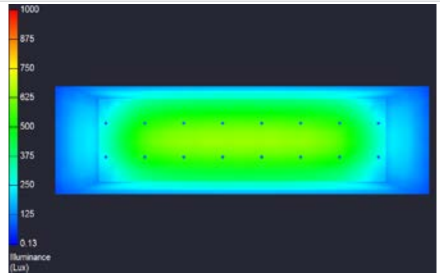
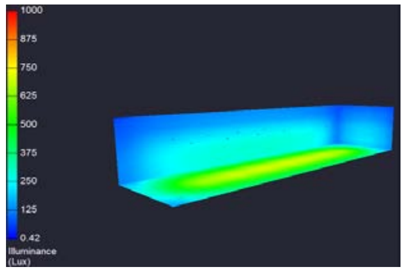
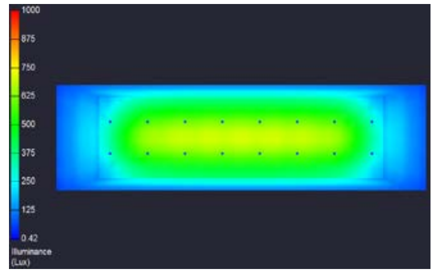
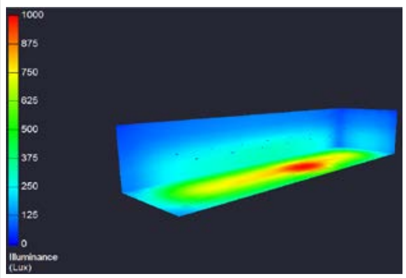
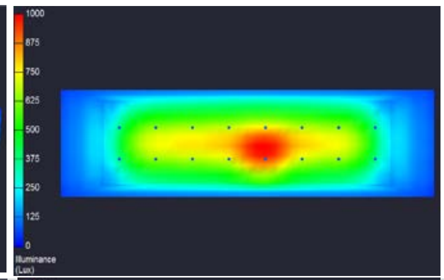
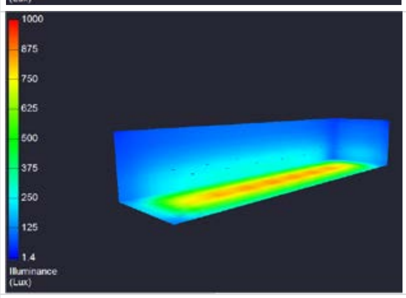
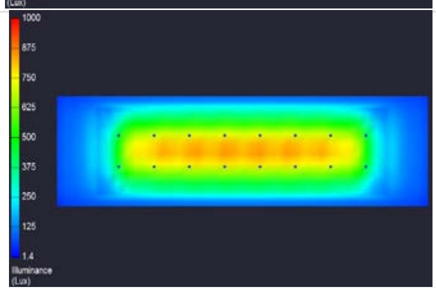
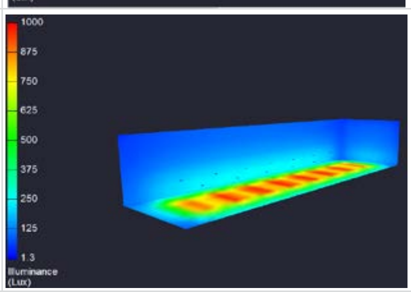
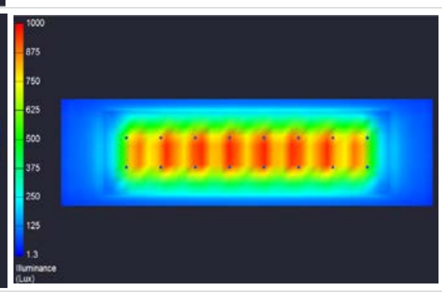
Pattern	Graphical illuminace distribution	
End glow 2 lines 14in CV= 0.268%		
End glow 2 ines 12in CV=0.296%		
End glow 2 lines 10in CV= 0.371%		
End glow 2 lines 8in CV=0.406 %		
End glow 2 lines 6in CV= 0.526%		

Figure 21. End glow (2 lines) experiment conducted at 5 different heights with their corresponding CV values.

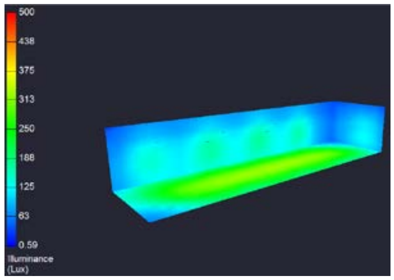
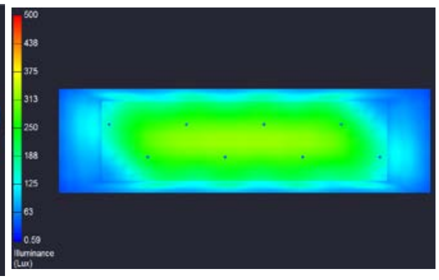
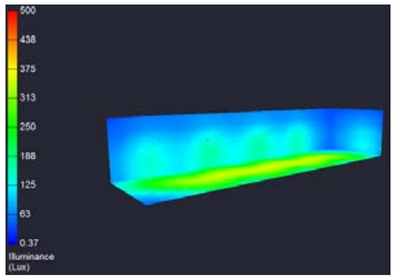
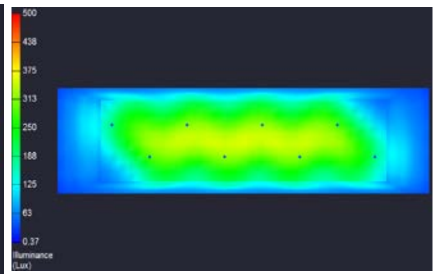
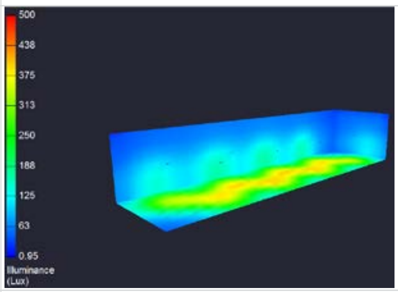
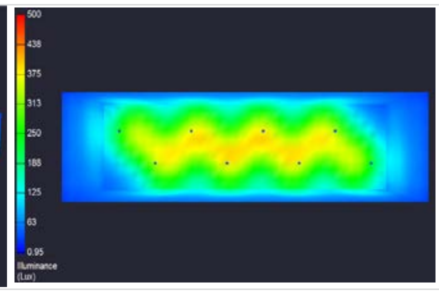
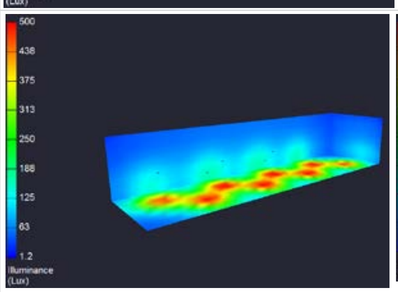
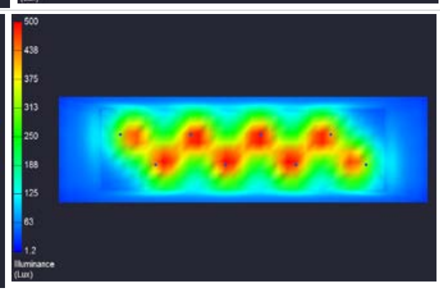
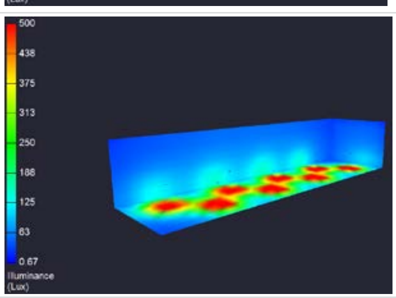
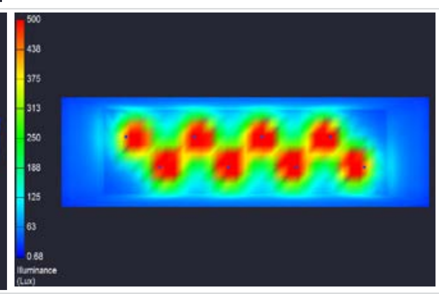
Pattern	Graphical illuminace distribution	
End glow Zig Zag 14in CV=0.275 %		
End glow Zig Zag 12in CV=0.312%		
End glow Zig Zag 10in CV=0.385 %		
End glow Zig Zag 8in CV=0.543 %		
End glow Zig Zag 6in CV= 0.771%		

Figure 22. End glow (Zig Zag) experiment conducted at 5 different heights with their corresponding CV values.

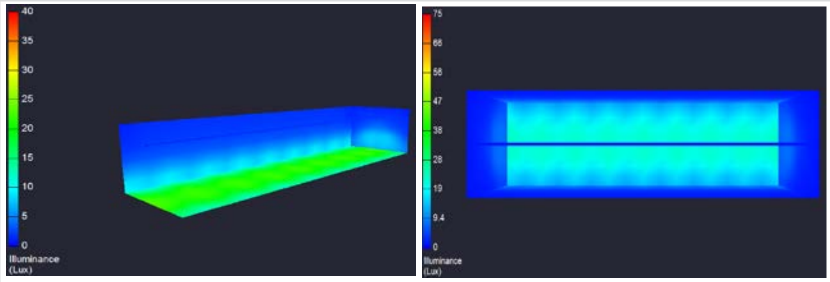
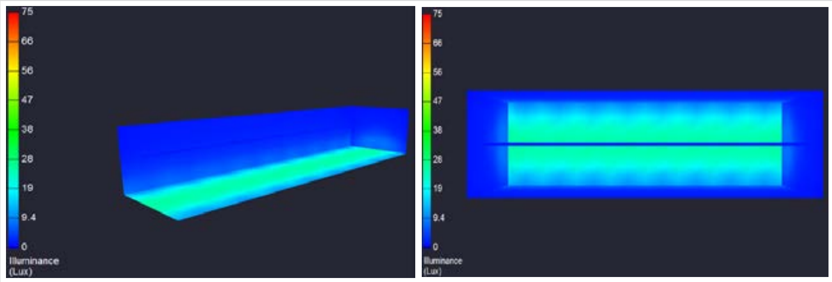
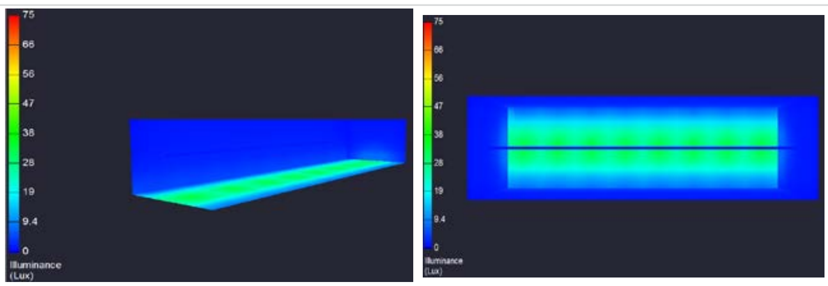
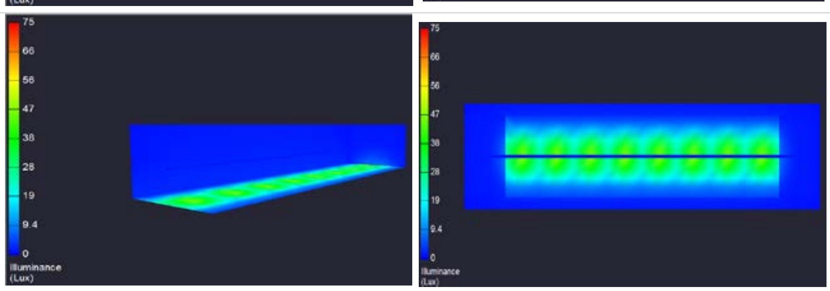
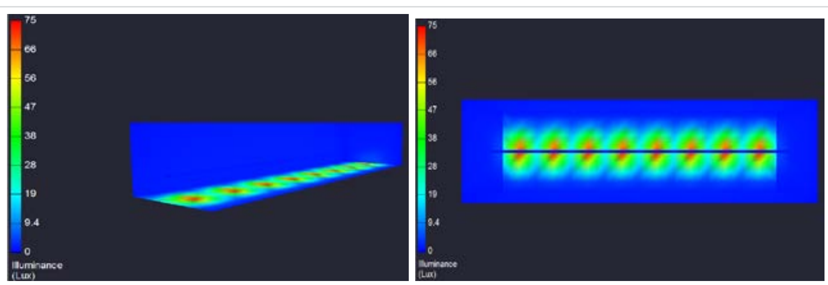
Pattern	Graphical illuminace distribution
Side glow 1 Bar 14in CV=0.203 %	
Side glow 1 Bar 12in CV=0.319%	
Side glow 1 Bar 10in CV=0.409 %	
Side glow 1 Bar 8in CV= 0.741%	
Side glow 1 Bar 6in CV=1.195 %	

