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Development and Prototyping of a Solid State Lighting Product for Architectural and Accent Applications

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ABSTRACT

Far from being simply a necessary appliance to extend our day, artificial light has a great influence on human behaviour and wellbeing, perception of the surroundings and comfort. The energy needed for lighting is also a significant impact on our natural resources. For these two broad reasons lighting systems that improve the human visual and perceptual experience and reduce energy use are of widespread value.

This work covers research into the application of LED technology as the next generation of mainstream lighting. It looks at the reasons why this technology is set to become the dominant way in which we light our lives, and the technical hurdles that are slowing this shift in lighting.

It also presents the development, testing and prototyping of such an LED lighting product for use in the architectural market. This niche application is where LED lighting is currently most suited, due to the compactness, colour adjustability and lower colour rendering required. Establishing the technology here will help to gain consumer appreciation and acceptance of this beneficial and useful new paradigm in lighting.

The design incorporates a shape that is pleasing to the eye with a simple oval profile. It was designed to be subtle and compact, blending into the ceiling as cleanly as possible. Practical testing on the finished prototype showed it to produce a wide range of colours and colour temperatures, while maintaining a safe LED temperature. The simplicity also makes the unit competitive in terms of cost.

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1 INTRODUCTION

1.1 Background of Study

As the world population continues to expand and develop, the pressure on our remaining resources rises with it. Achieving energy savings in any possible way is something that is destined to become increasingly vital in the future. Lighting consumes more energy than is often appreciated, around 19% of electricity produced worldwide is used purely for our lighting needs (Belshe & Kinney, 2006). The cost involved, both financially and in terms of carbon emissions, means any improvements are worth investigating. Moreover, finding ways to improve the everyday experience of people at work is significant for human productivity, enjoyment and wellbeing. Light emitting diodes (LEDs) are the next generation of lighting, and are set to become superior to conventional sources both in terms of performance and human benefit in the near future (Serpengüzel, 2003). While this fundamental change will not happen overnight, LEDs are beginning to find uses in niche applications. Promoting their use in these niches will help to bring in Solid State Lighting (SSL refers to the use of LEDs for illumination, as opposed to indication) as the new standard light source in the future.

Generally, artificial light is considered by most people to simply be a necessary tool to help complete tasks and make the useful day longer. Rather than being a simple appliance, light has more of an effect on humans than it is often given credit for. There are three main ways in which light influences behaviour, the most obvious being as an aid to complete visual tasks. Light also has a perceptual effect, giving an impression of the environment and affecting motivation and contentment. Finally the illuminance, spectral content and duration of the light controls our circadian pattern and the wake/sleep cycle (Duffy & Wright, 2005).

1.2 Statement of the Problem

This leads to the motivation for this project. The aim for the literature review was to understand the background, benefits and peculiarities of LEDs in lighting applications. The review covers the use of SSL in a general illumination sense,

with some of the information gathered used for the more specific architectural lighting application. Following this, the applied side of the project aimed to take this knowledge and develop a practical, working LED product for the architectural lighting market.

More specifically, there was a need to research the reasons why LEDs are yet be widely accepted as a source of general illumination, and what can be done to overcome the problems. It also looks at the history, other uses and future potential of LEDs. The development of the working prototype included designing, building and large scale manufacturing methods and potential. The prototype was also used for testing and measurement of cooling ability, white light and colour range, intensity, power consumption and light intensity distribution.

2 RESEARCH INTO LEDs, THEIR CHARACTERISTICS AND MARKETS

2.1 State of the Art

2.1.1 Specific questions that guided the research

The principle reason for the research was to find why LEDs are largely yet to be accepted as replacements for traditional lighting, despite the benefits they promise. Secondary to this was to understand the performance differences between LED and traditional sources in terms of spectral distribution, colour production and operating requirements. To help guide the research the following questions were proposed:

- What are the benefits to the end user that will make the high initial cost of Solid State Lighting systems more acceptable? How can consumers be convinced of these benefits and what effects do these benefits have on enjoyment, productivity, and visual perception?
- Solid State Lighting has the potential to save vast amounts of electricity through lower power consumption and efficiency, reducing carbon emissions. What is being done to promote Solid State Lighting research and what are the problems it faces?
- Many aspects of SSL are much different to traditional lighting (spectral output, power requirements, thermal management, lifetime etc). What do these differences mean for the design of lighting products? How can the benefits of SSL be enhanced by the design of the products?

2.1.2 Brief History and Development

Lighting technology can be grouped into three main areas; initially it was fire based (candles and lanterns), followed by vacuum tubes (incandescent and fluorescent) and gas discharge (Mercury and Sodium) and now semiconductors (LEDs) (Serpengüzel, 2003). While there were overlaps with the development of

the different technologies, there is no doubt LEDs are the most modern. The principle behind them was first seen back in 1907, when a yellow glow was observed coming from a silicon carbide (SiC) crystal when an electric current was applied. However, the first practical, visible light emitting diodes were developed in 1962, based on gallium arsenide phosphide (GaAsP), which gave a red emission (Holonyak & Bevacqua, 1962). The measure of the ability of a light source to convert energy into light is called the “efficacy”. This is measured in lumens of light output per watts of input electrical power (Ian Ashdown, 2006). Essentially, this gives the portion of input energy that is converted to visible light and not lost as heat or non visible radiation. The early LED described above only had an efficacy of around 0.15lm/W, but found use as an indicator in control panels and similar applications (Steranka et al., 2002).

Throughout the 1970’s and 80’s, the efficacy improved and a new compound; aluminium gallium indium phosphide (AlGaInP), allowed orange and yellow LEDs to be produced. Red LEDs still had the highest output however, which explains their dominance of the indicator market. They also began to be used for centre stop lights on vehicles in the late 1980’s. Efficacy had increased to around 10lm/W by this time. In the early 1990’s gallium nitride (GaN) LEDs emerged and allowed blue, green and, importantly, white. The flux (light emitted by a source) output of red LEDs had also increased to the point where they began to be used as principle automotive brake lights and single colour signs. The user still needed to look directly at the LED to see the light however, rather than the intensity being high enough for illumination purposes. Efficacy exceeded 20lm/W during the late 1990’s.

Since their beginnings in the early 1960’s, the efficacy of indicator LEDs had been approximately increasing by a multiple of 10 per decade. A diverging point came in the late 1990’s when high power LEDs suitable for illumination (as opposed to indication) were developed. These formed a separate product market to the traditional signal LED. Up until this time LEDs were typically packaged in the “T1” style or surface mount (SMD) housings suitable for mounting in signal applications and on printed circuit boards. The new “high power” illumination LEDs, most

notably the Luxeon range from LumiLEDs, required new packaging due to the heat produced. The fundamental LED developments are illustrated in Figure 1.



Figure 1 (From left) the first LED, T1, SMD & High Power

The Luxeon became somewhat of an industry benchmark and other manufacturers quickly produced similar products, and LumiLEDs also improved the design by reducing the thermal resistance, allowing higher input power and flux output. Now there are a number of these high power LEDs on the market from manufacturers such as Osram and Cree. In addition, systems become available that combined LEDs, heat sink and drivers, making them suitable for integration into lighting products.

2.1.3 LED Operation

The core of an LED is the semiconductor chip; this has two regions, where they meet is known as the junction. The 'p' region is dominated by positive charges while the 'n' is negative; this creates holes and electrons respectively. A voltage across the junction causes the electrons to recombine with the holes and release energy as photons of light (Shur & Zukauskas, 2005). This is shown in simple terms in Figure 2. This energy requirement is equal to the "band gap" energy; in semiconductors such as LEDs, the conduction band contains mobile charge carriers, while the valance band contains electrons bound to atoms. The band gap energy is that necessary to move an electron up a band. This band gap energy varies with temperature and current (S. Muthu, F. J. Schuurmans, & M. D. Pashley, 2002a).

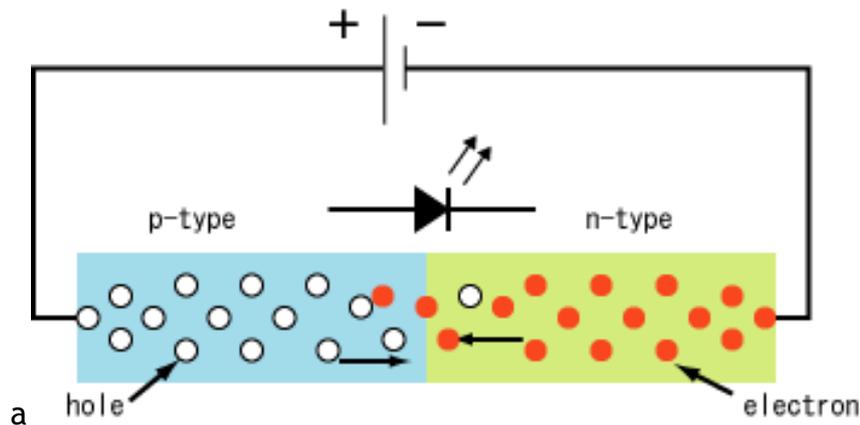


Figure 2 LED junction

Both the chromaticity (essentially colour) and intensity of the LED are determined by the material composition of the semiconductor. Aluminium Gallium Arsenide (AlGaAs) gives red, Indium Gallium Aluminium (InGaAlP) gives yellow and green, and Aluminium Gallium Nitride (InGaN) produces blue and green. This covers much of the colour spectrum and the materials can be fine tuned to give the intermediate colours.

Interestingly this principle is essentially the opposite of a photovoltaic cell (solar panel), a semiconductor which converts the incoming light into a voltage. Somewhat ironically, these two technologies are often used in conjunction.

2.1.4 The Electromagnetic Spectrum

Collectively, light emitting diodes are able to produce light in all visible regions of the electromagnetic spectrum (shown in Figure 3), and on into the infra red and ultra violet regions. However, they are narrow band sources; each LED can only produce light or electromagnetic radiation (the more correct term for IR and UV) at its particular peak wavelength and perhaps 25nm either side of this value. The specific colours and their corresponding wavelengths are given in Table 1. This is in contrast to traditional sources that produce light over much of the visible region. The sun produces light over the entire visible region and the ultra violet and infrared regions; this is known as a blackbody radiator. Despite this, some wavelengths are absorbed or scattered by the atmosphere depending on the time

of day, giving the different sunlight shades we see. The inability of LEDs to produce light covering the entire spectrum has implications for the quality of the emitted light and is discussed next.

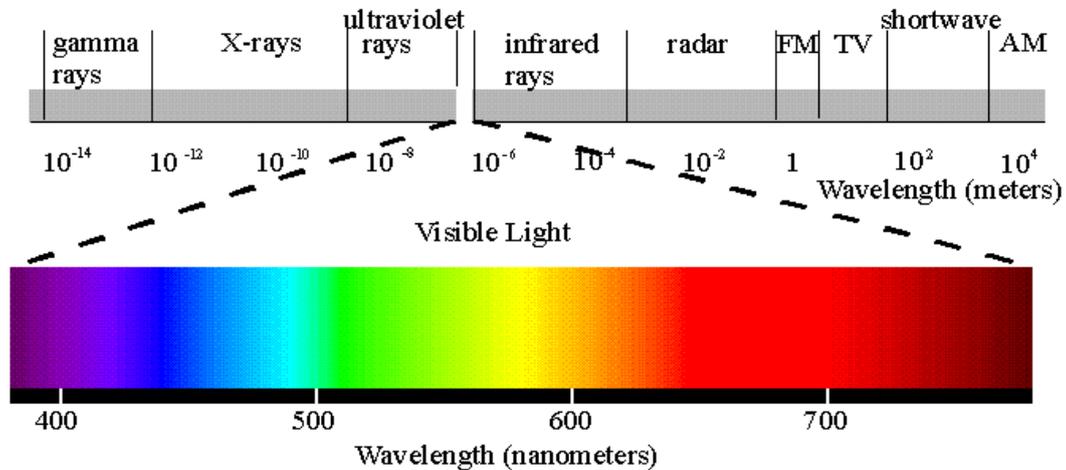


Figure 3 The electromagnetic spectrum

Table 1 UV, visible & IR light and their wavelengths

Colour	Wavelength (nm)
UV	< 390
Violet	390 - 455
Blue	455 - 490
Cyan	490 - 515
Green	515 - 570
Yellow	570 - 600
Orange	600 - 625
Red	625 - 720
Infrared	> 720

2.1.5 White & Coloured Light Generation from LEDs

Our perceived colour of an illuminated area depends on the Spectral Power Distribution (SPD) of the incident light (S. Muthu, F. J. P. Schuurmans, & M. D. Pashley, 2002b). The SPD is the range and strengths of different wavelengths emitted by a light source. Figure 4 shows an example; light from a mix of two LEDs, and an incandescent source. The latter, with an SPD covering the entire

spectrum gives good quality light and renders the colour of objects it illuminates very accurately (meaning they appear very close to their “true” colour).

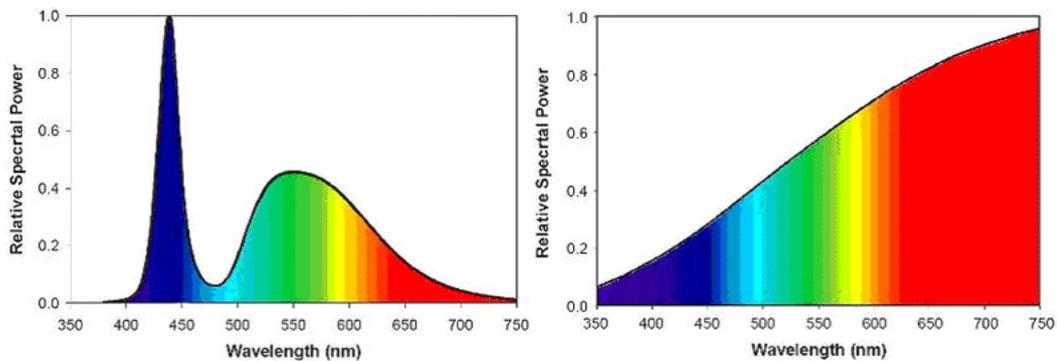


Figure 4 SPD of a dichromatic LED (left) and an incandescent lamp

Ideally, all artificial light sources will emit light covering the entire spectrum, making them similar to natural light in terms of quality, colour rendering and human enjoyment. This is not always the case, but the more of the spectrum that is produced the better the colour rendering will be.

The Correlated Colour Temperature (CCT) also becomes relevant here; this is a measure of the temperature of white light in degrees Kelvin. This measure is based on the output of a “black body radiator”; this is an object that emits a light spectrum that varies with temperature, such as the sun. Increasing temperature produces shorter wavelengths until white light is achieved. Slight variations are the basis for the CCT scale. This can range from reddish “warm” white with a value of around 2500K, to blue “cool” white at around 6000K (Yoshi Ohno, 2006). An indication of the CCT is given in Figure 5. This varying white light can be also be seen in examples such as very warm late afternoon sun and the much cooler fluorescent lighting often seen in hospital operating theatres or dental surgeries.

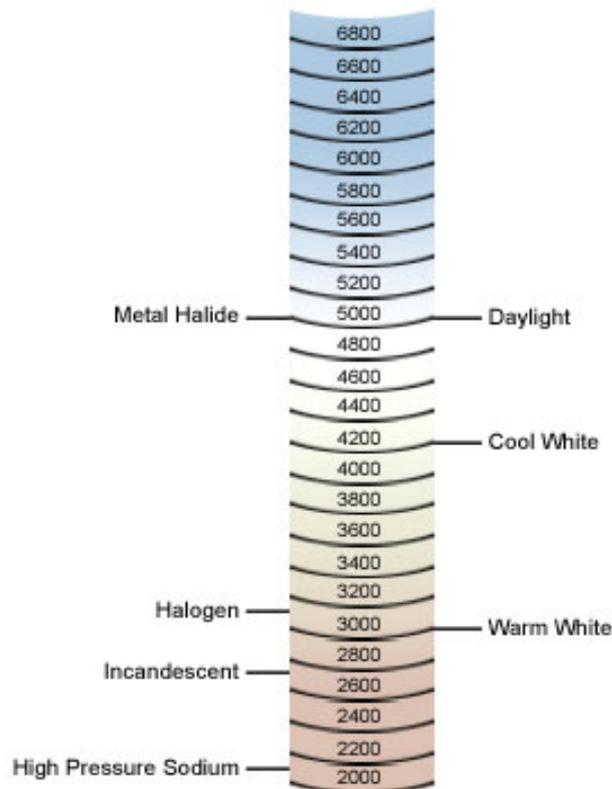


Figure 5 Indication of CCT

It is not currently possible to produce white light from a single LED, so instead several methods are used. One is phosphor conversion, where a coloured phosphor coating is used with a different colour LED to give white light. Polychromatic methods mix light from different coloured LEDs to give white. Schubert et al. (2006) gave the basic combinations to achieve acceptable white light:

Phosphor Conversion:

- blue LED with a yellow phosphor coating
- near ultra violet LED with red, green and blue phosphor coatings

Polychromatic:

- blue and yellow LEDs (dichromatic)
- red, green and blue LEDs (trichromatic)
- red, green, blue and amber LEDs (tetrachromatic)

Phosphor conversion allows cheap and simple white light with only one power source, although the efficiency is not as high as the polychromatic approach. The chromacity is also fixed at the time of manufacture, and is difficult to control accurately (Steranka, et al., 2002). Sheu et al. (2003) also compared the two phosphor conversion methods and found the UV approach to be more optically stable.

As mentioned, traditional sources produce colour from all regions of the visible spectrum, and hence are combining many colours to produce white light. LEDs produce light in peaks so must take advantage of the human eyes' ability to only perceive the primary colours and combinations thereof. The emergence of tetrachromatic (RGBA) LEDs was in response to this problem, and aims to "cover" a greater proportion of the visible spectrum than trichromatic (RGB) sources, and therefore provide a better perceived quality of light. Unfortunately, a greater number of chips involved gives a greater reduction in efficacy. Schubert et al. (2006) reported upper limits of 400lm/W, 300lm/W and 275lm/W for dichromatic, trichromatic and tetrachromatic sources respectively. At the current time it is accepted that using two colours to create white gives very low colour rendering but with good efficacy, three colours give reasonable values for both, and four colours have excellent rendering but lower efficacy. Five or more colours tends to give negligible increases in colour rendering but increases the complexity and cost (Zukauskas, Vaicekauskas, Ivanauskas, Gaska, & Shur, 2002).

Crucially, this polychromatic approach also allows the CCT of the white to be varied, and produce an immense range of other colours, provided each individual LED can be properly controlled. The limits of this are defined by the particular colours of the LEDs used, and is discussed next.

In 1931 the Commission Internationale de l'Éclairage, (International Commission on Illumination or CIE) devised the colour space diagram, which equates colour to an (x, y) coordinate system. A third value (Y) gives the luminance of each colour. Although the diagram was updated in 1960 and again in 1976 to give a more uniform colour variation, the 1931 edition is still widely used. Figure 6 shows this

diagram and also includes the approximate wavelengths of the colours at the perimeter in green text.

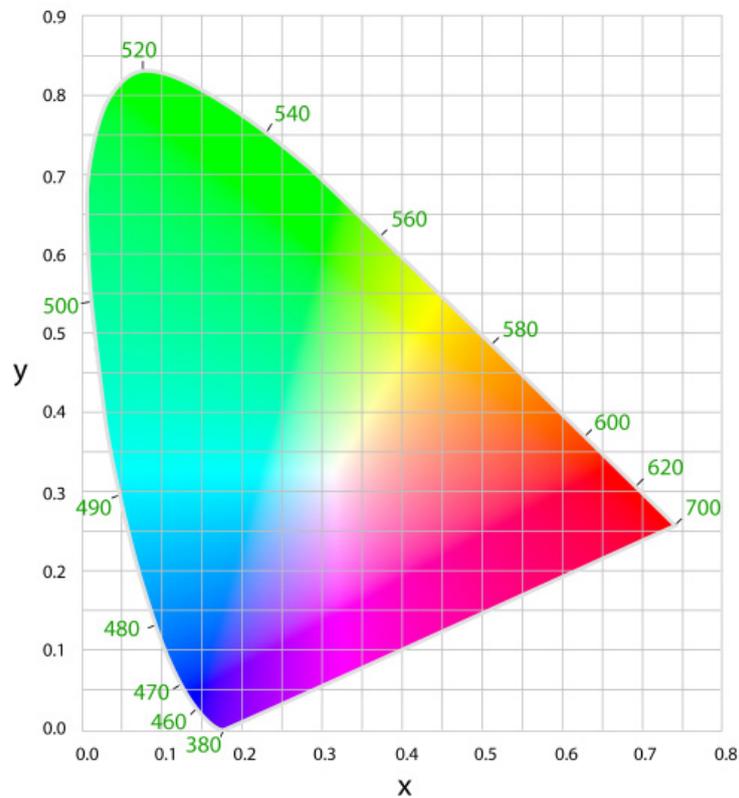


Figure 6 1931 CIE Colour Space Diagram

In a polychromatic LED system, the coordinates of each LED can be plotted on this diagram, and the area between the points represents the range of colours achievable with that LED system (Ries, Leike, & Muschaweck, 2004). It follows that with two LEDs, only a straight line is given and poor colour rendering is achieved. For the RGB approach, the three LED points cover a triangular area, while RGBA gives a quadrilateral, and so on. This range of colours possible is known as the colour gamut. The greater the number of different colour LEDs used, the greater the colour gamut and colour quality possible, although the law of diminishing returns applies. The particular wavelengths of the colours used in a polychromatic system of LEDs have an impact on the colours gamut, the colour rendering and the efficacy, so they must be carefully chosen.

2.1.6 Colour Rendering Index and Colour Mixing

The Colour Rendering Index (CRI) is the current standard measure of the colour rendering ability of light sources. The values range from below 40 for poor quality lighting (such as the low pressure sodium used in street lighting), to 100 for natural midday sunlight. This is why colours appear “washed out” or simply wrong under street lighting. Conversely, much more accurate perception of colour is possible under sunlight. Perfect colour rendering sources are considered to be an incandescent lamp for warm white sources and natural daylight for cool white (B. G. Ashdown et al., 2004).

In simple terms, the process to determine the CRI is first to match the CCT of the test light source to that of a reference light source. In turn, the test and reference sources are used to illuminate 14 standard colour samples. Of these samples, some are highly saturated and others are of a medium saturation, while skin and leaf tones are also included. The difference in perceived colour between the test and reference light sources on each sample is calculated using the 1964 CIE colour space diagram. This gives 14 values, but generally only the average is stated, this is the CRI (Yoshi Ohno, 2006). A high CRI theoretically indicates better colour rendering, with 100 being the maximum. Values of around 85 are generally given for trichromatic LED sources, and around 90 for tetrachromatic. The approximate CRI requirements for different situations have been given by Muthu et al. (2002b) and are shown in Table 2. Indoor retail space is considered the most demanding as consumers need to have the best possible appreciation of the appearance of products.

Table 2 CRI guidelines

Situation	CRI
Indoor retail space	>90
Indoor office or home	80
Indoor work space	60
Outdoor pedestrian area	60
General outdoor lighting	40

Even though it continues to be in widespread use, work by Bodrogi et al. (2004), Sándor & Schanda (2005) and Ohno (2004b) and others has shown that the CRI does not give an accurate representation of colour rendering for LED sources. (Narendran & Deng, 2002) even found that the perception of colour quality increases as CRI decreases and that, for LEDs, RGB sources are preferred. One contributing factor to this problem is that the 1964 colour space diagram is highly non uniform and is now obsolete, but is still the basis for the calculation. Also, as the CRI is only the average of measured colour differences, the source may be poor at rendering colours needed for its particular application, but still have a reasonable CRI. Another problem is that the CRI only measures the absolute colour difference between the test and reference sources, and does not take into account the direction the difference is in. A higher chromacity will increase clarity, while a lower one will reduce clarity. Finally, the 14 colour samples do not cover enough of the colour spectrum (Wendy & Yoshi, 2005). There is now a consensus that a new metric is needed. Although it is widely used elsewhere, Philips does not list the CRI for its products in datasheets. Instead it states that the CRI is “not measurable” and directs readers to a 1995 International Commission of Illumination (CIE) paper entitled “Method of Measuring and Specifying Colour Rendering Properties of Light Sources”.

A replacement for the CRI specifically for LEDs is needed. One possibility under consideration is the Colour Quality Scale (CQS). This uses some of the same colour samples as the CRI, but bases the calculations on the improved 1976 $l^*a^*b^*$ colour space rather than the 1964 version. An increase in chromacity is not penalized, as this often increases clarity, the CRI does not recognise this. Extremely high or low CCT also has a negative effect on colour rendering, unlike the CRI the CQS takes this into account. The final difference is that the CQS uses the root mean square of the colour differences rather than just the average like the CRI does. This helps to make the effect of one large colour difference obvious in the final CQS score, while the CRI approach can hide such a variation. The colour gamut, discussed earlier, is beginning to be used as an indication of colour rendering ability, as a wide range of possible colours also gives a good spectral content.

Nevertheless, there has been intense interest in maximising the measured CRI while maintaining an acceptable efficacy; this is a balancing act as these two properties are in a trade off relationship. The fundamental reason for this is that the potential luminous efficacy is highest with a single colour light source at 555nm (green) as this is where the human eye is most sensitive, while the CRI is maximised with light that covers the entire visible spectrum (Y. Ohno, 2004a). The CRI is generally considered to be the more important of the two, as this lags behind conventional lighting sources while the efficacy is comparable or ahead, so it is given preference. Also, lower intensity is needed to achieve comparable perception of brightness if the CRI is higher.

Research into the areas discussed next became useful for the development section of the project. In a polychromatic white LED the wavelengths and the number of colours used (RGB, RGBA etc) have an effect on the CRI. Optimised setups are well known, an example for a RGBA setup given by Lei et al. (2007) is 460nm, 525nm, 590nm, 640nm, which gives a CRI of 95 and 306lm/W. The red wavelength in particular has the most impact on CRI and efficacy, although this is more of a problem for RGB than RGBA.

In addition, to optimize the CRI of white light unequal proportions of each wavelength are needed. Gaines (2006) has published some thorough research in this area. With target CCT's of 3500k and 7000k and two different sets of peak wavelengths, the proportion of each colour that maximise the CRI for an RGBA approach is given in the above study. Unfortunately similar information for an RGB approach is not provided. Further, the physical layout of 16 RGB or RGBA LEDs in a four by four array that maximise the CRI are given.

One possibility related to this work is to use the suggested proportions of each colour as a guide to the actual number of each colour LED required. They can then be driven at a constant intensity. In doing this, the optimal layout would need to be researched, as those given use a different quantity of LEDs. The uniformity of such an approach would also need to be analysed. The benefit of this being successful is a simplification of the control system.

One of the most important aspects of using solid state lighting is achieving an even and full mix of the different colours used, whether they are mixed to give just white or complete variable colour light. Without careful consideration, the illumination can appear to have a graduation of colour, or a “striped” effect. This is an area of intense interest as it directly as this striping will immediately discourage consumers, and as such is fairly guarded in the literature.

2.1.7 Binning to Reduce LED Variability

As high power LED manufacture is still a relatively new industry and as the LED substrates are actually grown, the production process is not entirely predictable. This leads to the number of holes and electrons in a substrate varying, not helped by impurities in the materials used. Because of this, the quality of LEDs varies and can result in different characteristics for the same model of LED. Even two LEDs grown and processed side by side can have different values. The variations include lifetime, chromacity, viewing angle, voltage drop, temperature dependency and intensity. When these LEDs are used in light fittings it can result in unacceptable variations in performance. To help overcome this problem manufacturers group the LEDs, usually by peak wavelength or intensity. This is known as binning and the more accurate the bin the higher the cost to the purchaser. In lighting products the variation problem can also be largely controlled by incorporating a feedback loop into the control system, discussed next.

2.1.8 Drivers & Control of LEDs

There are two protocols by which stage and effect lighting is controlled; DMX and DALI. The older of the two, DMX is widely used and reliable, but is unidirectional. This means it can only send commands to a fixture; it cannot receive error messages from them. DALI (Digital Addressable Lighting Control) is a newer system that is bidirectional but has a lower maximum cable length than DMX. The DALI system has a further advantage in that its wiring requirements are much less strict.

On a more basic level, there are two ways to drive LEDs; constant current and constant voltage. Rubinstein (2007) researched current drivers for LEDs.

The constant current system simply uses the mains alternating current and converts it to 350mA to drive non dimming LEDs. In a dimming application, a constant voltage supply is used between the AC input and 350mA converter. The dimming is controlled with a low voltage signal to the converter.

In a constant voltage system, which is often used for RGB LEDs, the AC supply is first converted to DC. This low voltage is then split and maintained across the 3 channels, which are each varied by potentiometers or voltage controllers. This approach uses pulse width modulation to control dimming, discussed next.

Another important aspect to the control of LED lighting is the dimming; this is handled in a similar way to conventional fluorescent light sources. One of two methods is used; the first, constant current reduction, is self explanatory. The second is pulse width modulation. This is where the LED is strobed on and off at a frequency of several thousand hertz. It is the ratio of 0% and 100% output that gives the dimming, as the human eye perceives the extremely fast strobing as different levels of brightness.

Another phenomenon associated with dimming is the non linear response of the human eye. Essentially this means that increasing the intensity of a light source by, for example, 50% will not make it appear 50% brighter to the human eye. Figure 7 shows the relationship between intensity and perceived brightness, known as the “square law” dimming curve (Robinson & Ashdown, 2006). While most controllers take this into account, it shows again the subjective nature of many aspects of lighting.

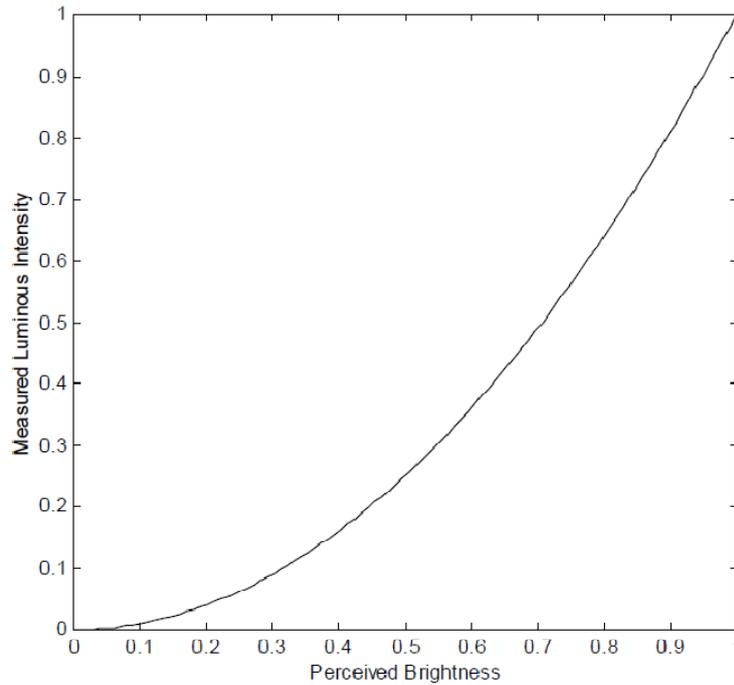


Figure 7 Square Law Dimming Curve

Consumers place great importance on adjacent lighting products appearing to have the same colour temperature, chromacity and intensity. All of these parameters change with junction temperature, lifetime, and from LED to LED, even with accurate binning. The minimum perceptible colour difference (MPCD) can be calculated but a guide is a value of 50K to 100K near 4000K CCT (Muthu, et al., 2002a). This is a small amount so a method to maintain the colour point is necessary if binning is less accurate.

A feedback loop is often used to maintain the emitted light as there are many factors that affect the light output, junction temperature being the most obvious. Complicating this is the different responses of each colour to temperature. Amber LEDs decrease in efficiency by 80% over a temperature range of 25°C to 120°C, while blue and green lose from 5% to 35% efficiency (Ian Ashdown, 2006). Furthermore, LEDs degrade at different rates, white and green wear faster than blue or red.

The junction current also affects the light output parameters. As current increases the chromacity shifts to a shorter wavelength, while the shift for red is small, blue and green are much higher. This is alleviated somewhat by the fact that

increasing junction temperature results in longer wavelengths, although there is still variability (Muthu, et al., 2002a). Monitoring these variables and adjusting the drive current to suit can be achieved in two ways:

The simplest method involves measuring the temperature of the heat sink and using this to estimate the temperature of the junction. The junction temperature then gives the approximate colour point. The graphs of heat sink temperature versus junction temperature, and of junction temperature versus colour point, must be accurately known. These can be tested in a lab situation for each model of LED used, but there is still uncertainty with this method. The more accurate way to control the output is to use a colour sensor to measure the colour directly in terms of its coordinates on the CIE colour space. This of course is more expensive due to the sensors needed, and a portion of the light is blocked and lost by it, but it is much more accurate (Man & Ashdown, 2006).

Regardless of which method is used, it will require the drive current to be gradually increased over the life of the LED as it degrades, to maintain intensity. This leads to further degradation, exacerbating the problem. Long life is still achievable, but it is less than if the LEDs are driven at a constant current and the intensity gradually declines. These systems allow some sort of end of life warning feature to be built in; one approach used is to run the LEDs at 100% up until the final 10 hours, where they operate at 50% intensity. The life claimed by LED manufacturers should not be taken as a guarantee, testing within the proposed fitting should be carried out as the temperatures will be different.

2.1.9 Other Applications of LEDs

There are five main areas where LEDs are used are; indication, automotive, signage, general illumination and communication (Arik, Petroski, & Weaver, 2002).

Easily the largest market is communication, with the backlighting of keypads and LCD screens in mobile phone and other personal electronic devices using about 40% of LEDs produced. Backlighting for signs and video displays represent around 23%

of production, while automotive (brake, signal and interior lighting) uses 18%. Indicator LEDs for traffic lights, electronic products and instrumentation panels use about 14% of total production. Finally, general illumination (architectural/accent, torches, boats and recreational vehicles) makes up 5% of the market (Schanda, 2005). The single colour indication and automotive stop light applications are particularly suited to LEDs as they are much more efficient than filtered incandescent bulbs at producing the needed colour. White applications are slightly less advantaged in this respect.

Also worthy of note are LEDs relation; OLEDs, which are made from organic materials. Although development of this type of semiconductor is less advanced than LEDs, they have different properties that will make them suitable for different applications. OLEDs are a much more diffuse light source, and are typically found in a panel form rather than many single light points. As outputs increase, these will find use as screens (with lower power draw and no need for a backlight as with LCD), glowing illumination panels and even flexible displays as they do not need to be rigidly mounted.