Figure 23. Side glow (1 Bar) experiment conducted at 5 different heights with their corresponding CV values.

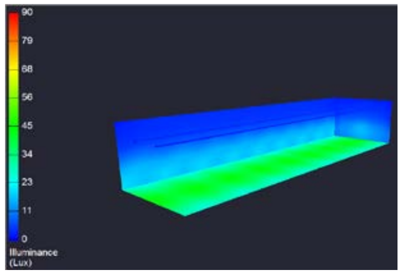
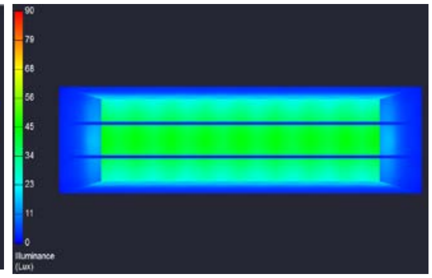
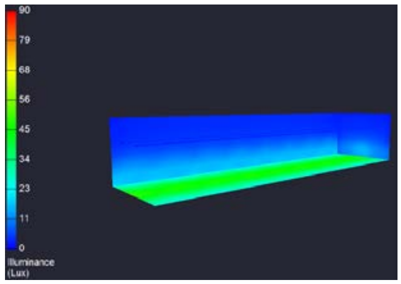
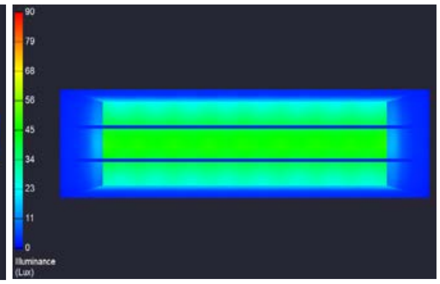
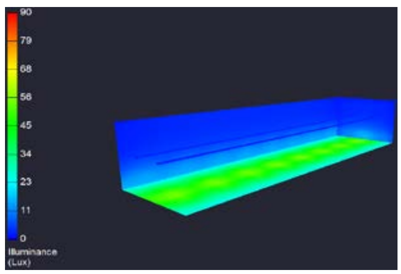
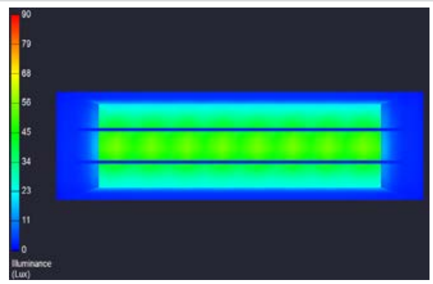
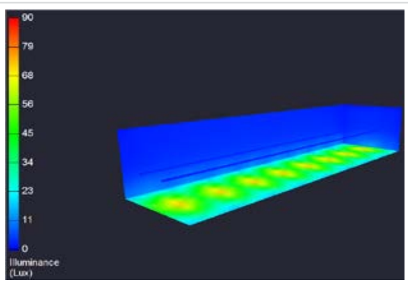
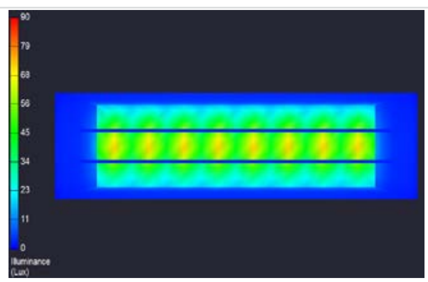
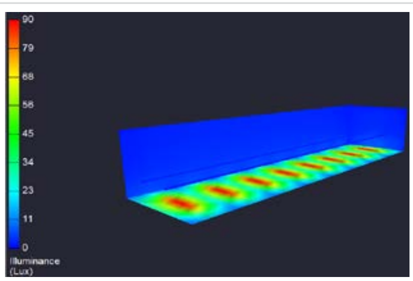
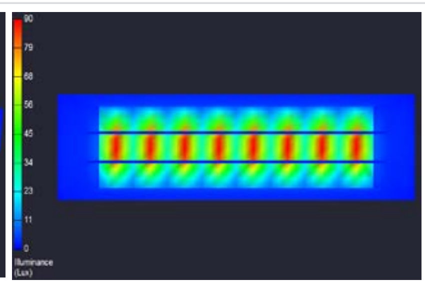
Pattern	Graphical illuminace distribution	
Side glow 2 Bar 14in CV= 0.159%		
Side glow 2 Bar 12in CV=0.173%		
Side glow 2 Bar 10in CV= 0.245 %		
Side glow 2 Bar 8in CV= 0.431%		
Side glow 2 Bar 6in CV= 0.792%		

Figure 24. Side glow (2 Bar) experiment conducted at 5 different heights with their corresponding CV values.

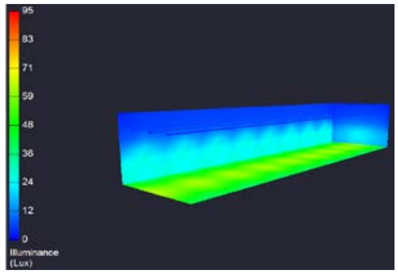
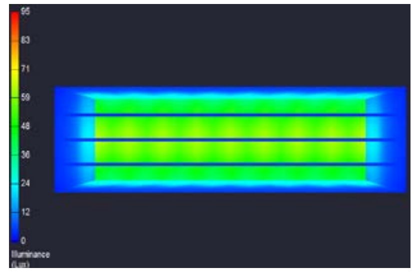
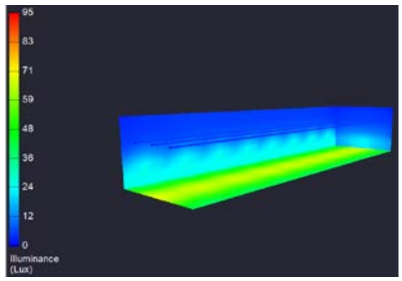
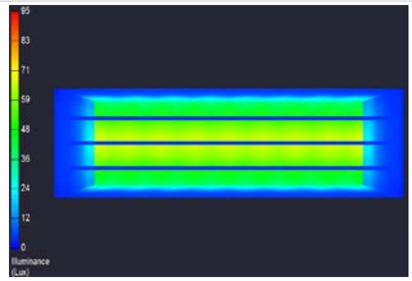
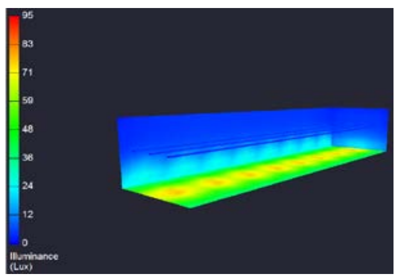
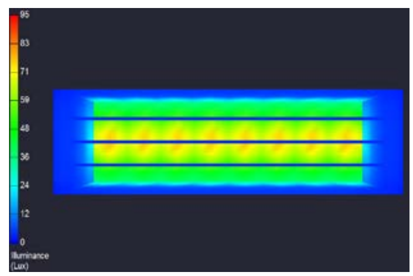
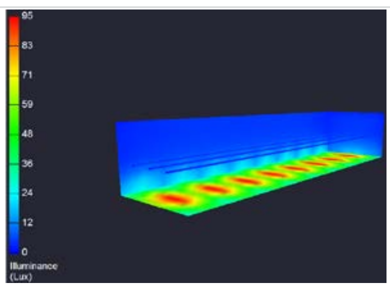
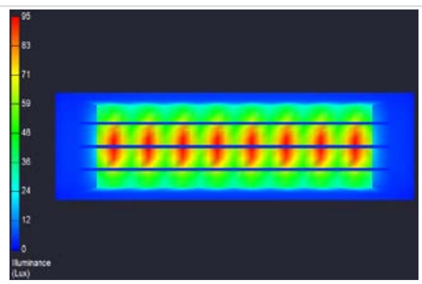
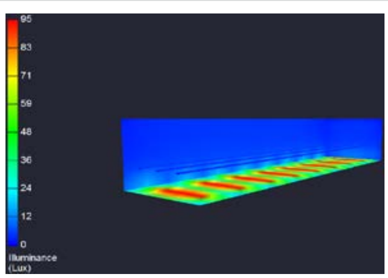
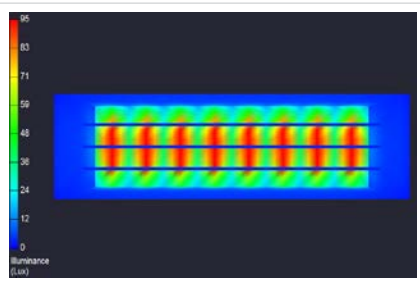
Pattern	Graphical illuminace distribution	
Side glow 3 Bar 14in **CV= 0.139%**		
Side glow 3 Bar 12in **CV=0.179%**		
Side glow 3 Bar 10in **CV= 0.230%**		
Side glow 3 Bar 8in **CV= 0.358%**		
Side glow 3 Bar 6in **CV= 0.570%**		

Figure 25. Side glow (3 Bar) experiment conducted at 5 different heights with their corresponding CV values.

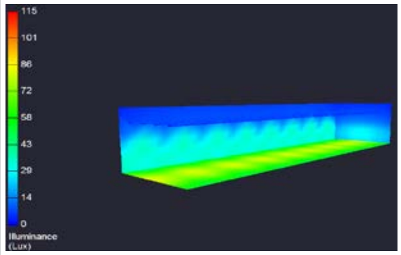
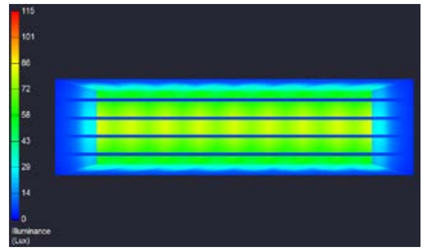
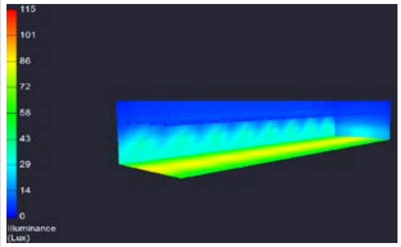
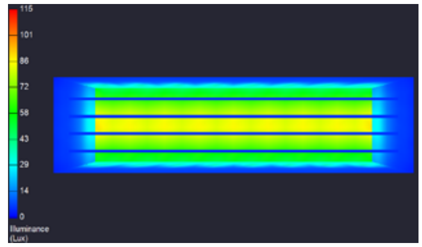
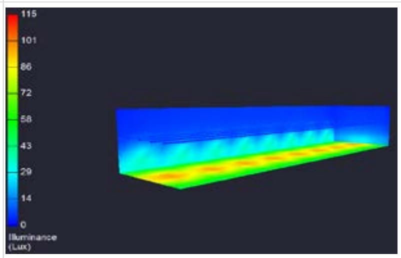
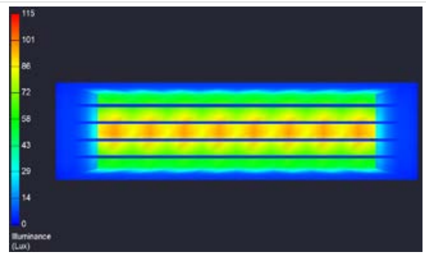
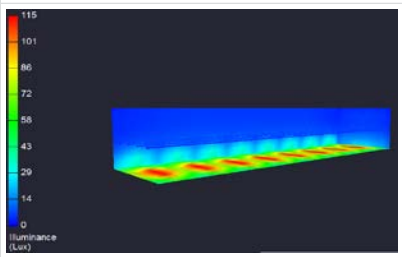
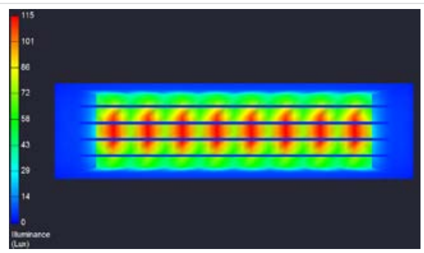
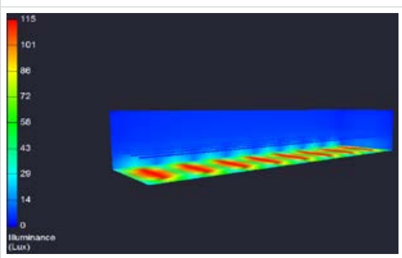
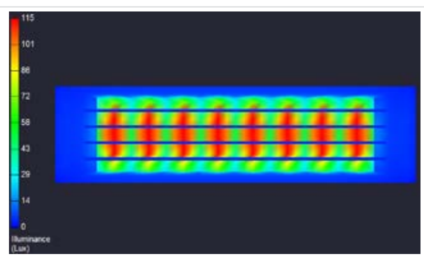
Pattern	Graphical illuminace distribution	
Side glow 4 Bar 14in CV=0.150 %		
Side glow 4 Bar 12in CV=0.171%		
Side glow 4 Bar 10in CV=0.228 %		
Side glow 4 Bar 8in CV= 0.352%		
Side glow 4 Bar 6in CV= 0.597 %		

Figure 26. Side glow (4 Bar) experiment conducted at 5 different heights with their corresponding CV values.

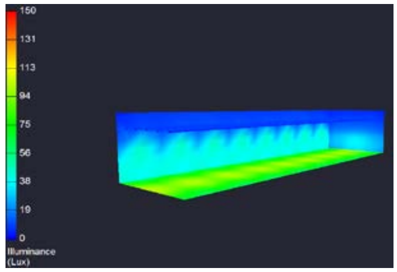
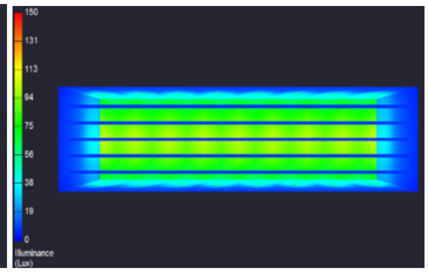
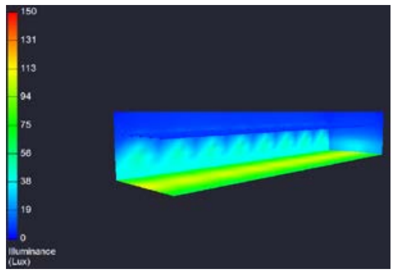
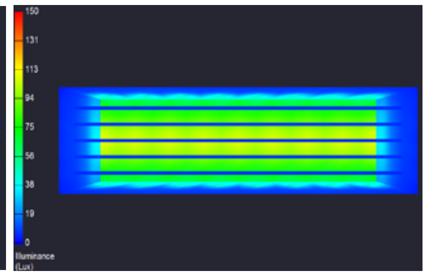
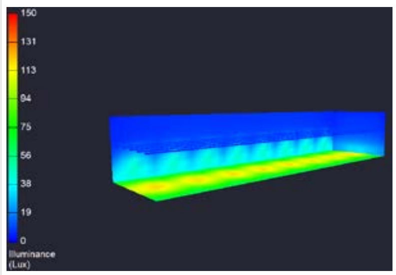
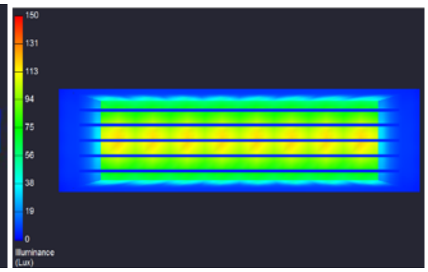
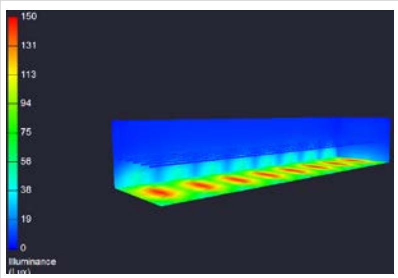
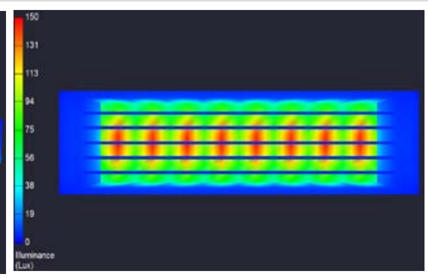
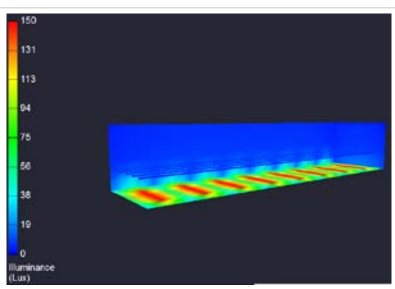
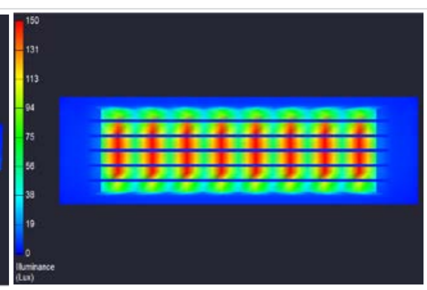
Pattern	Graphical illuminace distribution	
Side glow 5 Bar 14in CV=0.149 %		
Side glow 5 Bar 12in CV=0.136%		
Side glow 5 Bar 10in CV=0.217 %		
Side glow 5 Bar 8in CV=0.350 %		
Side glow 5 Bar 6in CV=0.596 %		

Figure 27. Side glow (5 Bar) experiment conducted at 5 different heights with their corresponding CV values.