2.1.10 Global Lighting Markets & Government Promotion

The current global lighting market is dominated by fluorescent, incandescent and HID systems. Market information on LED systems is scarce and proprietary, but these conventional sources can aid in understanding the lighting industry. Lighting uses from 5 to 15% of electricity generated in developing countries, and up to a substantial 80% in developing nations, averaging to a global figure of 20% (Bhusal, 2009). This shows how important energy savings through lighting have become.

In the developed world, residential lighting practices vary from country to country. In recent years, residential US customers used incandescent for 86% of their lighting, a similar value is used in New Zealand and Australia. Meanwhile, Japan has a much higher proportion of fluorescent, around 65%. In Russia residential lighting is supplied almost entirely by incandescent. In developing countries, on grid residential lighting is largely fluorescent (off grid is mostly fuel based).

In commercial buildings lighting is split differently; with developed countries (data is based on OECD members) using fluorescent for three quarters of commercial needs. Notably the US is lower than this average, with around half fluorescent, one third incandescent and the remainder made up by HID. Again, usage varies across the developed world, with American opening hours and therefore lighting requirements being longer than the rest of the OECD.

Finally, industrial consumers in developed countries used an average of 62% fluorescent, 37% HID and only 1% other sources (Bhusal, 2009).

Although residential lighting is generally the least efficient, its short usage times mean it has low energy use for the size of the building. The opposite is true for fluorescent sources. Efficiency gains can be made in all areas with LEDs, this suggests fluorescent users should be targeted first, i.e. the commercial and industrial sectors.

The US Department of Energy (DOE) actively encourages research and development by the industry. With the CALiPER program (Commercially Available LED Product Evaluation and Reporting), whereby LED products are independently performance tested and the results made public. This allows consumers to choose the best products thus creates competition. It also helps promote SSL to consumers.

Through meetings with industry experts, the DOE has also established a framework of specific areas of LED research with targets for R&D progress, and a method for prioritising them. This is aimed at research organisations and helps the DOE to allocate funding.

The Japanese government introduced the “Akari Project”, an association of 13 business entities and seven universities. This aims to produce a commercial white LED light with 120lm/W by 2010. Taiwan has a similar group of companies. The JLEDS association (Japan LEDs) aims to standardise SSL and promote research in the technology. China is developing four industrial bases related to SSL with support from the government.

Despite the issues faced by the SSL industry, the high brightness LED market as a whole is considerable with a global value of \$4 billion (Phillips et al., 2006). The majority of these LEDs are produced in North America, Europe, Korea, Japan and Taiwan. The dominant companies in the lighting industry are Philips, Osram and General Electric, based in the Netherlands, Germany and the United States respectively. In recent years all three have developed partnerships with, or bought, companies specialising in LED development.

2.1.11 Future Growth & Potential

An interesting observation with regard to the future of LEDs is that as the efficiency improves and less energy is wasted as heat, less heat sink area will be needed, in turn reducing weight, cost and size.

Steel (2007) and Navigant Consulting Inc (2006) forecast the growth of many different aspects of Solid State Lighting. It has been shown that, although the overall market growth for high brightness LEDs (encompassing signals, signs, mobile phones, automotive and illumination) has slowed since 2004, the illumination component has increased. Predictions for the next three years also show a strong increase in LED lighting products, with the world market value expected to increase from \$400 million in 2008 to \$1 billion in 2011. While the majority of this rise is predicted to come from the increasing performance of white LED lighting products, the RGB market is also set to increase from around \$200 million in 2008 to nearly \$400 million in 2011. As of 2006 architectural lighting was the largest sector of the LED lighting industry, although general illumination will grow as white LEDs become more cost effective for that application.

Of course the main reason behind the expected growth of this displacement technology is the continued rise in life and efficacy, and the drop in price for high power LEDs. Navigant Consulting Inc (2006) gave a summary of the predicted values for life, efficacy and cost for different CRI levels, with extrapolation to 2027. These predictions have been converted to graph form and can be seen in Appendix 1, 2 and 3.

The adjustability of Solid State Lighting makes it appealing for future use. There is the possibility of varying the CRI of a polychromatic LED source to provide enough colour rendering ability for the given situation, and higher efficacy at other times. For example, the system could use low colour rendering for low occupancy or for night time security, with a high CRI for normal use, or other similar schemes. This modulation would increase the overall efficiency of the system and reduce energy use. The system could also switch to red at night to preserve the users' ability to see in the dark.

The possibility of using the fast strobe ability for communication has been suggested by Schubert & Kim (2005). While invisible infrared light from television remotes are already used for this purpose, the high pulse frequency ability that LEDs offer means visible light could also be used in this way without being noticed by the human eye. This would allow short range communication of systems in a room, an alternative to overcrowded radio waves. Automotive LED head and tail lights could also communicate speed and distance information to other vehicles with no perceivable effect on the light output.

There is also the possibility of using LEDs as standby or backup lighting, with fluorescent sources for normal use. This "hybrid" idea is a possible short term use for LEDs until the outputs increase sufficiently and they become cheaper. This concept would also make the technology more palatable to consumers for general illumination and show that it is useful in the meantime.

As residential users are generally drawn to the lower purchase cost and compactness of incandescent sources (B. G. Ashdown, et al., 2004), LED "lamps" could be used in the residential retrofit market to replace older technology. This is much like compact fluorescent lamps which are currently replacing incandescent sources. While the major technical hurdle of converting the input power to low voltage in such a small space is a problem, a simple "plug and play" solution would be simple for consumers to adopt. Standardisation of the connectors and controllers would need to be increased for this to be successful.

The low power needs of LEDs make them suitable for remote solar powered applications such as sea beacons, runway lights, general lighting for developing countries lacking infrastructure and so on. The use of LEDs for general illumination in developing countries also has great merit, if SSL is used in areas as they become connected to a national grid, the low efficiency and heavy metals of incandescent and fluorescent sources can be avoided entirely.

Consideration has also been given to using LEDs for a lighting system to match our circadian rhythm. The benefits of such a system include more comfort and less stress, although this it is possible these benefits would not be attributed to the lighting type by many people. As their colour and intensity are variable LEDs are very much suited to this application. To be effective, a circadian system should be the main source of general illumination, which is currently too expensive with LEDs. However, there are some reduced light, general illumination applications that may be feasible sooner. One possibility is passenger aircraft interiors, which could benefit greatly with such an approach on long haul flights to reduce jetlag among passengers. The well known LED traits of robustness, compact size and low power consumption are also beneficial in this application. The weight of heatsinks would need to be considered given how strictly weight is monitored in aircraft design.

One final intriguing possibility has been suggested by B. G. Ashdown et al. (2004). This involves using a single, invisible UV LED in a room to excite phosphors in special “bases” around a room, causing them to emit white light. This means a single powered source can be used to create light throughout the room via these movable, wireless bases. The only limiting factor is that the UV radiation would need to be kept to a safe level.

2.2 Current LED Limitations

There are a number of technical areas where LEDs need to develop to become a genuine alternative for traditional lighting technology. These include quantum

efficiency, thermal management, packaging and importantly, consumer acceptance. These issues are discussed next.

2.2.1 Internal Quantum Efficiency

To increase the brightness from each LED, the internal quantum efficiency needs to improve. This relates to the number of holes and electrons that successfully recombine. Currently this stands at around 80% and 50% for red and blue LEDs respectively, while the “green hole” has less than 10% (Yoshi Ohno, 2006). (Conveniently, the green region is where the human eye is most sensitive so light at these wavelengths appears brighter than other regions with the same intensity.) These efficiencies are increasing as the manufacturing process improves and produces fewer defects, and new materials are discovered. This offers insight into the future potential of LEDs, as the quantum efficiency is theoretically 100%.

2.2.2 Packaging & External Efficiency

The packaging of the LED chip is another avenue where improvements can be made and the overall efficacy raised. The optics used to define the shape of the light can cause internal reflections which reduce the light emitted. The necessary electrical contacts do not reflect light well, also hindering the efficiency. Improvements have been made to the substrate material, moving from partially absorbing to fully transparent to allow more light to reach the reflective surfaces. External efficiencies above 50% have been reached for infrared and red radiation/light emitting diodes, if similar levels are reached for LEDs over the whole visible spectrum 150 to 200lm/W is achievable for white light sources (Tsao, 2005).

The rate that internal and external efficiencies are improving leads to an interesting trade off suggested by Tsao (2005). The efficiency that improves the most will eventually dictate the type of structure used by LEDs. If external efficiency proves to be highest, large area, lower power density and lower cost per

area chips will result. The other case is with higher internal efficiency. This will lead to small area, higher power density, low high cost per area chips.

2.2.3 Heat Management Issues

The other major concern that LED makers and lighting designers need to be aware of is the importance of managing the thermal needs of the LED system. The intensity, life and chromacity of LEDs are extremely dependant on the temperature of the chip. While one of the benefits of LEDs is that heat is not used to produce the light (as with incandescent), part of the input power is lost as heat due to inefficiencies. This is a serious problem as junction temperature increases of just 14°C can reduce intensity by 14% for red LEDs, although less for blue and green. The life of the LED is also reduced by 10% for every 10°C increase in temperature above the recommended maximum (I. Ashdown, 2002). Heatsinks (either blocks or fins, made from aluminium) are commonly used, with simple convection used to maintain the temperature. Heat pipes are also sometimes used in more complex or compact designs, while more extreme setups use cooling fans, although these can add noise and will increase energy use.

The move to larger, “high power” style packaging was partly due to these thermal issues, as the increased chip sizes could now tolerate higher drive currents and heat. The older T1 style package, and especially the electrical contacts, could not. Nevertheless, good heat dissipation is still crucial to an LED system. Another issue here is that the larger the chip the more light is absorbed by internal reflections and lost. Compromise is a recurring aspect of LED design. The thermal resistance becomes relevant here; this is listed in most LED product literature. This is a measure of how effective the transfer of heat from the junction to the LED mounting surface adjacent to the heatsink. Obviously the lower this value the more input power the LED junction can withstand while maintaining acceptable temperatures.

2.2.4 Consumer Acceptance

Consumer research regarding specific preferences and demands of SSL is one of the key areas of interest for manufacturers and designers. Accordingly, it is almost always undisclosed to protect the research and investment they are undertaking. However, the Governments of various countries, in particular the United States, are keen to encourage the uptake of LED systems for energy and environmental reasons. To this end, they have released research and recommendations on making LED products as appealing as possible to consumers. Unsurprisingly, these studies inevitably find that the acceptance (or lack thereof) of LED systems is closely related to the cost. In a report prepared for the US Department of Energy, (B. G. Ashdown, et al., 2004) presented the various lighting characteristics and the importance given to them by consumers.

The principle attribute found here was cost, in terms of initial purchase price, maintenance and efficiency. The key finding was that residential users are more interested in the initial cost, while commercial consumers are concerned with the total cost (which considers efficiency and replacement frequency). While LEDs currently have a place in niche applications, this and other investigations have shown that most residential consumers are generally not prepared to pay the higher initial cost of LED lighting yet, even though they will recover this cost through longer life and reduced energy use. This suggests that LEDs will find more applications in the commercial sector sooner, as the cost structure is more suited to this area.

The colour of the light is also considered important in general illumination. Warm, reddish white light gives a sense of comfort and relaxation, while cooler, more blue light conveys awareness and activity. Further, some colours are perceived better when illuminated by cool white and others by warm white. It has even been reported that people prefer warmer white light in winter and cooler in summer (B. G. Ashdown, et al., 2004).

In terms of quality of light output, the same study found mixed preferences. While consumers value a high quality of light, they are not generally aware or appreciative of the wider benefits of good lighting. It also found that the colour rendering ability of new general illumination sources is critical and should approach that of incandescent bulbs. Consumers do value full, pure colour from light sources. However, in the case of LEDs, the area illuminated may be less aesthetically appealing than the emitted light from the LED itself.

Complete control of light sources is another feature appreciated by consumers. This includes being able to digitally tune the colour, temperature and dimming so it can be controlled remotely and integrated into other systems. Long life for lighting sources is also highly valued by consumers. This is beneficial both in terms of the cost of replacing lamps/bulbs and the inconvenience of doing so. Although to a lesser extent, the report also found consumers value compactness, safety, durability and low environmental impact for light sources.

With the exception of cost and colour rendering, LEDs outperform conventional sources in all of the areas discussed above; suggesting cost is the main factor holding back market penetration. While improvements in manufacturing techniques and increases in production scale are reducing cost continually, the expenditure issue will need to be carefully considered and compensated by additional features and benefits.

It has been reported that consumers are generally unaware of the possibility of using LEDs as a general “white” source of illumination, with the perception that they are limited to coloured and novelty applications. The use of LEDs in torches and desk lamps is helping to break this belief, but ways to increase understanding of LED potential are needed.

Further, it has been shown that the measures used by engineers and designers to describe and compare performance (CRI, CCT, efficacy and so on) are of little interest to consumers. This suggests that a more qualitative approach be taken to measuring lighting performance with perceptions and “feel” of the light likely to

be a more valuable indicator of preference than the raw numbers. A related observation regarding differing markets by (B. G. Ashdown, et al., 2004) is also relevant. They found that, in very general terms, US consumers tended to over light an area, while European and Asian markets were more aware of the aesthetic benefits possible. Additionally, these latter markets are more likely to consider the light fixtures as a piece of art as opposed to a simple appliance.

Convincing commercial users that the benefits of LED systems for general illumination outweigh the purchase cost will need to be tackled as LED output becomes more usable. (B. G. Ashdown, et al., 2004) suggests that the principal benefit that should be made known is the strong positive influence good lighting has on behaviour. LEDs can be controlled to match the human circadian rhythm, making workers more alert and less stressed. The variability also allows interesting effects and atmospheres to be created. These benefits are more appealing to consumers than the technical and engineering qualities the designers and manufactures are concerned with, such as CRI and efficacy. It is clear that initially the commercial market will be more accepting of LED systems, than residential consumers. Part of the reason for this is that this market is more willing to pay a higher initial cost and have lower maintenance and energy consumption.

2.2.5 Health & Safety

The low heat and low voltage requirement of LEDs have safety advantages, but there are some dangers to be aware of. There is a recognised “blue light hazard” with any intense light. As shorter wavelengths have more damaging energy, “blue” refers to that general area of the spectrum, as opposed to the red or green regions. Ultraviolet light is absorbed or blocked by the cornea and lens of the eye, but wavelengths around 440nm can reach the retina (Algvere, Marshall, & Seregard, 2006). There has been much research into this problem with regard to lasers, and now the outputs of LEDs have reached the point where they pose a risk.

The environmental impact of lighting products should also be considered. In addition to the reduced emissions from lower energy consumption, LEDs also have

less harmful heavy metals. Fluorescent lamps are the main concern here as they contain mercury, making manufacture and disposal more dangerous than with solid state sources. The cost to dispose of a fluorescent lamp safely can actually be higher than the initial purchase cost.

2.3 Benefits & Drawbacks of Solid State Lighting

2.3.1 Benefits of Solid State Lighting

The principal benefit and main driver for LEDs increasing penetration into the general lighting market is the reduction in energy costs they offer. The fundamental reason for this is that LEDs convert electricity to light directly, while with other sources the light is a by product of other conversion processes. From initial efficacy values of around 0.1lm/W in 1960 for indicator lamps, high power LEDs now achieve over 100lm/W. In comparison, incandescent light bulbs give less than 15lm/W, fluorescent tubes between 60 and 80lm/W and metal halide around 120lm/W.

However, as the materials and packaging technology for LEDs are constantly improving, the rate at which LED efficacy is increasing is far greater than other sources. The efficacy trends are illustrated in Figure 8 (Krames et al., 2007). The superiority of LEDs in terms of efficacy is further shown by the theoretical maximums of each source, imposed by fundamental physical reactions. Incandescent lamps are limited to around 17lm/W by the filament temperature. Fluorescent lamps have a maximum of around 90lm/W due to losses converting UV to visible light (Schubert & Kim, 2005). On the other hand, LEDs have theoretical maximum efficacies approaching 400lm/W, although it is lower for multicolour clusters as discussed later. This is because they directly convert electricity into light, rather than heating a filament or exciting a gas first.