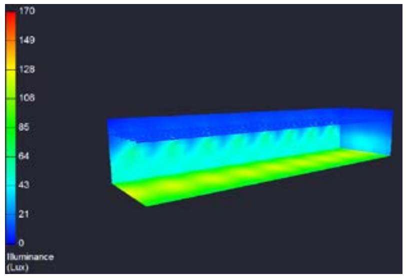
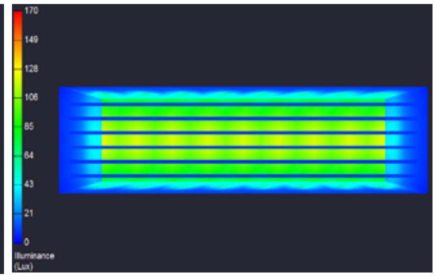
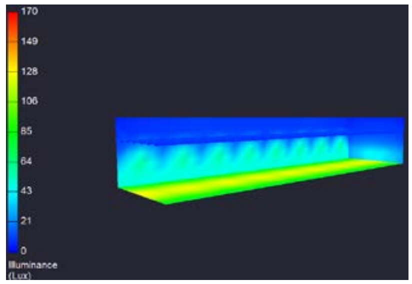
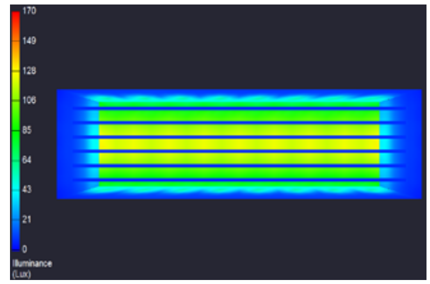
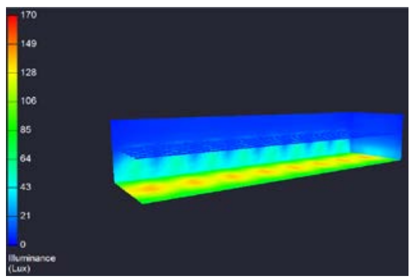
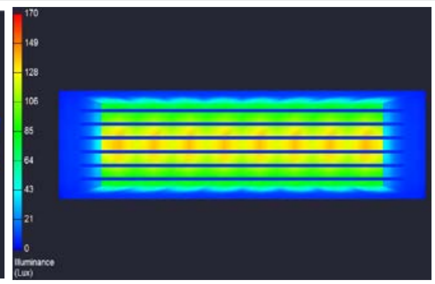
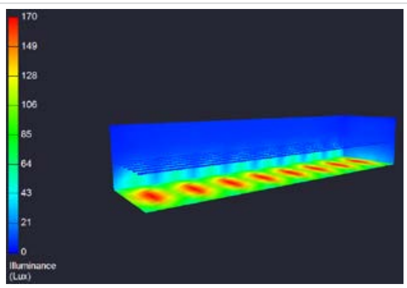
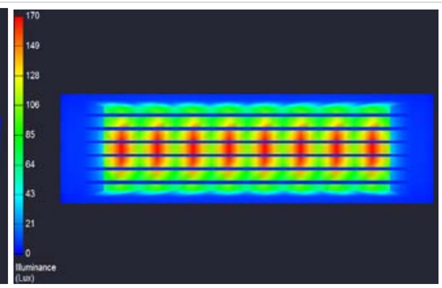
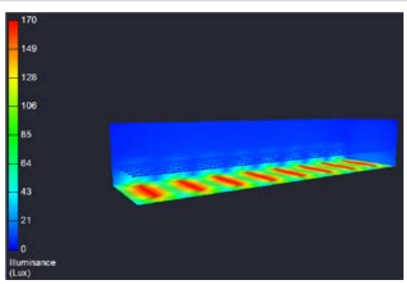
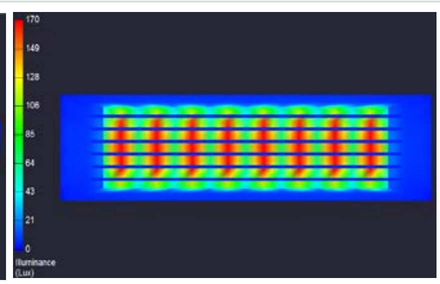
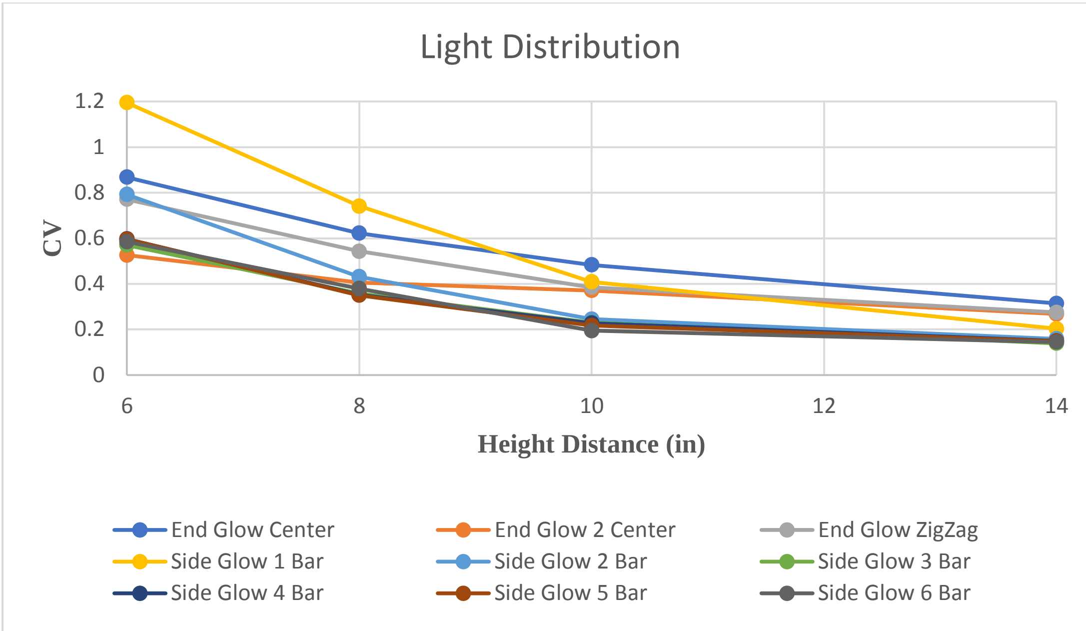
<table>
<tr><th>Pattern</th><th colspan="2">Graphical illuminace distribution</th></tr>
<tr><td>Side glow 6 Bar 14in
CV= 0.145%</td><td></td><td></td></tr>
<tr><td>Side glow 6 Bar 12in
CV=0.148%</td><td></td><td></td></tr>
<tr><td>Side glow 6 Bar 10in
CV=0.195%</td><td></td><td></td></tr>
<tr><td>Side glow 6 Bar 8in
CV= 0.379%</td><td></td><td></td></tr>
<tr><td>Side glow 6 Bar 6in
CV= 0.585%</td><td></td><td></td></tr>
</table>

Figure 28. Side glow (6 Bar) experiment conducted at 5 different heights with their corresponding CV values.

Table 4. Light Distribution Designs and Coefficient of Variation.



<u>Discussion</u>

The illumination software (AGI32) was an efficient tool to evaluate the preliminary patterns in order to determine the design of the rack and the placement of the end effectors. The results show promising data for the application of these patterns on the indoor environment. When the luminaires are placed closer to the surface the light does not distribute uniformly. When the lights are in greater quantity, have a greater surface area, and are placed at a higher location, the light distribution gives desired results. The side glow light patterns have a higher distribution than end glow (point-to-point) distribution. A three, four, five and six side bar setup at 14 and 10 inches are equally good for highest uniformity. The end glow design would probably work best with an application with smaller dimensions or using attachments that can distribute light more uniformly.

Furthermore, more alternative patterns can be performed in order to find the optimum design with uniformity. The distribution of light could be expanded given the proper space to do so. The drawback of adding more distance to the design can result to less intensity. For instance, side glow design produces less light intensity than end glow so if more distance were added the light intensity would be poor. End glow has high light intensity points but are not uniform and do not provide consistency like side glow. The light type in the simulation was determined by the light source which was gathered from the measurement of the amount of light emitted from the end glow and side glow when powered by the light source. These were measured by a device which can measure the amount of lux.

VI. SYSTEM INFRASTRUCTURE OF THE MECHANICAL/OPTICAL/ELECTRICAL COMPONENTS

Background and Implementation

The system infrastructure used in this research requires multiple ongoing tasks for the completion of this system. These tasks include holding, securing, placement, and light distribution. The completion and set up was done with the help of student to complete the tasks of assembling the rack, where the placement of the optical fibers would take in place. With the use of product development process (PDP), the component that was used to hold the optical fiber and the end effector in place was fabricated and cut with the use of a water jet software and machine. These were accessed at the labs in Texas State University. The goal of PDP on this mechanical system is to help conduct the experiments, to be a user-friendly product, to replicate the product for any user. The customer needs were identified and used to create the mechanical system specifications. These include having flexibility of space for future attachments such as adding a water system, air filtering, and LED system (backup light system).

Mechanical components

Part and Assembly CAD files of the mechanical system parts were generated with the use of Autodesk Inventor software in order to provide a better view of the mechanical parts used to design and conduct this investigation. Many of these pieces were acquired by buying the parts online, hardware stores, or made using the waterjet to create the final outcome of the mechanical system to conduct this experiment.

Figure 29. End effector draft. Inventor Autodesk draft of the end effector used to diffuse light and distribute light on the rack for uniformity.

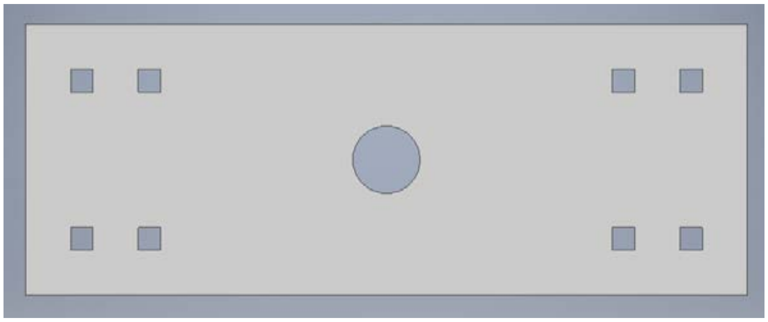


Figure 30. Metal plate draft. Inventor Autodesk draft used to hold the fiber optic in pace on the rack for minimum movement.

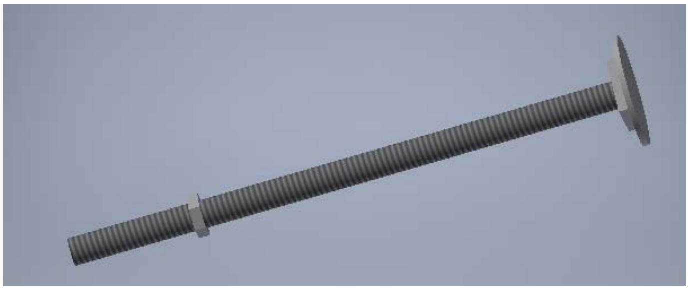


Figure 31. Bolt and nut draft. Inventor Autodesk draft of the assembly of the bolt and washer used to hold the metal plate attachment to the rack.

Figure 32. Assembly draft of fiber optic, end effector, metal plate and bolts. Inventor Autodesk draft assembly of parts used for the placement of fiber optic on racks.

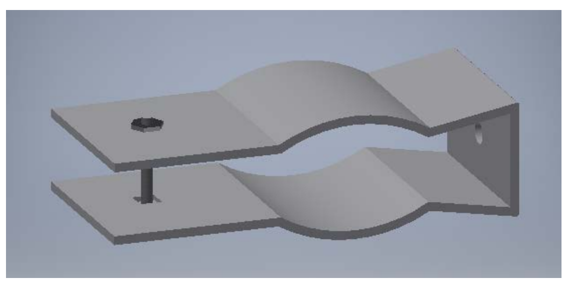


Figure 33. Clamp draft. Inventor Autodesk draft of clamp used to hold the fiber optic side glow cables.

Figure 34. Metal hook and nut draft. Inventor Autodesk draft of the metal hook used to hold the clamp on the rack.

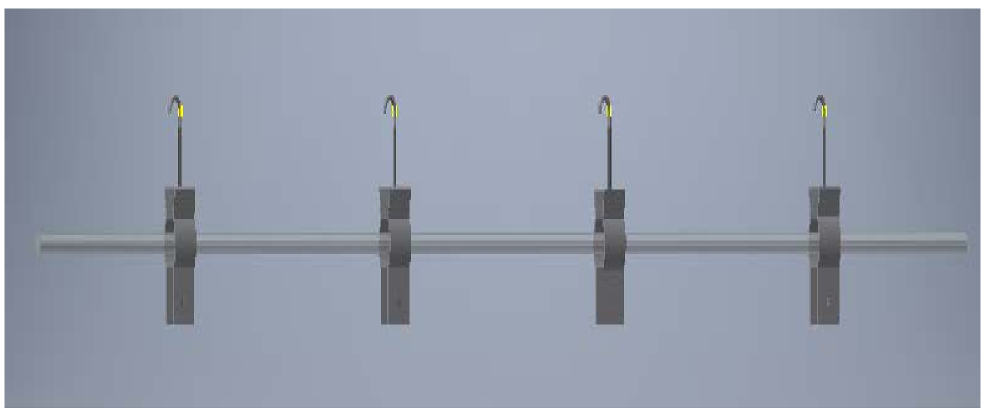


Figure 35. Assembly draft for side glow attachment. Inventor Autodesk draft of the assembly of fiber optic (side glow) cable with the attachments to hold on the rack.

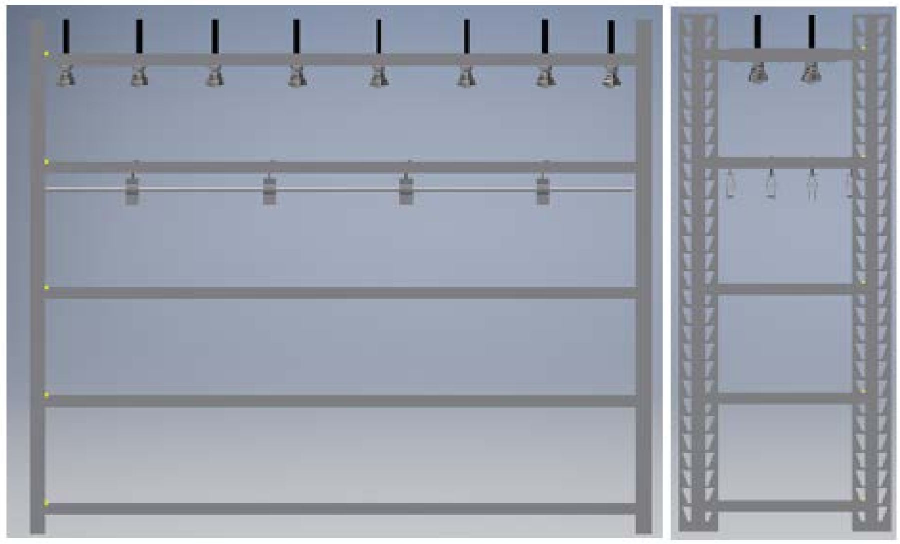


Figure 36. Final assembly draft. Inventor Autodesk draft of final assembly of fiber optic cable.

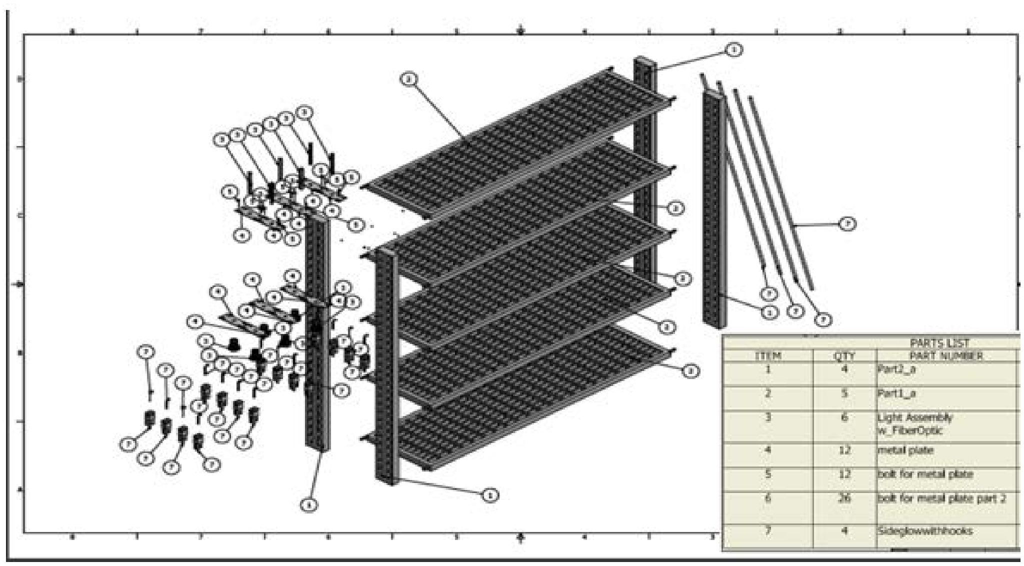
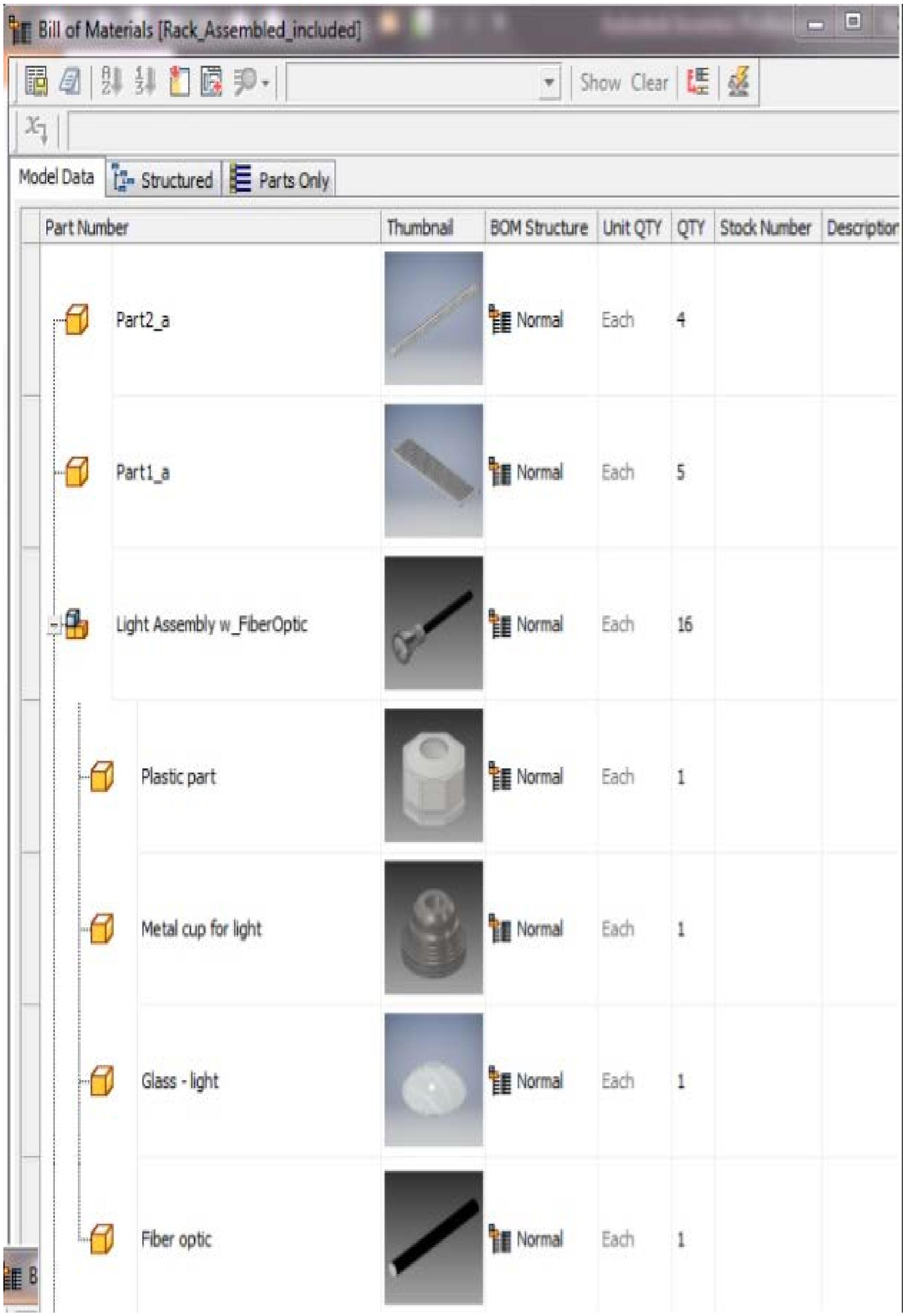


Figure 37. Parts draft list. Parts draft and list generated by Inventor Autodesk.

Finally the following table shows the bill of materials (BOM) used in the mechanical system.

Table 5. Bill of Materials.


Bill of Materials [Rack_Assembled_included]

Show Clear

Model Data | Structured | Parts Only

Part Number	Thumbnail	BOM Structure	Unit QTY	QTY	Stock Number	Description
Part2_a		Normal	Each	4		
Part1_a		Normal	Each	5		
Light Assembly w_FiberOptic		Normal	Each	16		
Plastic part		Normal	Each	1		
Metal cup for light		Normal	Each	1		
Glass - light		Normal	Each	1		
Fiber optic		Normal	Each	1		

Table 5. Bill of Materials (Continued).

metal plate		Normal	Each	32
bolt for metal plate		Normal	Each	32
bolt for metal plate part 2		Normal	Each	32
Sideglowwithhooks		Normal	Each	4
SideGlowAttachment_assembled1		Normal	Each	4
metal plate		Normal	Each	32
bolt for metal plate		Normal	Each	32
bolt for metal plate part 2		Normal	Each	32
Sideglowwithhooks		Normal	Each	4
SideGlowAttachment_assembled1		Normal	Each	4

Implementation

Utilizing IGEMS software and Waterjet the needed brackets were designed and cut into the size and were used to create desired light distribution patterns.

Figure 38. Water jet machine used for the production of parts.

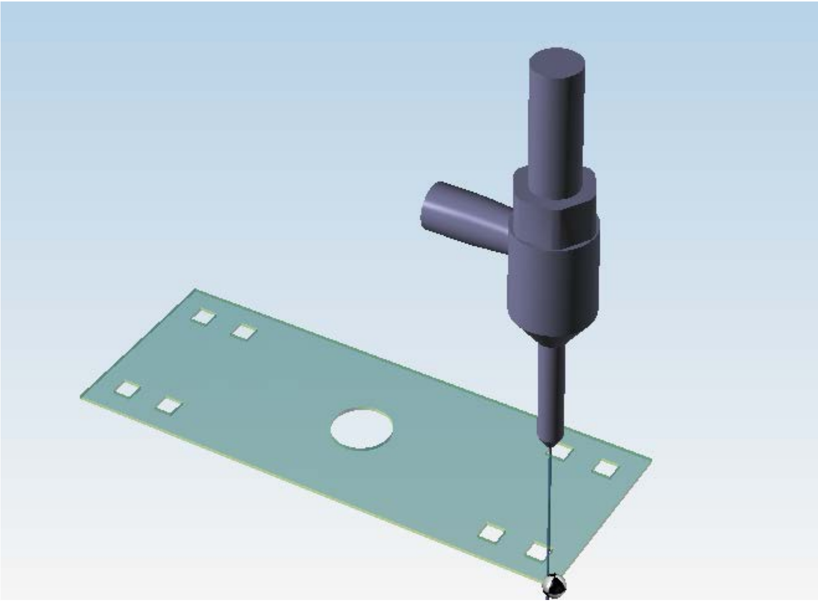


Figure 39. 3D simulation. IGEMS program cutting simulation of the part.