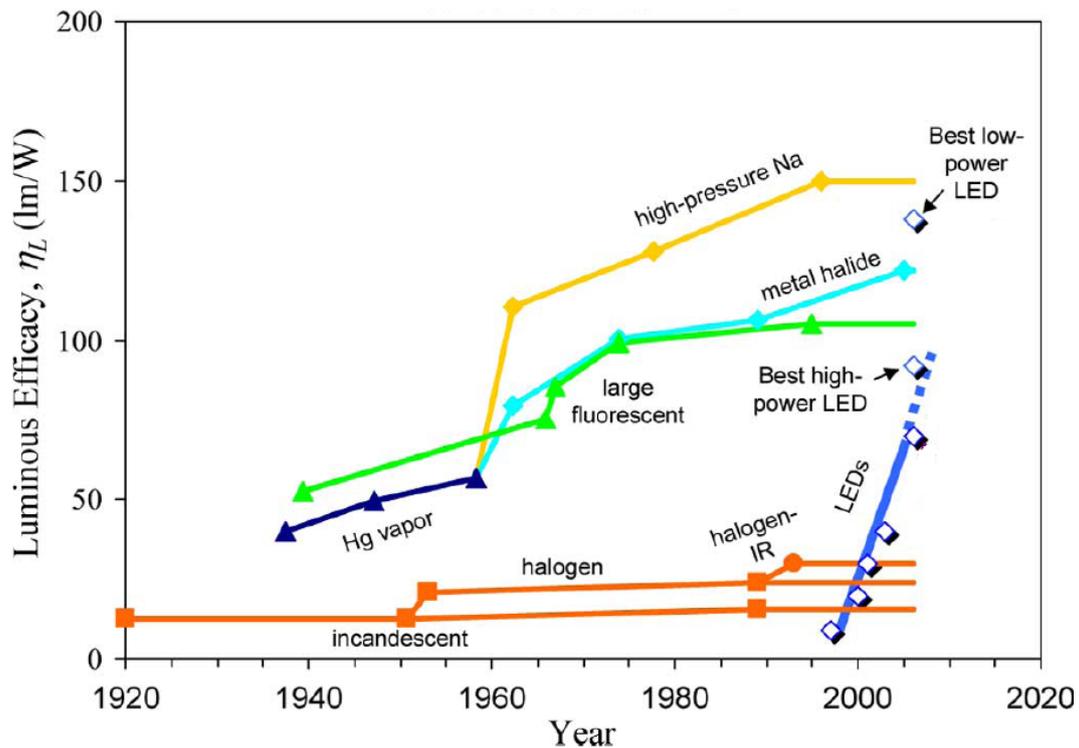


Figure 8 Efficacy trends for LED and conventional sources

There was much optimism in the literature in the early 2000's that the efficacy of LEDs would improve enough to replace fluorescent lamps within the decade. While this does not now appear realistic, the technology has improved greatly and few doubt that it will become the mainstream lighting system in the future.

This is where the potential of LEDs is most obvious; the possible reductions in energy use are significant and important as environmental pressure increases. Around 20% of electricity generated globally is consumed simply by lighting, resulting in around worldwide carbon emissions of 2900 million tonnes annually (Singh, Gupta, & Poole, 2008). Guidelines and limits on the lighting power density are already in place and will likely become more stringent in the future.

The US Department of Energy roadmap predicts the efficacy of white light LED sources will be 137lm/W by 2015. Although optimistic to the point of being simply hypothetical, a worldwide switch to LEDs by that time would yield energy savings of around 1000 tera watt hours per year. This equates to savings of US\$100 billion and a reduction in carbon emissions of about 200 million tons, per year (Krames, et al., 2007). A side benefit is the reduction in heat produced by lighting placing

lower loads on air conditioning systems. Savings of this order are one of the principle motivators for SSL.

The other major benefit of LEDs as a light source is the long life they offer. Typical lifetimes are in the region of 100,000 hours, compared to 2000 hours for incandescent and 15,000 for fluorescent. However, as discussed later, the degradation of LEDs over their life means that in practice around 50,000 useful hours is achievable and is the lifetime claimed by most LED makers.

As mentioned by (Steranka, et al., 2002), this long life fundamentally changes the way lighting fixtures can be designed as the LED can be expected to outlive the fitting. This removal of the need to access the light source for replacement means the product can be made more compact and aesthetically pleasing. As well as making manufacture cheaper through fewer moving parts, the maintenance cost of a fitting over its life is significantly reduced. It also means that the LEDs and control gear can be manufactured as one unit, easing manufacture and making the device more compact.

In addition to the long life of LEDs, as they are a solid state device they are durable and impact resistant, again they are much better than incandescent and fluorescent sources in this respect. As other sources generally emit light in a 360° range, reflectors are needed to direct it, causing light losses and light pollution in some situations. LED offer flexibility in terms of light output pattern; they can range from spot to wash (from 10° to about 120°). LEDs also remove the need to isolate the “bulb” from people to prevent breakage. While they do produce heat, with adequate heatsinking an LED product is much less likely to cause burns than discharge type sources.

The preferred correlated colour temperature has been investigated by Scuello (2004) who found that while typical white museum lighting is around 3000K, the participants in his trial believe that 3600K gives the most pleasing appearance. Furthermore, Ashdown (2002) reported that perceived CCT need only be reported in six (non uniform) increments across the white light range, as higher levels of

accuracy are not sufficiently different enough to be justified. This suggests that the issue of CCT is subjective and should be assessed qualitatively in each application. LEDs allow infinitely variable CCT to be built in and therefore give the full range of white colour temperature spectral distributions to suit each situation and audience. LEDs also have no warm up time to achieve a given CCT.

Continuing this idea, the use of RGB or RGBA (a mix of red, green, blue and often amber) LEDs allows the full range of colours to be created, as discussed earlier. This has great benefits in the architectural and stage/theatre markets as DALI/DMX control protocols allow each fixture to be identified and the colour changed instantly, remotely and individually. This is a great improvement over conventional sources where filters must be used to change the chromaticity of the light, these filters burn out and must be manually changed to achieve different colours (Gerlach, 2005). Like conventional fluorescent and halogen, dimming of the light output is also possible with the DALI/DMX interface.

The light source in a museum or art gallery environment must only emit wavelengths in the visible region of the spectrum and not infrared and particularly not ultra violet, which is more damaging to delicate artwork (Scuello, Abramov, Gordon, Weintraub, & Weintra, 2004). While other sources such as metal halide and tungsten halogen lamps need a filter to block UV radiation, LEDs are free from this as they have such a narrow, controllable emission band. UV can be deliberately added for other applications. This removes the need for additional UV blocking filters and allows more certainty in claiming a “low/no UV source”. It should still be noted that, although to a much lesser extent, all visible light is potentially damaging to art.

LEDs are also safer than traditional lighting as they operate on low voltage and are cool to the touch (although heat sinks can become hot). As they are solid state, they are durable with no fragile glass or filaments. Reliability is also a factor in some environments as they can operate at lower ambient temperatures than fluorescent. The compact size of LEDs allows new mounting options as well as reducing ceiling space requirements. Finally, they have less impact on the

environment as, aside from the reduced energy consumption, they also contain fewer heavy metals, particularly mercury.

2.3.2 Drawbacks of Solid State Lighting

The principle disadvantage of LEDs used in Solid State Lighting is that, despite their high efficacy, they have a lower light output than conventional sources. Essentially they are not very bright, despite the concentrated point source appearing so. Because of this more LEDs are needed to offer comparable overall light levels, increasing the initial cost. While the total flux of high power LEDs is constantly increasing, they have only recently reached levels that begin to be useful in lighting applications. (Gerlach, 2005) offers the following comparisons between various lamps and their retail dollar per lumen output value, reproduced in Table 3.

Table 3 Comparison of lamps and lumens

Lamp Technology	Lumens per Dollar
LED	0.5 to 10
High Intensity Discharge	250 to 500
Halogen	500 to 1000
Incandescent	1000 to 3300

The lumens per dollar can be used to compare different sources and LED will perform poorly at this comparison in the short term. However, when the lumen hours per dollar is calculated, LEDs offer similar value. Although LEDs have a higher initial purchase cost than other sources, there is almost no maintenance costs, and lower energy requirements. Conventional sources have a lower setup cost but need replacement lamps much more frequently. These contrasting cost structures often have a similar total, (Gerlach, 2005) provided this comparison given in Table 4.

Table 4 Comparison of lamps and lumen hours

Lamp Technology	Lumen Hours per Dollar
LED	50k to 1000k
High Intensity Discharge	1000k
Halogen	200k to 1000k
Incandescent	100k to 500k

The problem is that convincing consumers that the higher initial outlay is justified by extra features and a similar overall cost can be difficult.

Cowling et al. (2008) note that, as realistically priced LED products are not yet capable of replacing fluorescents which are still very efficient, their use should be restricted to accent, emergency and secondary lighting. This is preferable to attempting to use them for general illumination before the technology is sufficiently developed, potentially souring consumers on the technology. This appears to be the general consensus for now.

2.4 Summary of Literature Review

It can be seen that the literature review has allowed the research questions raised earlier to be understood, and is summarised in this section. It has shown that despite all the bold promises of LEDs, their use must be carefully applied to gain the most benefit from their positive features, while minimising the negatives.

The first question related to the direct benefits to consumers that SSL offers. Firstly, LED systems offer intangible benefits, such as improved wellbeing and happiness. There is potential for them to replicate the changing colour of sunlight through the day, helping to match the human circadian rhythm, reducing stress and improving concentration. Like fluorescent sources controlled with digital ballasts, energy use can be reduced by monitoring the changing natural light level and adjusting lighting intensity to maintain a set level. For architectural applications they allow highly saturated and easy electronic (rather than mechanical) colour adjustment. They also offer high efficiency, compact size, robustness and long life. With fewer heavy metals they have less environmental

impact at disposal. In fact the only drawback is the current cost of achieving a usable light output that is comparable with conventional sources. However, the lifetime cost is similar due to the longer life, reduced energy and lack of maintenance needs already mentioned. Promoting the lifetime cost over the initial cost in marketing is crucial, as is the fact that LED lighting products can be “installed and forgotten” with regard to maintenance. The “feel good” benefits mentioned above are also important to help consumers overcome the high setup cost of LEDs.

The next question asked of the steps being taken by Government and research organisations to promote LED use in lighting. SSL has been recognised as a key method for the developed world to reduce energy use and has been supported by programmes by the governments of the United States, China, Japan and several European countries. Most of these are partnerships between Universities and the private sector. There are also several programmes in place to educate consumers on the benefits of SSL and give impartial reports on available products.

The final aspect questioned was the key differences between LED and conventional lighting and the ramifications for lighting design. There are a number of aspects to this point and it is important take note of the advantages offered, and manage the disadvantages. For example the spectral power distribution is much different, being “peaky” rather than covering a large section of the spectrum. This does mean care is needed to achieve reasonable colour rendering suitable for the application. Similarly, the colour possibilities of LEDs are far superior, with no filters needed. The lack of necessary maintenance means the fitting does not need to be opened to replace lamps. This, and the fact that LEDs are physically small, allows the designer to make the product compact and simple with no hinges or removable panels. This allows the LEDs can be sealed to prevent dust that reduces output. However, LEDs have a much greater need for cooling than conventional sources; the heat sinks will need to be ventilated to allow cooling via convection. Also, while the LEDs themselves are small, the optics needed to direct and mix the light will probably need to be larger. These issues can make the

product more bulky and unsightly if not designed carefully. A summary of the most important benefits and drawbacks is given in Table 5.

Table 5 Summary of SSL benefits & drawbacks

Benefits	Drawbacks
<ul style="list-style-type: none"> - Commercial consumers attracted to low lifetime cost (no lamp replacement & less energy use) - Fewer toxic materials - Range of colour including white, electronically controllable - More design freedom - Compact & durable 	<ul style="list-style-type: none"> - Residential consumers put off by the high initial cost - Colour rendering lower than fluorescent - Intensity lower than fluorescent

3 DEVELOPMENT OF AN LED FIXTURE

3.1 Brief

The literature review showed a market gap that is beginning to be exploited. Firstly, the high initial cost of LED systems is more acceptable to commercial customers. These users will also value the colour adjustability of LEDs, this feature is not as important for residential users. Also the compact size allows more aesthetically appealing fixture designs. Finally, as the colour rendering and intensity are not yet competitive with fluorescent, LEDs are not yet suited to a general white illumination.

These factors lead to the brief for development of a new product; an architectural/accent LED fixture for the commercial market that appreciate the artistic qualities and ambience offered by both the fixture and the light produced. Although these attributes are difficult to quantify, they are considerations for the product. The main aims with regard to this will be to keep the visible parts of the product as compact, discrete and aesthetically pleasing as possible. This also means keeping weight low; a total less than 1kg would be advantageous but not a necessity. Similarly, a maximum distance below the ceiling of 200mm will ensure the unit is not too intrusive. Again, this is not a necessity that would prevent the project going ahead, but a useful aim nonetheless.

After some consultation with a lighting expert (Roy Speed), the quantitative performance aims for the fixture were defined. This new fitting must achieve illumination of at least 300 lux over an area beginning 0.5m below ceiling and ending 2m below it, with visually uniform intensity. This is with the product mounted to the ceiling at a standard 1.25m away from the wall. This layout described above is shown in Figure 9. As the LEDs will be close together relative to the distance to the wall, a point source is assumed for simplicity at this stage. Finally cost is obviously a necessary consideration. Given the high cost of current LED products, if the product can be produced for less than \$500, a sale price that gives a worthwhile return on investment will be achieved.

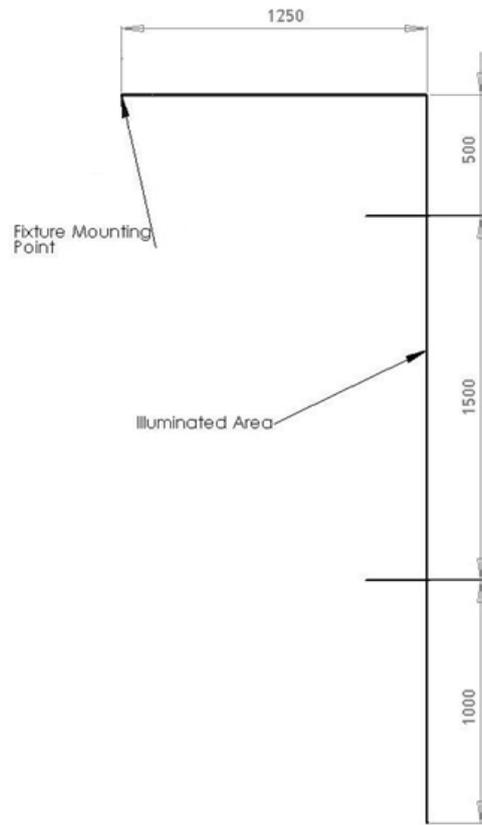


Figure 9 Geometry of fixture mount and wall

The width of the area of 300 lux of illumination is at least 1m. This is to ensure the units are not mounted less than 1m apart in the ceiling rail, creating a crowded appearance, and adding to the initial purchase cost.

Using the geometry in Figure 9 and an equation that relates illumination to source intensity the polar plots can be derived. This plot gives the intensity profile of the emitted light needed for the above brief. The equation is given below and the associated diagram is given in Figure 10.

$$E_v = (I \sin\theta) / d^2$$

$$E_h = (I \cos\theta) / d^2$$

E_v = Illumination on vertical plane (lux)

E_h = Illumination on horizontal plane (lux)

d = Distance from source to target (m)

I = Source intensity (cd)

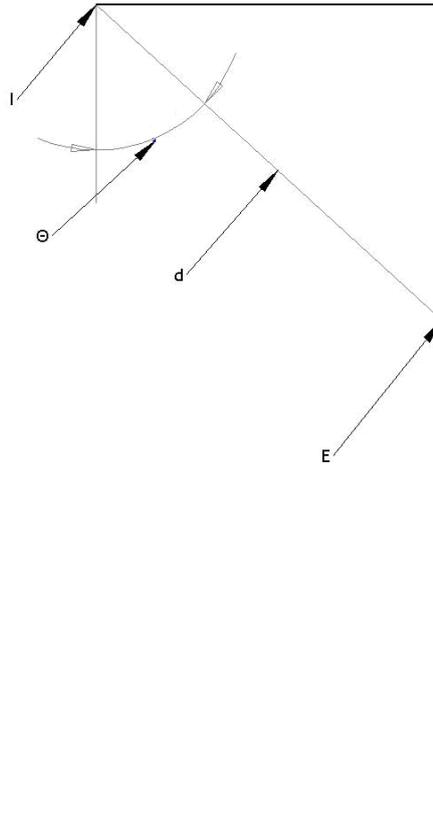


Figure 10 Diagram for illumination equation

With this information the two polar plots where created, the first (Figure 11) assumes the LEDs are mounted parallel to the wall and pointed directly at it. The second plot (Figure 12) assumes the LEDs are pointing directly at the centre of the area to be illuminated.

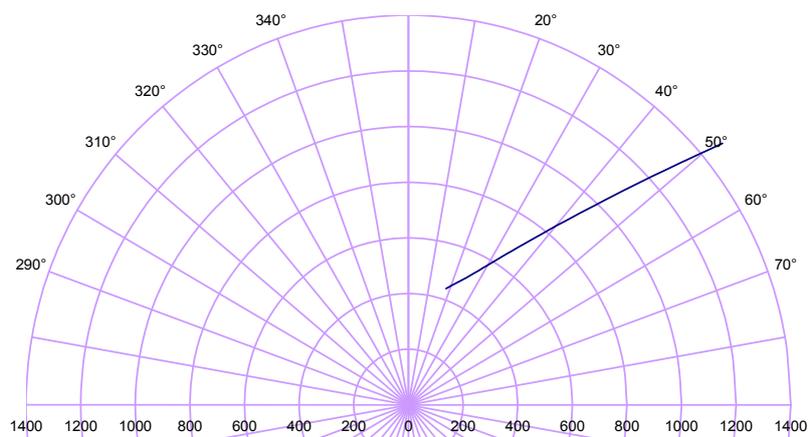


Figure 11 Polar plot (Parallel Mount)

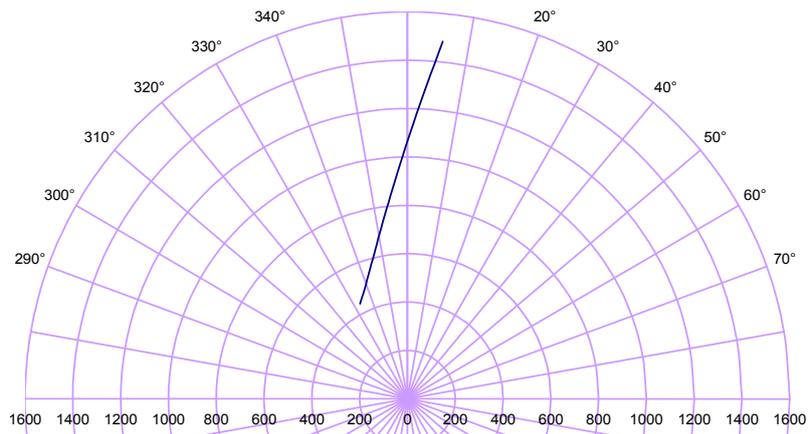


Figure 12 Polar plot (Angle Mount)

These plots show the intensity (in candela) along the X axis and the corresponding angle around the edge. For example; the LED source used in the angle mount arrangement needs to emit around 1050cd perpendicular to its body (0°).

These show that (perhaps obviously) the angle mount is the better choice. While both require similar intensity of 1500cd at the brightest point, the angle mount has a lower angle to distribute over (around 30° versus 40°), requiring less flux from the source. Also, the distribution pattern is much closer to what is commonly available in that it is centred at approximately 0° .

The problem is that the required intensity is asymmetric in one direction, and LEDs give symmetric intensity. While some have oval outputs, the intensity over this area is uniform. Nevertheless, this gives a useful guide to begin selecting components and layouts.

3.2 Competitor Products

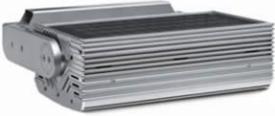
Table 6 gives a summary of similar products to the proposed design. Some of these are designed for outdoor use and as such are IP rated, and have higher light outputs and costs, but give perspective on cost versus features for LED wall washers. The prices listed are indicative as they depend on volume, preference to the supplier and do not include shipping. The majority of these products are from

overseas suppliers. Philips publishes useful intensity distribution information for its product brands (TIR and ColorKinetics here); this is examined later in section 3.11.

Table 6 Competitor Products

Image	Make & Model	LEDs	Control	Wattage	IP	Price (NZD)
	TIR Destiny CW	60 RGB	DMX	70W	IP66	\$2500
	IllumiVision Light Wave LX	27 RGB	DMX	84 W	IP 66	
	LEDWaves SSR12	4 red 4 green 4 blue	DMX	22 W	IP65	\$980
	LEDWaves Wall Washer	12 red 12 green 12 blue	DMX	36 W	IP65	\$1300

Image	Make & Model	LEDs	Control	Wattage	IP	Price (NZD)
	Dorton Wall Washer RGB 324	108 red 108 green 108 blue	DMX	48 W		\$300
	Festive Lights LED Wall Washer	12 red 12 green 12 blue	DMX	48 W	IP65	\$1050
	Lamplust XB36	12 red 12 green 12 blue	DMX		IP65	\$2080
	Arkanz Sevilla 18	18 RGB	DMX	18W	IP44	\$1240
	Gemini HWW-3A	10 red 10 green 10 blue	DMX	45W	IP20	
	ColorKinetics ColorBlast 6	6 red 6 green 6 blue	DMX	25W	IP66	

Image	Make & Model	LEDs	Control	Wattage	IP	Price (NZD)
	ColorKinetics ColorBlast 12	12 red 12 green 12 blue	DMX	50W	IP67	
	TIR Destiny CG	16 red 16 green 16 blue	DMX	35W	IP66	

3.3 Integrated RGB Vs Multiple Single Colour

There are two fundamental approaches that could be taken for the LED setup. The first is to use individual red, green, blue and possibly amber LEDs (such as Luxeon Rings, LumiDrives spots or Optek LEDs), and then develop optics to distribute the light output. This is likely to be cheaper as much of the development is done personally, but adds to the complexity of assembly in a manufacturing situation. As this approach uses more individual components, it does have the benefit of more design freedom when it comes to their layout.

The second option is to use products such as the Lamina Titan, Enfis and LumiDrives light engines and ColorKinetics DLE's (and many others). These are a complete unit that claim to provide colour mixing with the setup and optics. Potentially no further optics would be needed to give uniform distribution and colour mixing. This approach is preferable, as the mixing problems have been solved to an extent, largely because the integration allows the different colour chips to be mounted close together on the board. The integration also means the heat transferred from the LED junction to the board has also been resolved and sufficient airflow around the LED unit is all that needs to be considered. Assembly of the final product is simplified with much fewer parts. Finally, the main market for RGB type LEDs is lighting equipment manufacturers, so most have

recommended suitable drivers as well as information on integration into specialist lighting equipment.

3.4 Light Distribution Options

Regardless of which approach is taken for the LEDs, a method of distributing the light asymmetrically is needed, as shown by the polar plots earlier. This essentially means more light is needed towards the lower part of the wall, as some intensity will be lost with the increased distance. While it was suggested that a reflector be used to give the required intensity distribution of light, it was quickly decided that this would simply cause a shadow on the wall as the LEDs would block a portion of the reflected light. Therefore three further methods were considered to provide this asymmetric distribution, shown in Figure 13.

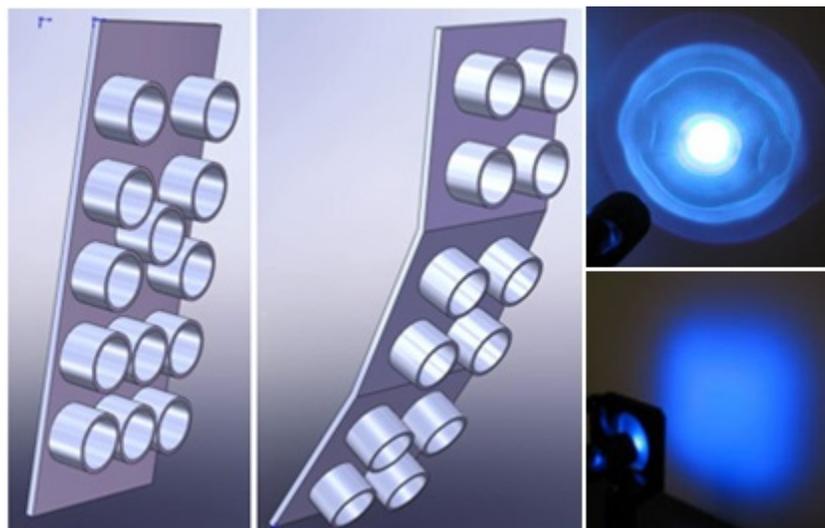


Figure 13 Light distribution concepts 1, 2 and 3

The first concept was a flat plane mounting with non uniform LED density. This option involved arranging the LEDs so a higher quantity are directed to points lower on the wall, so the most light is going to the furthest point. Obviously some experimentation would have been needed to achieve an even distribution. The drawback with this approach is that the number of LEDs would need to be high to allow for a smooth increase in output over the mounting area, increasing driver and assembly complexity.

Slightly different to this approach was the second concept, whereby the LEDs would be mounted on a sectioned panel. The angle of each section would have needed to be tested to give an even distribution.

Finally, the third concept involved a using simple flat LED mounting and uniform density of LEDs. A special asymmetric diffuser would then be needed to distribute the light. Figure 13 also shows what is possible with diffuser technology; in this case changing the light from a circular, highly uneven distribution to square and even. This is achieved with a thin sheet covered in many small prisms. This approach means the mounting of the LEDs become simpler, but producing the diffuser itself is challenging. This approach would require extensive custom design and prototyping by overseas businesses, proving prohibitively expensive. Also large scale precision manufacture of this part would have added to the final cost significantly.

3.5 Component Options

With the decision made to use either concept one, two or a combination thereof, the specific LED product options were considered. These include the LEDs, drivers, optics and heat sinks. Several suppliers were investigated and the following potential LED systems identified. The main considerations are the flux output, physical dimensions, optics options, driver/controller options and cost, although not all of these parameters were readily available.

3.5.1 Lamina

Lamina had two potential products. First is the Atlas (Figure 14), an RGB source that is claimed to produce 100, 142 and 40lm for each colour respectively. This is quoted at in input current of 525mA and a junction temperature of 25°C. While this flux level is lower than the other potential products, the unit is very compact with a diameter of just 20mm. However, optics and a heat sink would increase diameter to 65mm and overall length to between 35mm and 99mm (various optics and heat sinks available). Optics options are 10°, 33° and 45°. Lumen maintenance is 70% at 50,000 hours at 350mA. Lamina does not offer suitable

drivers/controllers so compatible products would need to be sourced. Also a higher number of individual Atlas LEDs would be needed to give sufficient light output, adding to the cost and complexity of control and manufacture. This higher number of point sources could give better light uniformity however.



Figure 14 Lamina Atlas

The second Lamina offering is the TitanTurbo, shown in Figure 15. Again this is an RGB product, and has a total flux of 1290lm at 2000mA and 25°C junction temperature. The unit itself is 45mm by 32mm, but heat sink and optics increase this to 135mm diameter and 140mm in length. Optics available are 20°, 30° and 45°. Lumen maintenance is 70% at 50,000 hours at 1050mA. This unit gives good total flux output, but again Lamina does not offer suitable drivers/controllers. The overall length is also prohibitive, but it will fit if a flat diffuser panel is used in place of the optics. The cost is high at \$275 before optics or controllers are added.

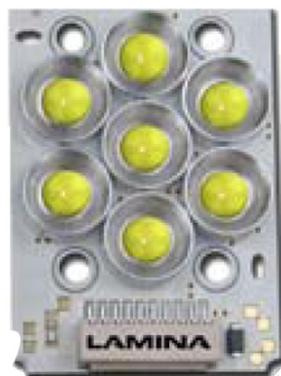


Figure 15 Lamina TitanTurbo

Figure 16 shows the Lamina products with optics and heatsinks attached. This increases the size considerable and is a fairly awkward shape to package neatly in a lighting fixture.



Figure 16 Lamina LED with heat sink & optic

3.5.2 Tridonic Atco

The Talex Eos from Tridonic Atco is modular; the different components need to be assembled after purchase, shown in Figure 17. Although the individual modules come in red, green, blue and amber, there are currently no controllers that have four channels, so it would be an RGB system in practice. One controller can run up to 15 LEDs, with each group of three (RGB) giving 99lm. The hardware to connect to a computer and software to control the LEDs are also available. A specific optic for wall washing is available, with a 40° by 10° output. While no heat sinks are provided, each of the 15 modules is very small, measuring 25mm by 25mm by 16mm when assembled. The cost is around \$17 for each LED and lens, plus controller of \$105.



Figure 17 Talex Eos LED and lens

3.5.3 Philips

The RGBA LED Module System should deliver better colour rendering and more accurate CCT's for white light. Lumen output is 71lm per RGBA module. The units are compact at 140mm by 35mm by 35mm, and are a sealed unit including optics and heat sink, shown in Figure 18. The only optics option is oval, 8° by 50°. Lumen maintenance of 70% at 35 000 hours is claimed. The product also includes a driver capable of running up to six 4x1 modules, and controllers that operate on DALI or DMX. Cost is around \$140 for each RGBA module and \$75 for the controller.



Figure 18 Philips LED Module

3.5.4 TIR

The Lexel LX-1000 has a flux output of 900lm and gives 100% lumen maintenance over 25 000 hours by monitoring light output and increasing forward current as the LEDs degrade. Optics are only 20° so would need to be used in conjunction with a diffuser panel or similar. This product is shown in Figure 19.



Figure 19 Lexel LX-1000

A summary of the component options is given in Table 7, showing all available information.

Table 7 Component Options Summary

Make & Model	Lumen Output	Input Current	Dimensions	Optics	Lumen maintenance	Price (NZD)
Lamina Atlas	Red: 100lm Green: 142lm Blue: 40lm	525mA	ø65mm x 99mm	10° 33° 45°	70% at 50k hours & 350 mA	
Lamina TitanTurbo	Total: 1290lm	2000mA	ø135mm x 140mm	20° 30° 45°	70% at 50k hours & 1050mA	\$275 + optics & controllers
TridonicAtco Talex Eos	Total: 99lm	350mA 700mA	75mm x 25mm x 16mm	40°x10°		\$51 + \$105 controller
Philips RGBA Module	Total: 71lm		140mm x 35mm x 35mm	8° x 50°	70% at 35k hours	\$140 + \$75 controller
TIR Lexel LX-1000	Total: 900lm			20°	100% at 25k hours	

After consideration, the Philips RGBA modules appeared to be the best suited. The reasoning here was that the RGBA would provide the best colour rendering, although this unit is slightly lacking in lumen output. The other benefit was the oval optical pattern suitable for wall washing, and the fact that the LED, optic and heat sink are integrated into a simple unit. While six modules are possible on the single controller, any more than four was deemed to be too bulky and would necessitate an obtrusive overall design. Using four modules would give a total light output of 284lm.

3.6 Selection and Initial Testing of LED Components

Cowling et al. (2008) noted some useful points to help ensure the testing and design of LED fixtures is as successful as possible. These were from their

experiences testing LED designs at the Queensland University of Technology Photometric Laboratory. The most important point given was simply to ensure a low LED operating temperature. They also noted that during testing, LEDs can need up to two hours of continuous operation to stabilise. A further finding was that using optics to shape the light output often caused large drops in intensity that make the fixture ineffective. LED systems are also very sensitive to reflector and lens positioning so these must be accurately designed. Finally they highlight that the optical and mechanical axes of an LED are often not the same. All of these points are useful guides for the development of the LED fitting.

To begin with, a simple 2D SolidWorks model was created using the LED output distribution (50° in the horizontal direction and 8° in the vertical) and the wall and illumination requirement geometry. This is given in Figure 20. The 50° horizontal distribution yields a predicted illuminated area around 1.6m wide.

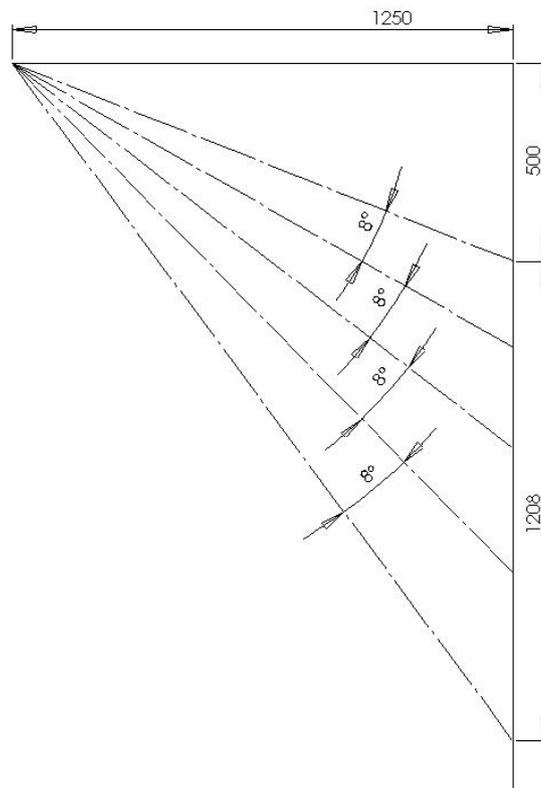


Figure 20 Philips light distribution

This predicts that projecting four Philips Modules with no overlaps or gaps will result in an illuminated area of 1.2m high by 1.6m wide, not quite the 1.5m by 1m required. Nevertheless, data on the drop in light intensity due to the increasing distance the light must travel was desired. It is also expected that the actual distribution will cover a slightly larger area as the light does not end abruptly as assumed by Figure 20.

From here a simple bracket was made to mount the Modules, positioning them perpendicular to the centreline of each to the four distributions. The control gear was connected to a power supply giving 23V and 350mA. Slight adjustments then made to the mounting angles to give the optimum, real world coverage. It should be noted that the bracket sits on the floor for this early testing for simplicity; the entire setup will be inverted later. The bracket and modules in operation is shown in Figure 21.

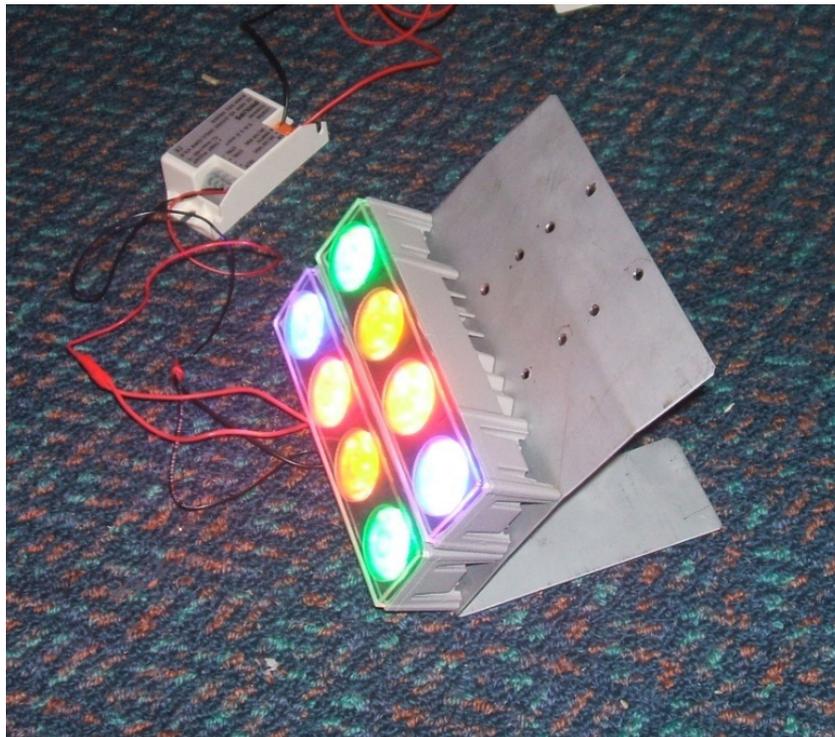


Figure 21 Philips Modules and test board

Although only two modules were available for testing purposes, by simply taking two sets of measurements the total light output of four modules was simulated. The noticeable light covers approximately 1.7 metres in width and 2 metres in

height, beginning 0.5 metres from the ceiling, although not all of this was of a useful intensity.