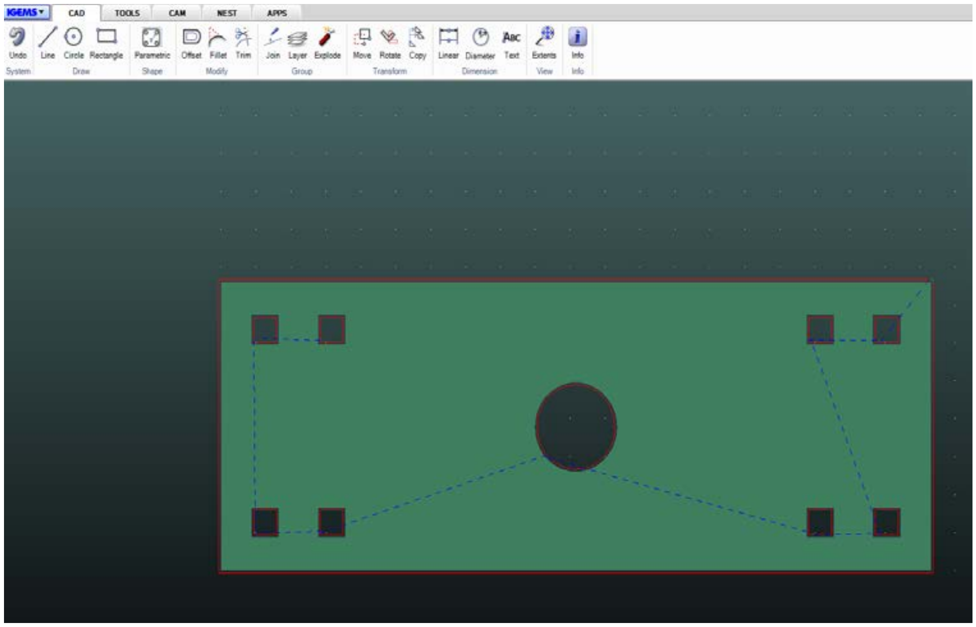


Figure 40. 40. Metal plate draft part using water jet software. IGEMS software with draft part.

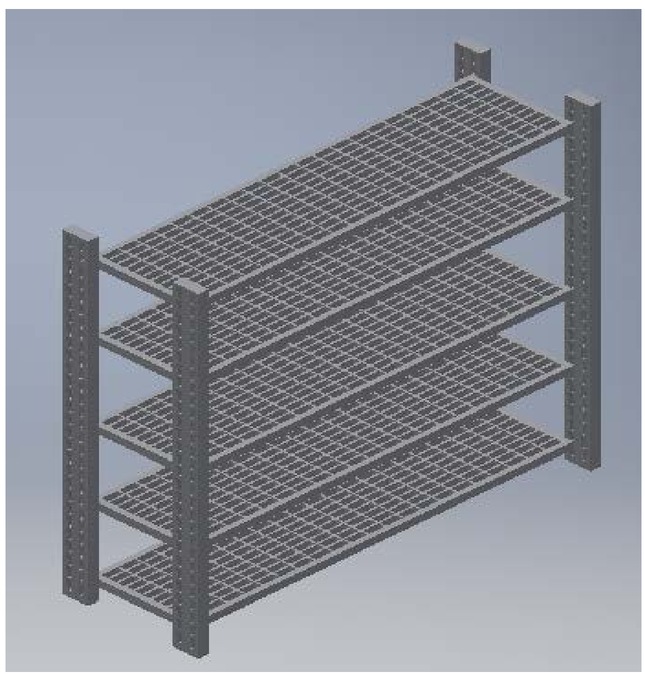


Figure 41. Metal rack draft. Inventor Autodesk assembly of the rack used in the mechanical system to place the light systems for testing.

Electrical Components

The Electrical components include the use of an LED light to distribute light through the optical fibers due to the unavailable time to complete the natural light system (first method of light distribution). The use of LED light can be a point of use when they natural light system can’t deliver natural light because of weather conditions.

Figure 42. The light system used to power the mechanical system.

Figure 43. The final assembly of the system.

Optical Components

The optical components consist of the optical fibers used to distribute the light through this system, which include optical fibers with pvc and optical fibers with no pvc. These fibers are used to deliver and distribute the light through the racks for more uniform distribution based on plant growth requirements. In addition to the optical components found in the natural light system, uses reflective/concentrated mirrors that can refract sunlight into the optical fibers.

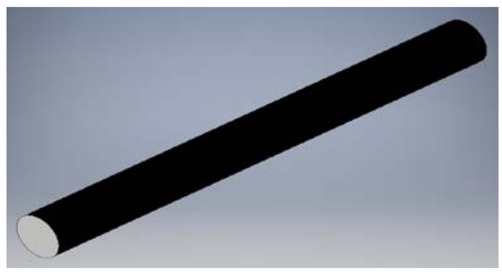


Figure 44. Fiber optic (end glow) draft. Inventor Autodesk draft of the fiber optic used to distribute light on the racks.

Figure 45. Fiber optic without black PVC (side glow) draft. Inventor Autodesk draft of fiber optic cable used for side glow light system.

Figure 46. End effector for fiber optic. Optical component used to distribute light was attached to the fiber optic.

VII. DESIGN OF EXPERIMENTS

Introduction

The experimental design for this research has been implemented to characterize the process in which the input parameters affect the output parameters. The full factorial design was chosen for the experiment, contains only one factor (height) at 5 different levels. Full factorial design, measures the response of the experimental runs at all possible combinations of the factor levels. The responses are then analyzed to provide the information of the experiment's main effect and interaction effect. Full factorial should only be performed on factors lower than 5, cost and time can be expensive when performed on more than 5 factors.

Spectrum Meter Device

The Sekonic Spectrum meter C-700, is a device that has the ability to record and measure LED, HMI, Flurescent sources, natural light and electronic flash (C-700 Light meter, available at www.sekonic.com). It offers advanced color measurement and analyzing features such as, measuring the light spectrum distribution. The accuracy of this device made it a great tool for the experiment when measuring and recording the data. With the use of this device and its software it is possible to access and obtain information such as, correlated color temperature, illuminance, color rending index (CRI), peak wavelengths and photosynthetic photon flux density.

Figure 47. Spectrum meter device. C-700 Light spectrum meter from Sekonic. Adapted from C-7000 SpectroMaster by Sekonic.

Input factor(s)

The distance on the height was the input factor in the experiment. The experiment consisted of 5 different heights: 14in, 12in, 10in, 8in, and 6in. These affected the output factor which was the light intensity. When light was positioned at a longer distance light intensity was affected causing the intensity to fluctuate and causing the light intensity to increase. Distance affects how the light reflects from an object but also the intensity of the light at that distance. For instance, the sun produces so much light and the closer it gets the more intense light and heat becomes (See Figure 47).

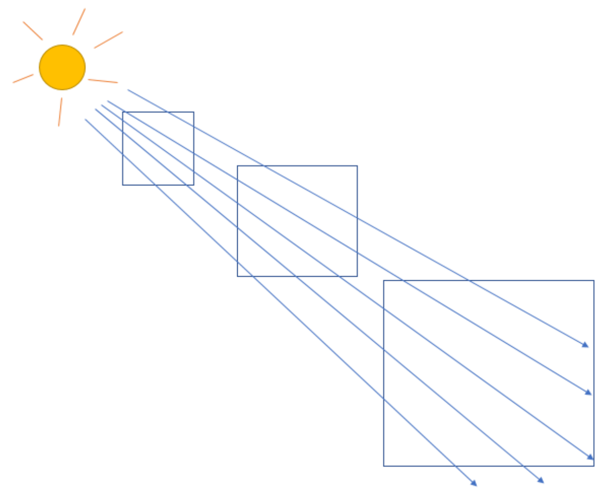


Figure 48. Light intensity affected by the distance illustrated by the sun.

Constant factors

- Cable size
- Cable length
- Cable curves
- Spacing
- Light type

Light type used

The light source used in the experiment was a halogen work light with a tripod. It had two halogen lights of 500 watts each. The intensity of light was measured from the point from which the optical fibers were placed; the optical fibers were placed about 4 feet away from the light. The light intensity was measured with a spectrum meter, the measurement was 45,000 lux.

Output factor(s)

The output factor was the light uniformity and light intensity these were measured in the unit of lux. The light or luminous intensity is referred to the power emitted by a light source in a particular direction; this is based on the luminosity function. The luminosity is then measured by the units of candela and lux.

Conducting the Experiment

The experiment was conducted and the readings were collected using Sekonic, a measuring device that can measure light and capture its spectrum. The runs conducted in the experiment consisted on the different heights of the end glow and side glow systems. While the end glow design consisted of 2 lines of 8 (16 lights) we were only able to get 2 rows of 4 (8 lights) because of the lack of material (See Figure 48). The light intensity of the light source (LED light) used in the experiment was measured about 4 inches away from where the cables were positioned, light intensity emitted from that distance was about 45,000 lux. The amount of light was assumed it split into the (12) optical fiber cables, delivering light on the rack based on the end glow and side glow designs.

Figure 49. End glow and side glow set-up on the rack.

Figure 50. Light source aligned with the end of the cables to transfer the light.