Although the light distribution covers a reasonable area, the intensity was noticeably uneven with the Philips system. To confirm this, a grid was devised to measure the light levels at a number of points. This grid is 1.5m high and 1.2m wide, beginning 0.5m below the ceiling. The wall was divided up into 16 evenly spaced points and a light meter (a Lutron LX-105) used to take illuminance at each point. This setup is shown in Figure 22.

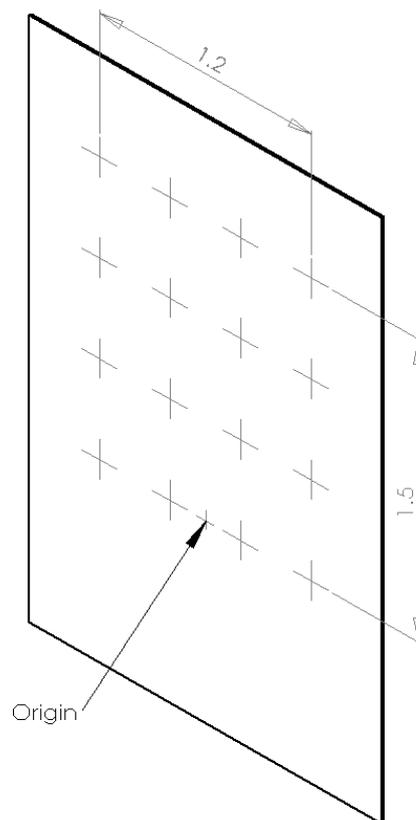


Figure 22 Illuminance testing wall

As only two LED modules were obtained the light levels were measured with them in the upper and lower positions separately. These two values were totalled and the ambient light subtracted from these values to give the lighting component provided by the LEDs. The final light levels are given in Table 8, distances given are relative to the origin given in Figure 22.

Table 8 Philips light level grid (lux)

1.5m	123	234	244	164
1.0m	99	142	140	102
0.5m	92	219	254	129
0m	52	64	71	52
	-0.6m	-0.3m	0.3m	0.6m

These values give a mean of 136 lux, with an average deviation from the mean of 55 lux (40%).

Experimentation was done with reflectors to limit the light and direct it more towards the needed region, it was soon discovered that reflectors create fringing problems with LEDs. While the proposed number of modules (four) could be increased to six with the current controller, at \$140 each this would increase the final cost sharply, as well as make the finished product bulky. Visually, the intensity distribution with this system was also noticeably uneven.

With this knowledge gained, the decision was made to try a different LED system; a Talex sample from Tridonic Atco had become available for testing. This promised higher light output as well as a lower cost. While this is only an RGB system, the total lumen output of 495lm is considerably higher than the 284 offered by the Philips, and it is physically smaller. It has slightly narrower overall optics (40° by 10° versus the 50° by 8° of the Philips system), so it concentrates the light output further which will also increase the illuminance. One controller can be used to operate 15 LEDs (five of each colour) so the decision was made to mount them in a grid five high by three wide, with one RGB per row.

The Talex system is component based and is not supplied with a heat sink, but can safely be run for short periods of time without one. This was the approach used to get baseline intensity measurements. While LED temperature and light output are closely related, indicative measurements can be obtained with this method. Further, as no heatsink was used here, the intensity is potentially lower than would be seen with one. The same procedure as the Philips Modules was used for

the Talex LEDs, beginning with a 2D SolidWorks model to predict the minimum illuminated area. This is given in Figure 23.

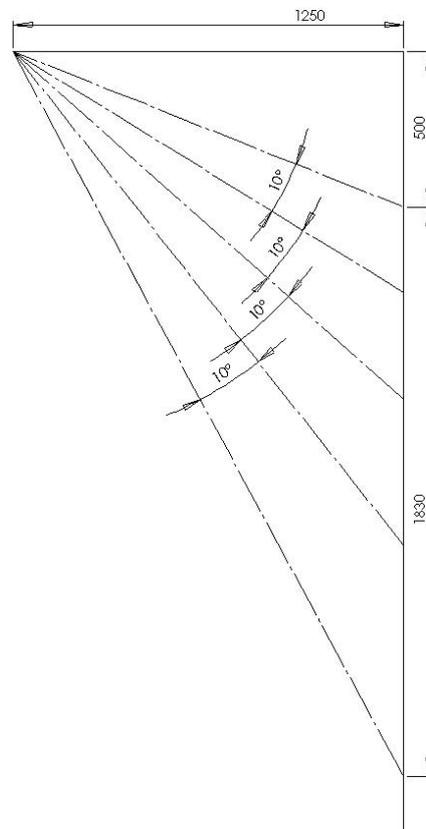


Figure 23 Talex light distribution

Figure 23 only shows the distribution outputs of four rows of LEDs. It should be noted that, as it predicts an illuminated area of 1.8m (above the 1.5m required), the final row of LEDs was directed at the same area as the fourth, thus doubling the intensity in this lower wall area and hopefully give more uniform intensity overall. The predicted width of illumination is 1.3m.

The Talex LEDs and optics were assembled onto a test board similar to the one used with the Philips LEDs, shown in Figure 24. Due to the segmented nature of this approach it could be expected that “bands” of illumination would be visible, but this has proven to be not the case. This is likely due to the combination of two aspects; a fairly rapid drop off of intensity at the edge of each LEDs illumination, and the particular care taken with the mounting design to ensure the edges of illumination meet as precisely as possible, with no gaps or overlaps.

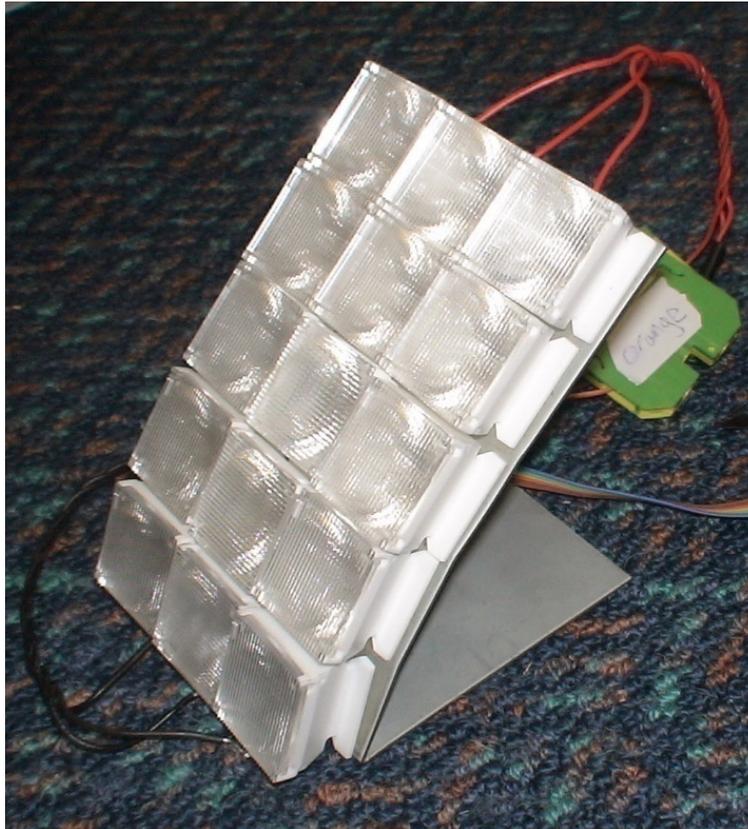


Figure 24 Talex LEDs and test board

Again, illuminance data was recorded and is given in Table 9.

Table 9 Tridonic Atco light level grid (lux)

1.5m	197	330	317	190
1.0m	266	391	386	254
0.5m	265	325	342	248
0m	221	247	251	193
	-0.6m	-0.3m	0.3m	0.6m

The mean light level over the entire area of interest is 276 lux, while the average deviation from this mean is 54 lux (20%). This is almost exactly double the light level and half the percentage variation of the Philips system.

As the intensity distribution of the light and the lux achievable on the wall is critical, the decision was made to use the Tridonic Atco system. The downside is that it is much more component based, requiring wiring, soldering and heatsinks to be added. It is also likely to have slightly lower colour rendering due to only being

an RGB system, but this is an allowable sacrifice given the accent application. The reasoning here is that it will typically be used for wall washing and not to illuminate areas where fine detail and highly accurate colour rendition is required. The datasheets for the LEDs and their driver are given in Appendix 4 and 5 respectively. By this stage the profile required for the LED mounting was also finalised, and is shown in Figure 25. The aforementioned fourth and fifth row feature is indicated by 180° between their mounting faces, giving essentially the same distribution direction.

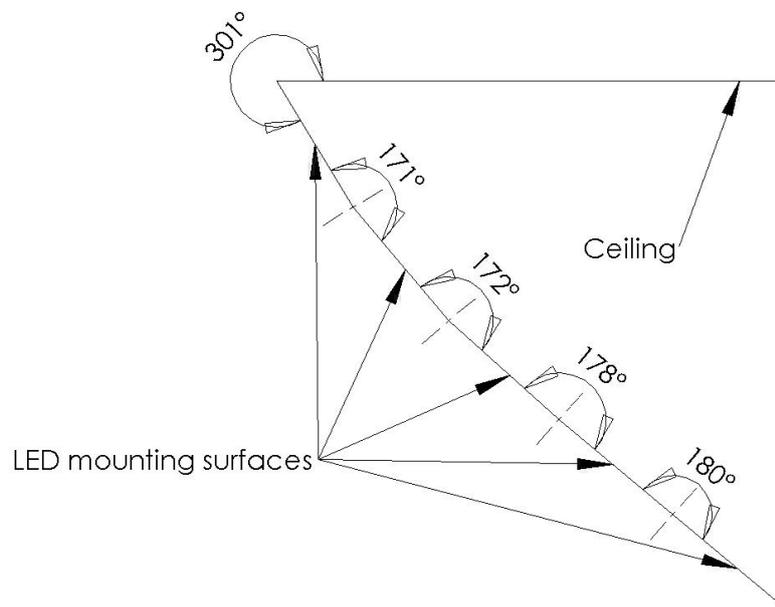


Figure 25 LED mounting geometry

3.7 Refining the Design

One of the advantages of LEDs is their compact size; this is one aspect that has been deemed important to the product. For this reason, some consideration was given to the location and layout of the various components in the system. The 15 Talex LEDs use one driver, which is controlled by a DALI USB interface and converter. While each light fitting must have a driver, up to 64 can be run on one DALI USB interface and DALI Power Supply. The setup is shown in Figure 26.

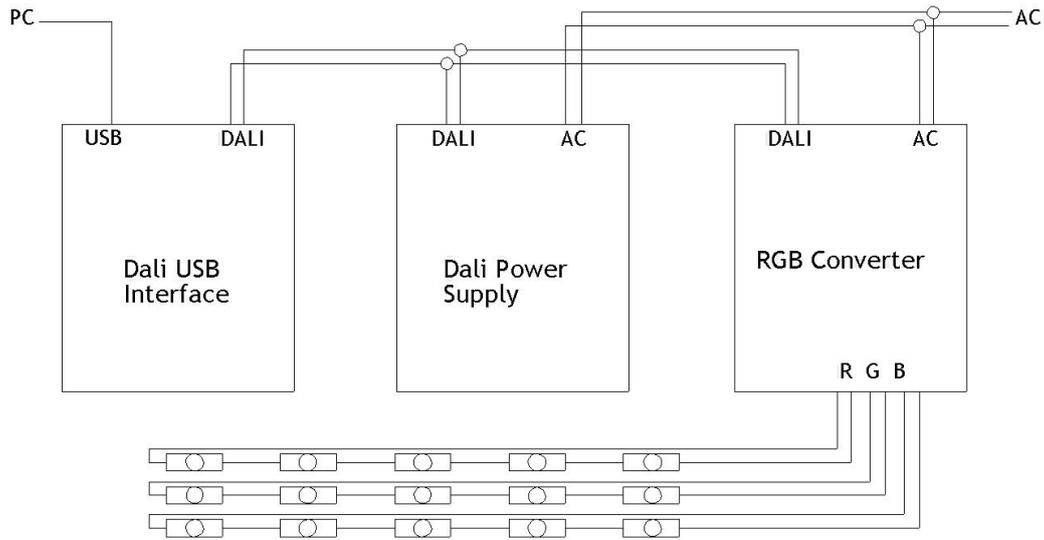


Figure 26 Talex system block diagram

The maximum length of the RGB cables from the Converter is 20m, while the DALI cables can be mounted a considerable distance from the LED unit, connected only by a low voltage “twisted pair” signal wire. The three components are nearly the same size, approximately 70mm by 100mm and 30mm deep. They are shown in Figure 27.

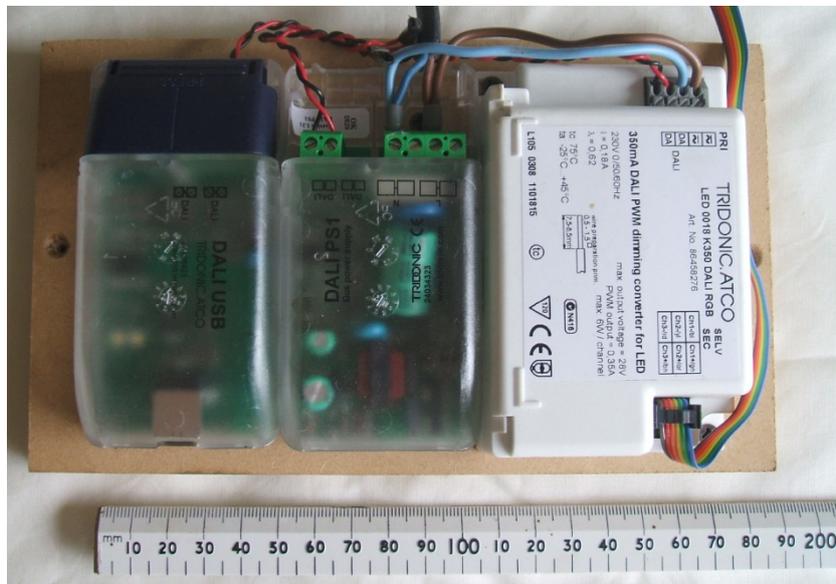


Figure 27 (Left to right) DALI USB, DALI Power Supply & RGB Converter

The situation for the Talex LEDs and their Converter presented two design options, essentially whether to mount the Converter in the fixture itself or remotely. The

combined LEDs and lenses are approximately the same size as the converter so packaging them needs some consideration.

The first option was to combine both the converter and LEDs into the fixture design. This would make it almost twice the size and less aesthetically appealing as the converter would need to be hidden somehow. The heatsinking would also be complicated as the converter needs to be isolated from the heat produced. The advantage of this approach is that fixture can be simply attached to the ceiling and connected to the mains power and DALI, no further space is needed for installation.

The second possibility is to have the LEDs mounted independently from the Converter, which eliminates the disadvantages of the first option. However, the converter would need to be mounted in the ceiling or elsewhere if a rail mount is used. As the maximum cable length is 20m, this should not be a problem but will make installation slightly more complicated. This option means that the design of the fixture itself could be simplified and reduced in size.

With the desire to maintain the compact size of LED products and produce a fixture that is as pleasing to the eye as possible, the second option became the obvious choice. With the decision made to remote mount the converter, the design of the fixture itself could be continued.

3.8 Heat Management

With the fundamental positioning of components finalised, further details could be considered; the first was heat management. The datasheet for the Talex LEDs gives a maximum thermal resistance of 19°C per watt of power and a minimum surface area of 35cm^2 for blue and green. Red is listed at $23^{\circ}\text{C}/\text{W}$ and 29cm^2 , all at 45°C ambient temperature. This gives a total required surface area of 495cm^2 . A simple “off the shelf” unit, which had a thermal resistance of $0.72^{\circ}\text{C}/\text{W}$, and sufficient surface area, was purchased. It should be noted here that the lower the

thermal resistance the better the heat sink will perform. This basic heatsink was cut down to reduce in size by approximately half to fit the width of the LEDs. This doubled the thermal resistance to around $1.5^{\circ}\text{C}/\text{W}$ and reduced the surface area to around 787cm^2 . These values are still within the specified boundaries of the LEDs. This means the temperature should theoretically be maintained at a safe level.

The second prototype was then built, and can be seen in Figure 28. An aluminium mounting plate was machined to the required mounting profile, which is given previously in Figure 25. The LEDs were then attached to the front and the heatsink to the back, with heatsink compound used between the two surfaces to aid heat transfer.