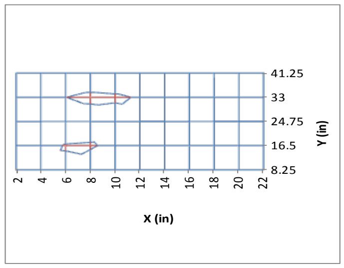
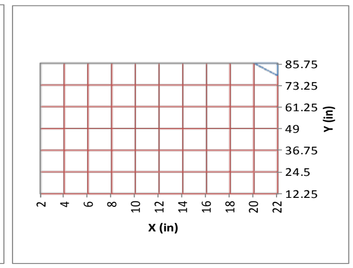
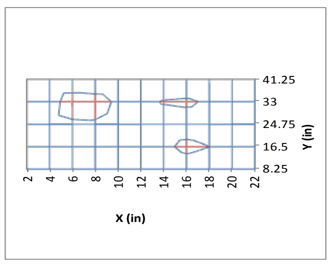
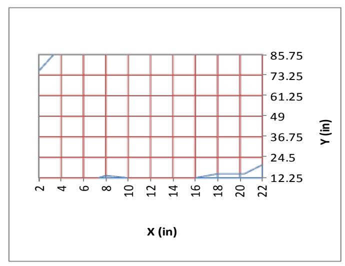
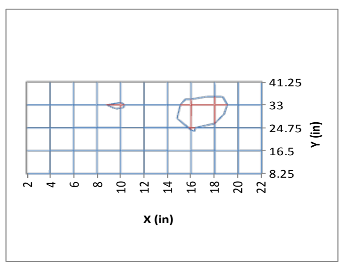
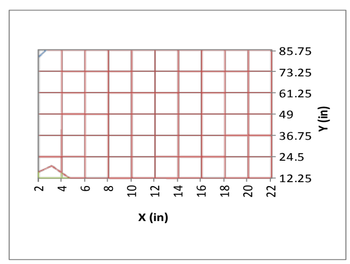
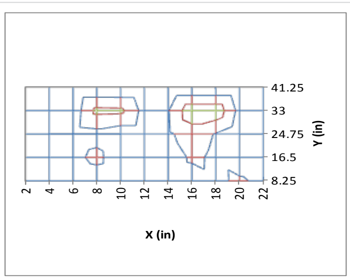
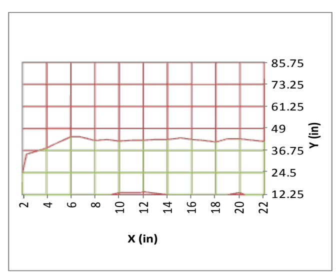
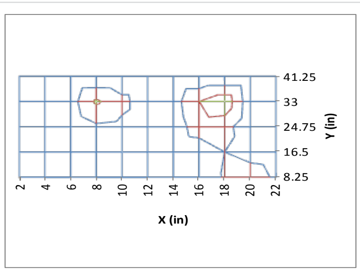
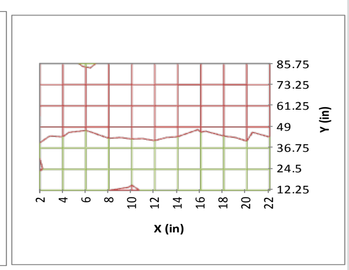
Figure 51. End glow and side glow powered by the light source.

VIII. RESULTS

Data Analysis

Excel software was used to demonstrate and calculate light uniformity using CV. For this purpose each sets of data for each experiment were inserted into an Excel tab and a graph and results including Min, Max, Average, Standard Deviation, and CV for each light exposure (side and end glow) for different distances were calculated and plotted. Table 6 demonstrates the results of both end glow and side glow and their Min, Max, Average, Standard Deviation, and CV values; these were based on the calculations performed based on the height distance between the light and the surface. The illustrations of Tables 6 show the light illuminance uniformity of both end glow and side glow. Figure 51 (end glow) and Figure 52 (side glow) show the Min, Max, and Average values based on the height (x) and the resultant lux (y) on that corresponding height. Figure 53 shows the combined results of both end glow and side glow based on the Min, Max, and Average values. Lastly, Figure 54 shows the Standard Deviation and CV values of both end glow and side glow.

Table 6. Light Illuminance for End Glow and Side Glow with Different Distances from the Measurement Plane.

Distance from Light	Light illuminance (Lux) End glow 0-115 115-230 230-315	Side glow 0-3 3-6 6-8	Results
14 in			End glow: Max: 140 (lx) Min: 5.8 (lx) Average: 61.049 (lx) Standard Dev.: 37.910 (lx) CV: 0.621 (lx) Side Glow Max:5.7 (lx) Min: 2.8 (lx) Average: 4.273 (lx) Standard Dev.: 0.804 (lx) CV: 0.188 (lx)
12 in			End glow: Max: 183 (lx) Min: 2.9 (lx) Average: 56.584 (lx) Standard Dev.: 44.186 (lx) CV: 0.781 (lx) Side Glow Max: 4.5 (lx) Min: 2.3 (lx) Average: 3.713 (lx) Standard Dev.: 0.496 (lx) CV: 0.134 (lx)
10 in			End glow: Max: 173 (lx) Min: 4.6 (lx) Average: 47.573 (lx) Standard Dev.: 40.898 (lx) CV: 0.860 (lx) Side Glow Max:6.4 (lx) Min: 2.9 (lx) Average: 4.416 (lx) Standard Dev.: 0.947 (lx) CV: 0.214 (lx)
8 in			End glow: Max: 343 (lx) Min: 3.9 (lx) Average: 61.484 (lx) Standard Dev.: 79.324 (lx) CV: 1.290 (lx) Side Glow Max: 7.5 (lx) Min: 3.9 (lx) Average: 5.619 (lx) Standard Dev.: 0.881 (lx) CV: 0.157 (lx)
6 in			End glow: Max: 311 (lx) Min: 3 (lx) Average: 53.105 (lx) Standard Dev.: 72.277 (lx) CV: 1.361 (lx) Side Glow Max: 8 (lx) Min: 3.8 (lx) Average: 5.796 (lx) Standard Dev.: 1.005 (lx) CV: 0.173 (lx)

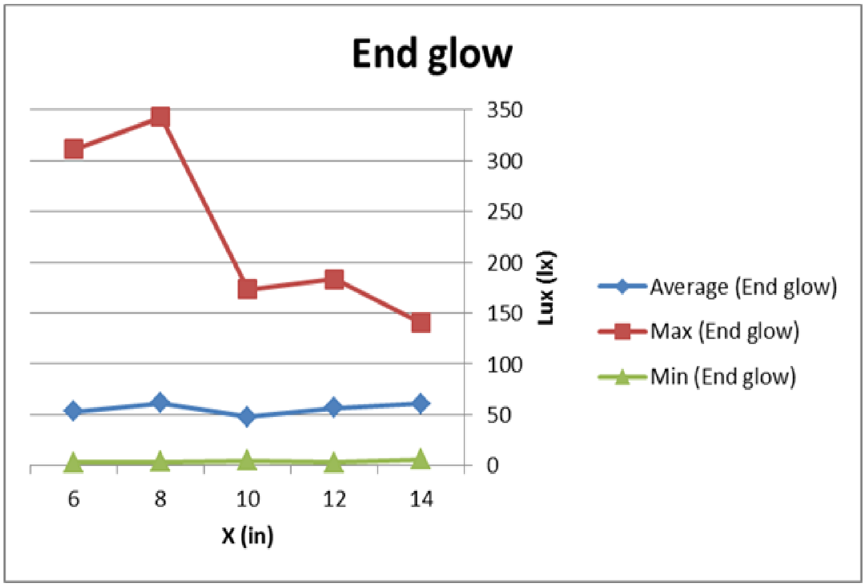


Figure 52. Maximum, minimum, and average lux for different height measurements for the End glow.

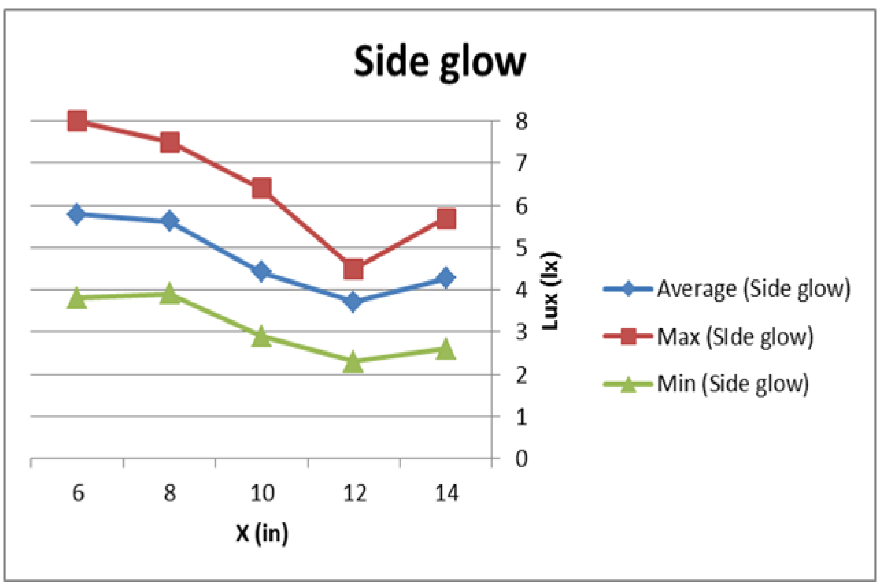


Figure 53. Maximum, minimum, and average lux for different height measurements for the Side glow.

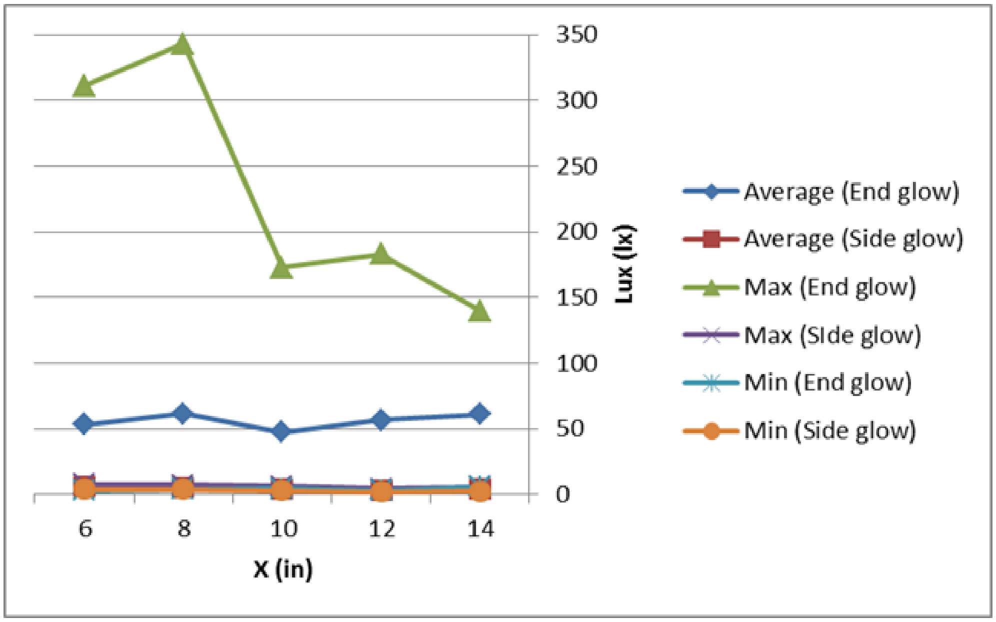


Figure 54. Maximum, minimum, and average lux for different height measurements for the End glow and Side glow.