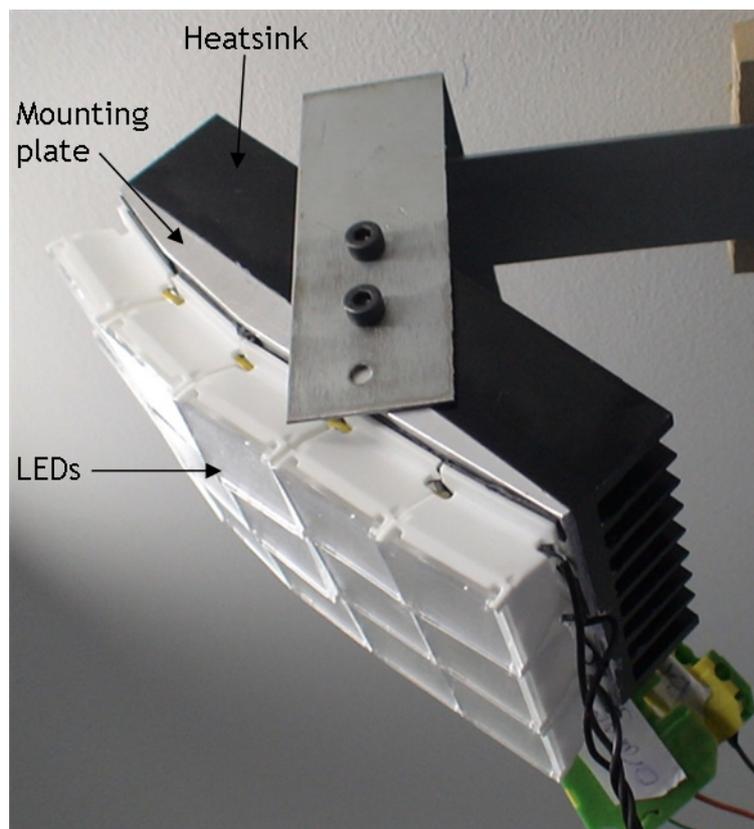


Figure 28 LEDs, mounting plate and heatsink

This setup was used to confirm the heatsink was performing as expected and kept the LED temperatures to a safe level. The temperature was checked with an infrared thermometer (Sentry ST632) numerous times over eight hours of operation

but it did not exceed 40°C , which is a full 25°C below the maximum allowable. The ambient room temperature was 22°C . While this proved that the heatsink was capable of maintaining a safe temperature, a full temperature test will be carried out on the final prototype.

3.9 Prototype Build

There is much talk in the literature of Solid State Lighting products often not taking advantage of the benefits afforded by using LEDs, including a compact size and simple design (B. G. Ashdown, et al., 2004; Muthu, et al., 2002a; Serpengüzel, 2003). Achieving these two characteristics was the focus when designing the prototype and various options were chosen to enhance this. This included mounting the RGB Converter in the ceiling as opposed to within the light fitting, and having a visible heatsink rather than enclosing it in a larger casing. Both of these decisions reduce the visible size of the unit as well as improve its heat transfer ability.

With this in mind, and as the required heat sink dimensions were known, the prototype design became an extension of that used in testing (see previous Figure 28). The major changes were the addition of a “wall” around the lenses to protect and align them, the extension of the heatsink fins at each end to improve the look and cooling, and finally to change the side profile to an oval to improve aesthetics. These changes can be seen in 3D SolidWorks form in Figure 29 and the actual machined prototype in Figure 30. The combined body and heatsink, and mounting plate are also shown. Engineering drawings for the machined parts are given in Appendix 6, 7, 8 and 9.

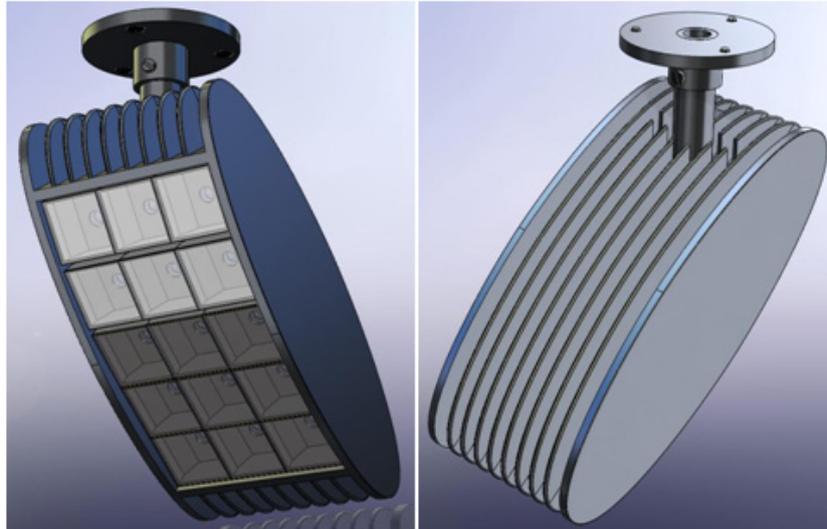


Figure 29 SolidWorks model of prototype



Figure 30 Machined prototype

A circular cut-out into the fins was part of the machining process; this was for the tube portion of the ceiling mount, helping to make a solid joint. This was then tig welded in place. This tube goes inside a short sleeve attached to the mounting plate, held in place with two screws. This means the plate can be attached to the

ceiling unobstructed and the fixture itself attached afterwards. Finally, holes were drilled from the surface the LEDs are mounted to, emerging on the back between the fins. This allowed the wiring to be run close to the body of the fixture before going up the hollow mounting tube and into the ceiling, making it largely invisible. These aspects can be seen in Figure 31.

The main body of prototype was machined from a billet of aluminium, so it could be one piece. Machining is not cost effective for large scale production, but for a single prototype is the only economic approach.

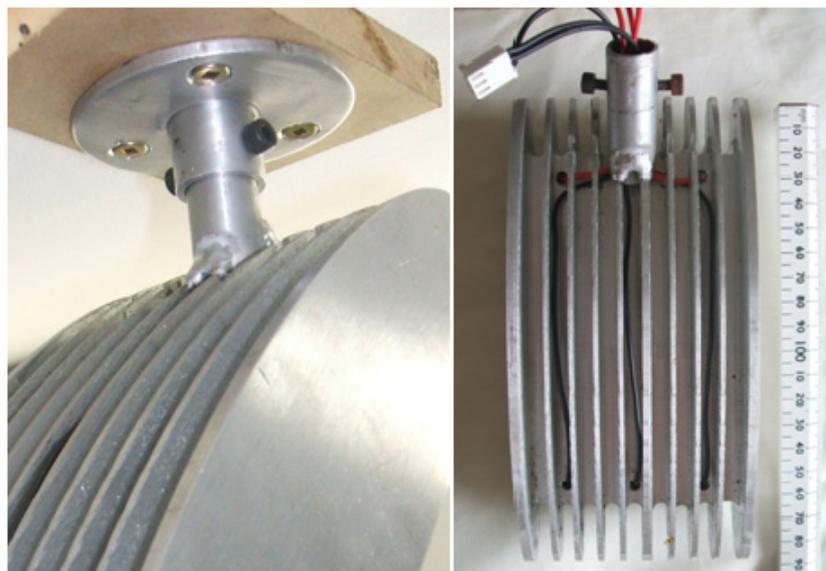


Figure 31 Mounting & wiring detail

3.10 Production

To fully evaluate the production costs of this product two different body types were considered for production; the preferable oval profile and a cheaper rectangular profile.

The oval version is visually identical to the prototype; it differs in that it is made from two pieces so it can be cast easily for manufacture. A standard view of this option is given in Figure 32 and an exploded view in Appendix 10. This was the preferred option for its superior aesthetic and heat transfer properties. It is also

only two pieces so assembly will be faster. However, the tooling cost for casting is expensive, as is the cost per unit.

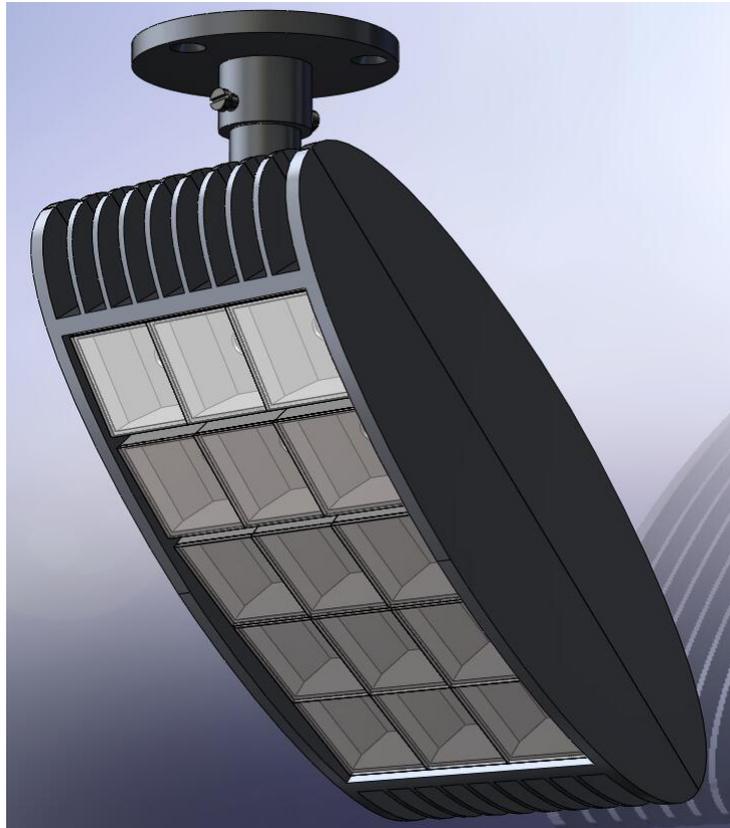


Figure 32 Production option 1: oval profile

The alternate production option was to simplify the design and extrude it, giving a rectangular profile and lower tooling and unit costs. To do so the design would be more like the model used in testing (seen in previous Figure 28). The side profile would become rectangular and the additional heatsink fins at either end removed, while maintaining the proven fin spacing and dimensions. With this approach the body would require three separate extrusions, and obviously is not as visually appealing, but it does become cheaper to produce. Again, a collapsed view of this rectangular option can be seen in Figure 33 and an exploded view in Appendix 11.

A cost analysis of the cast and extruded options is given in section 3.11.

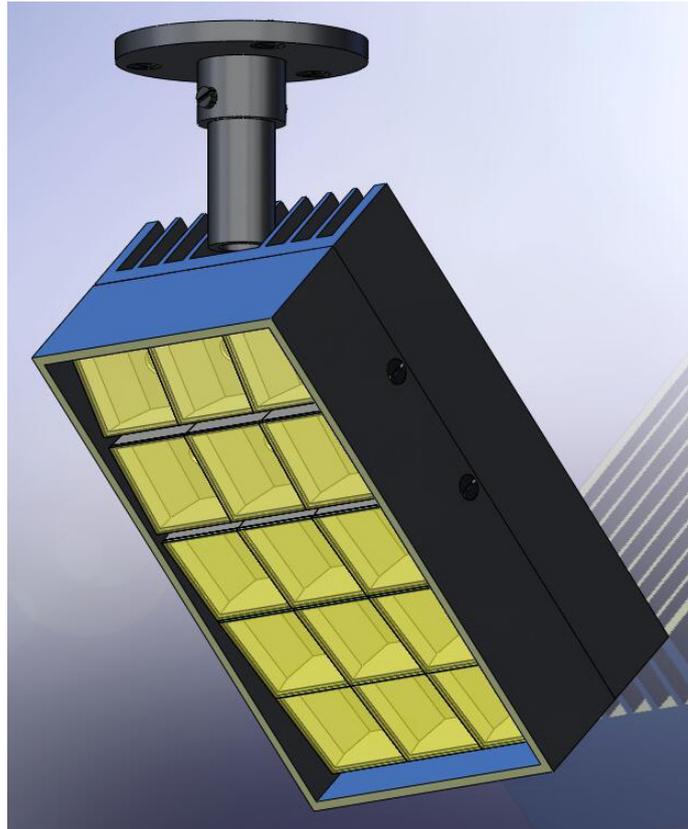


Figure 33 Production option 2: rectangular profile

3.11 Testing of Final Product

3.11.1 Aim

To ensure the product is competitive with other architectural lighting devices on the market electrical and photometric parameters need to be recorded using the final prototype (Figure 30). Some of these were simple while others needed to be carefully considered to remain fair. The aim for this product testing was to measure these parameters as accurately as possible given the available methods. The measurements taken were LED temperature, light intensity, Correlated Colour Temperature and colour range possible, an efficacy comparison, power consumed and weight. Where possible, this was completed with the LED fixture mounted in a bracket close to the ceiling to replicate normal use as closely as possible.

3.11.2 Method & Results

Cooling: As already mentioned maintaining the LED junction temperature is critical for the life, colour point and intensity of LEDs. Although the previous prototype iteration (Figure 28) proved the heatsink was sufficient, further testing was done with the final prototype (Figure 30) to ensure this was still the case with the additions made to create it. The total surface area required by the LEDs at 350mA is 495cm^2 and surface area of the unit is 735cm^2 , although a portion of this area is not specifically a heatsink. Similarly, the maximum thermal resistance is $19^\circ\text{C}/\text{W}$, and the prototype will have a value close to the known $1.5^\circ\text{C}/\text{W}$ of the design it is based on.

The heat management testing was conducted over several hours, in a small (6m^2) room with minimal airflow and an ambient temperature of 24°C . The centre red, green and blue LEDs (ie the third row of LEDs) were tested as these were the hottest running. The temperature of the specified test point of each LED was recorded at 10 minute intervals for one hour again using the infrared thermometer. After the first hour the LEDs appeared to stabilise as the temperatures reached a plateau. A final reading an hour later confirmed this. The graph of time versus temperature is given in Figure 34.

LED Temperature Vs Time

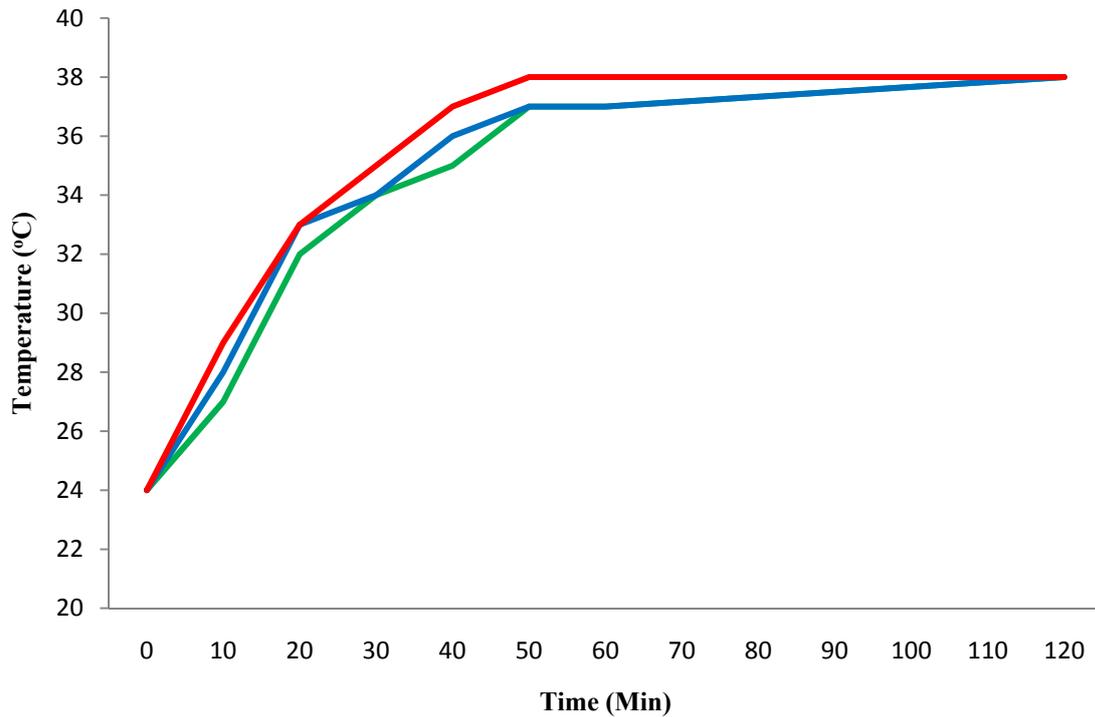


Figure 34 Temperature testing results

The maximum recorded temperature was 38°C, well below the 75°C limit. Considering this test was conducted with no airflow and a warm ambient temperature, there is a large buffer for the temperature to increase before it becomes damaging.

Intensity: The light target for a useful light intensity at the beginning of the project was specified to be 300 lux over the area concerned. The light levels over the grid were rechecked with the LEDs in this final prototype. As expected, there was a negligible difference between these results and those used with the first prototype. The light levels are reproduced in Table 10.

Table 10 Final light level grid (lux)

1.5m	197	330	317	190
1.0m	266	391	386	254
0.5m	265	325	342	248
0m	221	247	251	193
	-0.6m	-0.3m	0.3m	0.6m

The light levels are only slightly below the target, and show good visual uniformity. This is better illustrated in graph form later in Figure 39.

Correlated Colour Temperature Range: While colour temperature is more important for general illumination rather than decorative applications, it is still useful to be able to vary it. These preferences change from person to person and can even influence our perception of room temperature, as well as changing the feel of an area from cosy and inviting (warm colour temperature) to sterile and industrial (cool colour temperate). To what extent this product can produce these colour temperatures was measured with a chroma meter. This returned values ranging from 2900K to as high as 10500K, but at these extremes the light was possibly too yellow and blue respectively to be considered white. A more acceptable range would be from 3900K to 7500K. Although difficult to capture with a camera, these two extremes in CCT are shown in Figure 35.