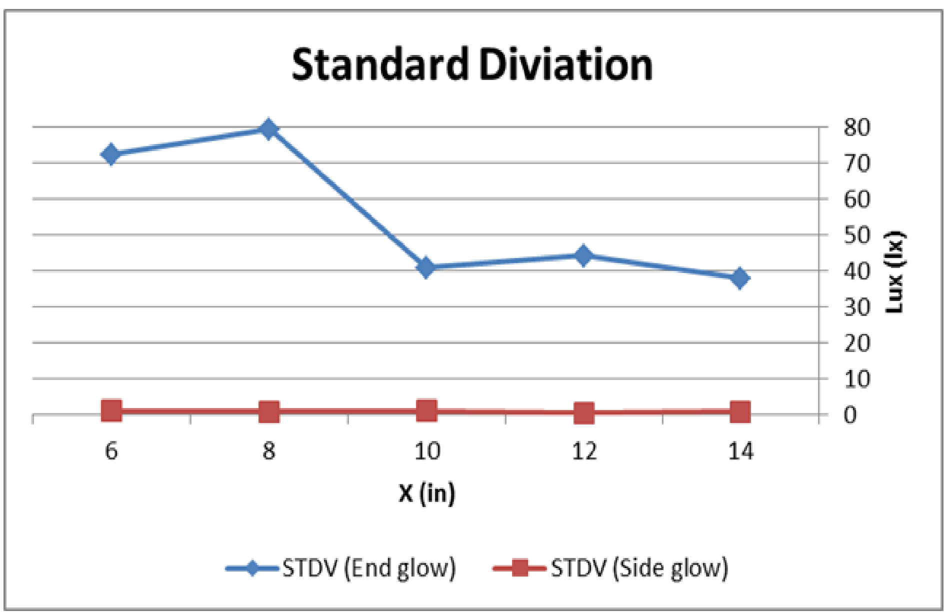


Figure 55. Standard deviation (lux) for different height measurements for the End glow and Side glow.

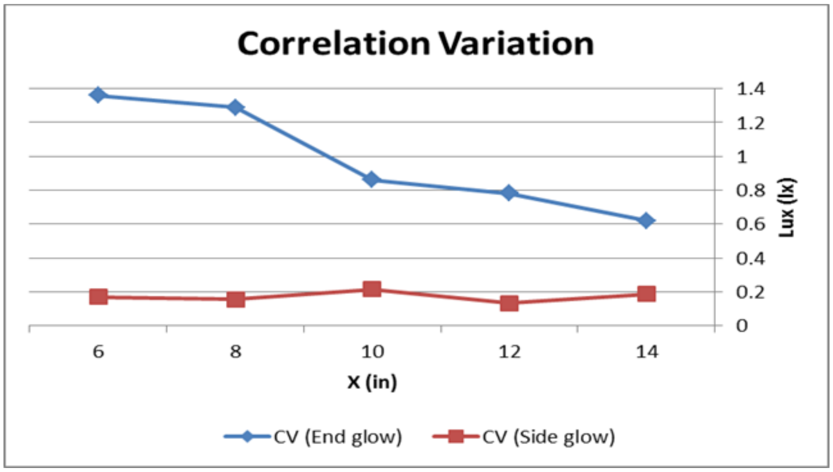


Figure 56. Correlation variation (lux) for different height measurements for the End glow and Side glow

Interpreting the results

The correlation between distance versus light uniformity was positive in the side glow experiment because of the light consistency of the design and was negative in the end glow experiment because of low uniformity due to the distance (See Figure 56).

The correlation between distance on light intensity was negative in the side glow experiment because of the poor light intensity; the further the light the less intense. Furthermore, the correlation between distance on light intensity was positive in the end glow experiment because it displayed high light intensity (See Figure 56).

The comparison between side glow and end glow regarding light uniformity is that because side glow contains a more consistent design the light uniformity will be better than end glow because of inconsistent design. Because end glow was placed at a vertical position in order for it to deliver light it would take a lot of end glow cables positioned one after the other in order to have the same consistency as side glow.

The comparison between side glow and end glow regarding light intensity is that because of the cladding and PVC being removed from the optical fiber in order to function as side glow, which causes the light to be less intense due to the loss of light being refracted inside the optical fiber due to the cladding. This means that because of the end glow still contains the cladding and PVC, which helps the light being transmitted through the optical fiber to contain less loss of light causing end glow to be more intense.

Spectrum meter results

The light spectrum distribution from the experiment was also examined for the sole purpose of examining the intensity of the light and temperature. The spectrum distribution was measured when conducting the End glow and Side glow experiment at a height of 12in. The End glow spectrum distribution shows smoother wave peaks than Side glow. The Tcp is the correlated color temperature. End glow Tcp is appears to be higher than the Side glow which appears to be lower, this based on the amount of lux emitted.

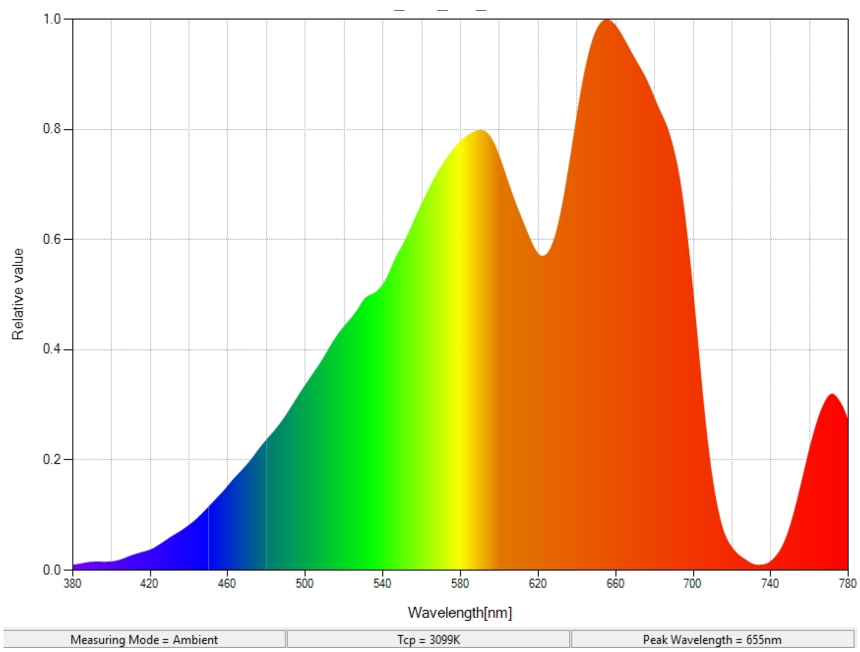


Figure 57. Light spectrum distribution. End glow (12in.) Spectrum at its optimum light point 183 lux.

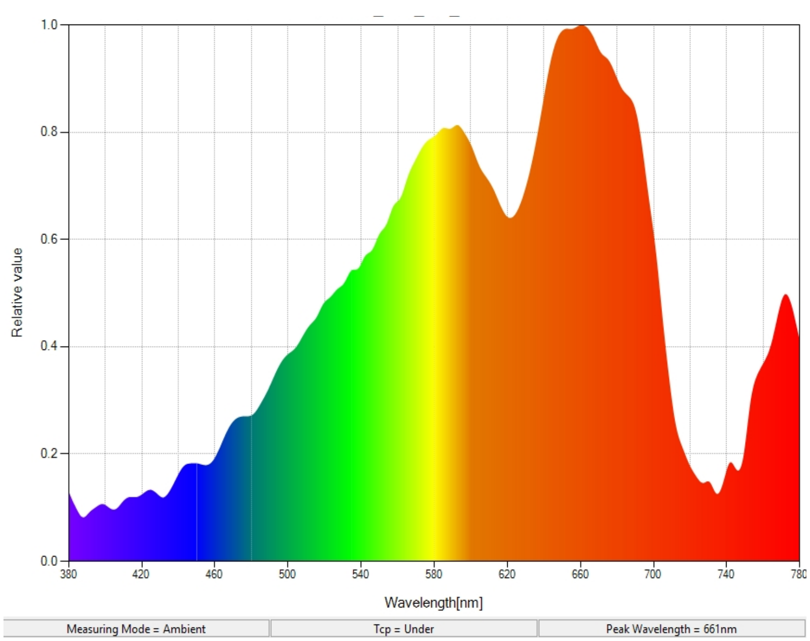


Figure 58. Light spectrum distribution. Side glow (12in.) Spectrum at its optimum light point 4.5 lux.

IX. DISCUSSION AND FUTURE RESEARCH DIRECTION

Conclusion

When developing a lighting system utilizing fiber optics and daylighting there are many design strategies that can conflict with each other; basic or advanced, small or large, and utilizing active or passive systems. The more turns and curves are put into the cable there will be extra losses causing the system to be more sensitive. It would be best that the viable design be simple and include few elements as possible. While artificial light was used because we wanted consistent light input to conduct the experiment it is always good to consider viable methods for the daylighting system, thus to contain sun tracking features and moving parts. This will create the system to be cost effective and easier to maintain. The use of artificial light can be an alternate method when sunlight is not being delivered by the daylight system. With the implementation of a design that works by utilizing both daylight and artificial lighting systems in the experiment in order to deliver the desired light intensity and light spectrum.

The research conducted revealed that the closer the light distribution was to a specific point the light would become stronger. The more optical elements on the design, the more illumination is found on the rack due to the refraction and reflection laws. Natural light is a renewable source of energy; therefore it should be used when available. Integrating artificial light and combining it with the daylighting is a key issue when designing a lighting system. Artificial light can be used when natural light is not available or during cloudy days when not enough natural light is being delivered through the fiber optics. Applying this system to an indoor hydroponic system can be challenging, considering that plants should grow consistent then light distribution should be uniform.

Future research

This research can be expanded in the following tracks:

- Utilizing and assessing different fiber optics cable sizes and materials.
- Evaluating the effects of physical and mechanical effects such as turning, bending, as well as heat and input light intensity on the output light intensity.
- Observing the correlation between plant growth and proximity of the plant to source of the natural light.
- Assessing the financial cost/benefit for such system in long-term and larger scale usage.
- Integrating and evaluating one unified system including natural light as well as nutrient delivery and artificial light systems in one test bed.
- Designing, implementing, and assessing different active and passive light collectors.

The use of natural light systems active and passive have been increasing. The sun as a natural and renewable source should be put to use. While nonrenewable resources continue to deplete without a complete estimate of their final abundance it is important to find more efficient ways to help the planet by using other methods of energy. The use of natural light in buildings has been integrated in various parts of the world in order to utilize the sun when available. With the growing stigma of indoor hydroponic systems using LED light, the use of natural light can have potential use in such system. While some hydroponic system function only using LED applications, this system can be integrated to utilize natural light when available while also using its LED feature when sunlight is not available. Such potential application can in turn be an efficient and useable worldwide.

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