Figure 35 Correlated colour temperatures of 3900K (left) and 7500K

Colour Range: This is a separate measurement to the CCT and is more important for this architectural application. As discussed previously, by plotting the colour points of a multiple LED system on the CIE colour space the range of colours possible with those LEDs can be seen. This is precisely what was done here. Using a Konica Minolta chroma meter (model CL 200), the coordinates for red, green and blue illumination were taken. Red gave (0.68, 0.31), green (0.20, 0.69) and blue (0.14, 0.02). When plotted, these coordinates show that a reasonable range of colours is theoretically possible with these three LED colours, see Figure 36.

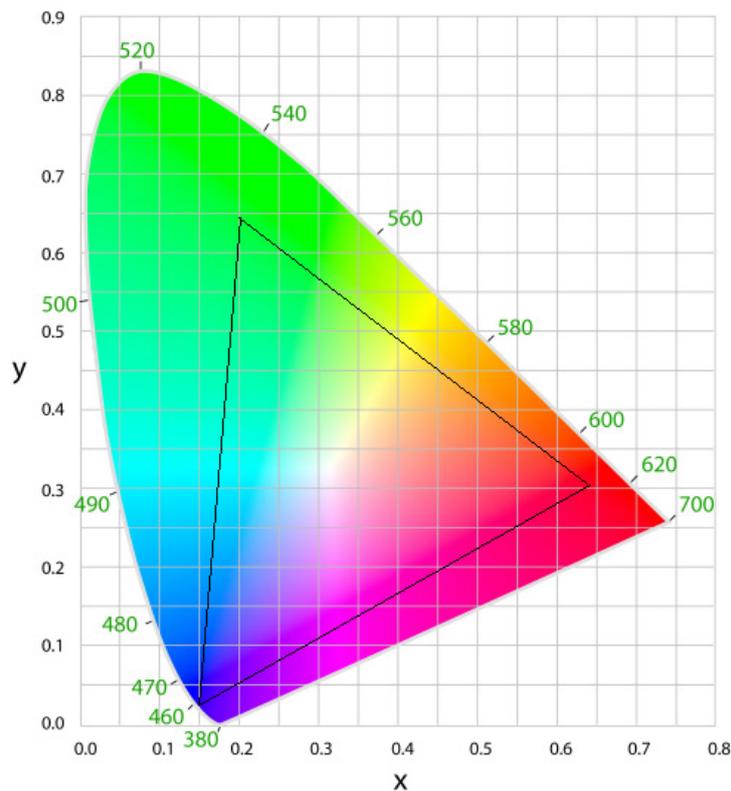


Figure 36 Theoretical colour gamut

Figure 37 shows illumination with the three primary colours, while Figure 38 shows two primary colours mixed at a time. This begins to demonstrate the range of colour possible. Due to the camera used, some colours are not reproduced entirely accurately, but are indicative. This particularly applies to the yellow in Figure 38.

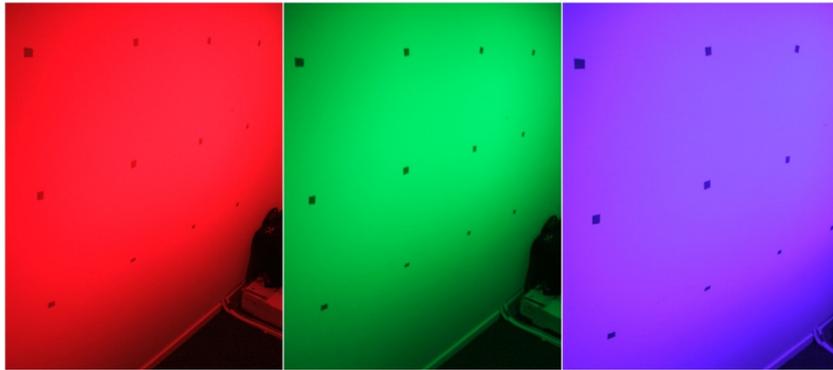


Figure 37 Primary colour illumination (red, green blue)



Figure 38 Mixed primary colours (yellow, purple, light blue)

The range of colours shown here is only a fraction of what is possible as the variability is huge (most RGB systems claim 16 million colours). This offers scope to match the consumer preference, company colours, architects designs and so on.

Power Consumption: With efficiency a key selling point for LED systems, the power consumed is a useful quantity. This only took the LED light itself into account, not the DALI controllers as these are a necessary, but separate, component. The voltage across, and current through the product (converter and LEDs) was measured. The power consumption was calculated by multiplying these according to the simple formula, $\text{Power (W)} = \text{Voltage (V)} \times \text{Current (A)}$. This shows how much power the unit consumes, but not how much of this is transferred into light. With the system (excluding DALI components) drawing 103mA at 240V, this equates to 25W.

Efficacy/Distribution: The power consumed is one half of a more useful measurement; the efficacy. The other half, the lumen output, is more difficult to

ascertain. Normally, this is measured with the use of an integrating sphere; a large, hollow, internally reflective sphere. They are used to collect photometric data, such as the total lumen output, by placing the luminaire inside and taking measurements. Unfortunately, the high cost of the precision optics means integrating spheres are not common and difficult to gain access to. The cost to do so was beyond the scope of the project so a simpler comparison technique was used, evaluation of the developed product with others already in the market. To do this, illuminance data for comparable LED products was obtained from their datasheets and plotted (some low parameter light values have been omitted to make comparison clearer with all graphs showing the same width). These graphs can be seen in Appendix 12, while the graph for the product developed here is given in Figure 39. The setback (distance from fixture to wall), optics, price and power consumption are also given if available. Both TIR and ColorKinetics brands are owned by Philips.

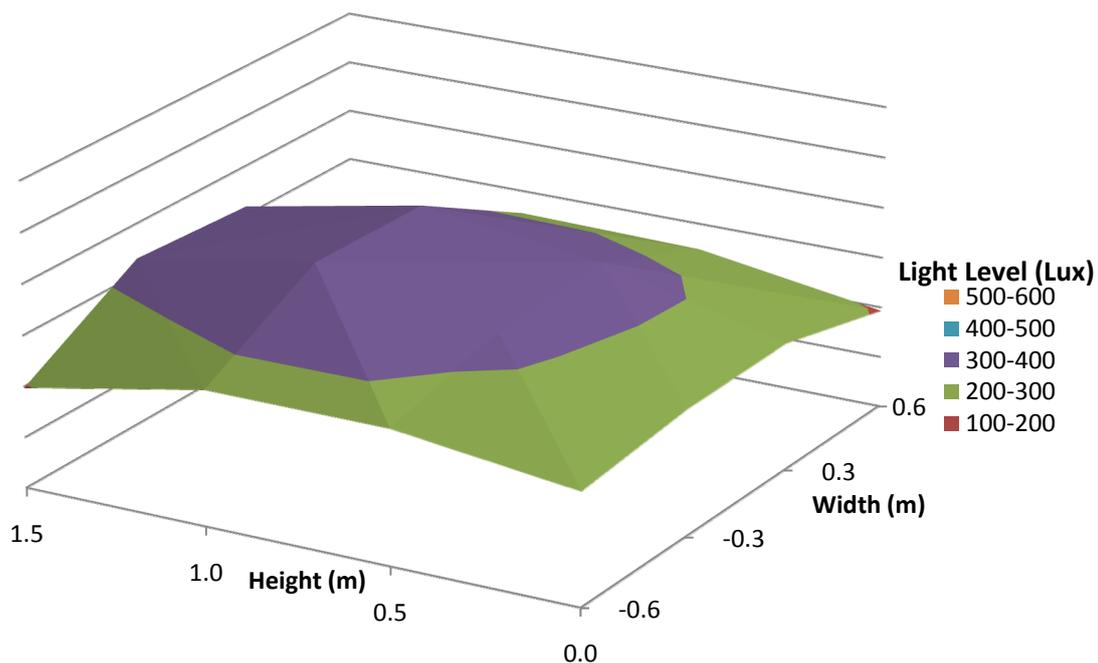


Figure 39 Developed Product - 1.25m setback, 29° optics, 25W

Weight: Finally the weight is useful as a comparison to other products in terms of shipping and mounting requirements. The unit itself is 780g and the converter is 150g, giving 930g in total.

3.11.3 Discussion of Prototype Testing

Given the intended architectural application the product performed well, with a wide variety of colours possible and a range of white extending from 3900K to 7500K, all infinitely variable between the extremes. The addition of an amber LED (making it an RGBA system) would have extended the colour range slightly and given slightly better colour rendering at low CCT, but unfortunately a compatible four channel DALI controller was not available.

Perplexingly, the LED temperature results were actually the opposite of what was expected (Yoshi Ohno, 2006). While the temperatures are similar, it is clear that the red LEDs are the hottest running, followed by blue then green. As already stated Ohno (2006), reported internal efficiency figures of 80%, 50% and 10% for red, blue, and green LEDs respectively. Higher efficiency should run cooler as a higher portion of the input power is transferred into light rather than heat. This could be attributed to this particular model of LED having different efficiencies, although this seems unlikely as the findings by Ohno were general rather than specific to one LED model. The same adhesive was used for all LEDs, which ruled out different rates of heat transfer to the heatsink as a cause. As the converter does not distinguish between colours, only channels, there is also little chance it is supplying different power level to each channel. Regardless of this finding, the LEDs are maintained at a safe temperature with this setup.

The average intensity of 276 lux is just below the target of 300, but the Eos LEDs are capable of drawing 700mA, double the tested current level. Unfortunately there is not currently a controller available rated to this value, but Tridonic Atco has indicated that this will happen in the near future. The surface area (735cm^2) and thermal resistance ($1.5^\circ\text{C}/\text{W}$) of the product and the requirements for 700mA operation (minimum of 730cm^2 and a maximum of $13^\circ\text{C}/\text{W}$), suggest that the production version of the product is capable of maintaining safe LED temperature at 700mA current up to an ambient temperature of 35°C . This would need to be confirmed when the new 700mA capable controller is available.

The efficacy and the intensity distribution comparisons provided some interesting results. Firstly it can be seen that both the Destiny CG and the ColorBlast12 have almost a spot optical output, despite being listed as wall washers. The actual intensity variations would be less obvious than appears from the graphs, but nonetheless still there.

The distribution of the product developed here is similar to the ColorBlast6, with a reasonably even intensity distribution; however the ColorBlast6 has lower overall intensity. The Destiny CW appears to have excellent wall washing ability, although again intensity is low. All products produce light outside the range of the graphs, but levels below about 100 lux are of little use. Overall, the product compares very favourably with its competitors, with an even distribution and high intensity.

3.12 Cost Analysis of Production

Nearly three dozen quotes were sought from tool makers (for both the die cast and extrusion production options) both in New Zealand and around the world to gain insight into the costs of production. As this is production is only hypothetical only some replies were received, and as the quotes are simply estimates they understandably vary in value and accuracy.

Nevertheless, they indicate the product could be manufactured reasonably cheaply and the tooling cost easily amortised, a three year period seemed reasonable. The companies that gave quotes for the casting and extrusions are given in Tables 11 and 12 respectively.

Table 11 Manufacturing quotes for preferred cast option

Supplier	Tooling Cost (\$)		Part Cost (\$)	
	Front	Back	Front	Back
Carlton Taylor (NZ)	30000	30000	3.90	5.10
RPM (NZ)	20000	20000	3.90	4.10
Star Prototype Manufacturing (China)	5063	5063	4.15	5.36
Thrivigo (China)	3302	3556	2.29	2.03

Table 12 Manufacturing quotes for cheaper extruded option

Supplier	Tooling Cost (\$)			Part Cost (\$)		
	Heatsink	Mount	Frame	Heatsink	Mount	Frame
Aluma (Taiwan)	1066	1066	1066	0.80	0.58	0.21
Aluminium Systems (NZ)	2500	1600	5500	1.74	1.04	0.30
Fletcher Aluminium (NZ)	2000	1500	2500	2.95	1.33	0.24
INEX (NZ)	2475	2475	3600	2.58	1.36	0.58
MCK Metals Ltd (NZ)	2250	2250	6750	2.24	1.62	0.59
Nalco (NZ)	2000	2000	3000	1.33	1.45	0.20

It can be seen that the Chinese and Taiwanese suppliers are considerably lower cost, particularly so for the casting tooling. Of course there are extra shipping costs and possible communication issues with such a supplier. Also, the quality of parts manufactured in these areas can be more of an issue than with local suppliers. For these reasons, (and to assume higher costs and thus give a more conservative financial analysis) local suppliers are recommended. These are RPM if the die cast option is elected or Fletcher Aluminium for the extrusion option.

The amortised cost for all the parts for both the die cast and extruded options are given in Tables 13 to 17. These also take into account various sales volumes based on estimates by Roy Speed and his consultation with other experts in the industry. They also assume an amortisation period of three years; hence the tooling cost is a third of the quote received.

Table 13 Cost amortisation for cast oval option (front)

Scenario	Sales	Tooling Cost per Year(\$)	Amortised Cost per Unit (\$)	Cost per Unit (\$)	Cost per Fitting (\$)
Worst	100	6666.67	66.67	3.90	70.57
Expected	250	6666.67	26.67	3.90	30.57
Best	500	6666.67	13.33	3.90	17.23

Table 14 Cost amortisation for cast oval option (rear)

Scenario	Sales	Tooling Cost per Year(\$)	Amortised Cost per Unit (\$)	Cost per Unit (\$)	Cost per Fitting (\$)
Worst	100	6666.67	66.67	4.10	70.77
Expected	250	6666.67	26.67	4.10	30.77
Best	500	6666.67	13.33	4.10	17.43

Table 15 Cost amortisation for extruded rectangular option (heatsink)

Scenario	Sales	Tooling Cost per Year(\$)	Amortised Cost per Unit (\$)	Cost per Unit (\$)	Cost per Fitting (\$)
Worst	100	666.67	6.67	2.95	9.62
Expected	250	666.67	2.67	2.95	5.62
Best	500	666.67	1.33	2.95	4.28

Table 16 Cost amortisation for extruded rectangular option (mount)

Scenario	Sales	Tooling Cost per Year(\$)	Amortised Cost per Unit (\$)	Cost per Unit (\$)	Cost per Fitting (\$)
Worst	100	500.00	5.00	1.33	6.33
Expected	250	500.00	2.00	1.33	3.33
Best	500	500.00	1.00	1.33	2.33

Table 17 Cost amortisation for extruded rectangular option (frame)

Scenario	Sales	Tooling Cost per Year(\$)	Amortised Cost per Unit (\$)	Cost per Unit (\$)	Cost per Fitting (\$)
Worst	100	833.33	0.12	0.24	0.36
Expected	250	833.33	0.30	0.24	0.54
Best	500	833.33	0.60	0.24	0.84

These figures allowed the bill of materials for each option to be established, given in Tables 17 and 18. The amortised capital expenditure (tooling cost) is included in the unit cost. Costs for the Tridonic Atco parts were obtained at the time of purchase, and advice was given that these prices are the same as those given to preferential, large volume customers. The sundry items are the wiring, screws and heat sink compound. Finally, the semi skilled labour cost is based on a trail assembly, including mounting and wiring the LEDs, joining the body components and tig welding the mounting.

Table 18 Bill of Materials for cast option

		Worst Case		Expected Case		Best Case	
Part	Quantity	Unit		Unit		Unit	
		Price (\$)	Total (\$)	Price (\$)	Total (\$)	Price (\$)	Total (\$)
Front Casting	1	70.57	70.57	30.57	30.57	17.23	17.23
Rear Casting	1	70.77	70.77	30.77	30.77	17.43	17.43
LEDs	15	11.50	172.50	11.50	172.50	11.50	172.50
Spot Lens	15	4.00	60.00	4.00	60.00	4.00	60.00
Wash Lens	15	1.30	19.50	1.30	19.50	1.30	19.50
Converter	1	104.70	104.70	104.70	104.70	104.70	104.70
Mounting Plate	1	4.54	4.54	4.54	4.54	4.54	4.54
Mounting Tube	1	0.22	0.22	0.22	0.22	0.22	0.22
Sundry	1	1.00	1.00	1.00	1.00	1.00	1.00
Labour	0.25	20.00	5.00	20.00	5.00	20.00	5.00
Total		508.79		428.79		402.13	
Sale Price		550.00		550.00		550.00	
Profit Per unit		41.21		121.21		147.87	
Total Profit		\$4 121		\$30 302		\$73 937	

Table 19 Bill of Materials for extruded option

		Worst Case		Expected Case		Best Case	
Part	Quantity	Unit		Unit		Unit	
		Price (\$)	Total (\$)	Price (\$)	Total (\$)	Price (\$)	Total (\$)
Extruded Heatsink	1	9.62	9.62	5.62	5.62	4.28	4.28
Extruded Mounting	1	6.33	6.33	3.33	3.33	2.33	2.33
Extruded Frame	1	0.36	0.36	0.54	0.54	0.84	0.84
LEDs	15	11.50	172.50	11.50	172.50	11.50	172.50
Spot Lens	15	4.00	60.00	4.00	60.00	4.00	60.00
Wash Lens	15	1.30	19.50	1.30	19.50	1.30	19.50
Converter	1	104.70	104.70	104.70	104.70	104.70	104.70
Mounting Plate	1	4.54	4.54	4.54	4.54	4.54	4.54
Mounting Tube	1	0.22	0.22	0.22	0.22	0.22	0.22
Sundry	1	1.00	1.00	1.00	1.00	1.00	1.00
Labour	0.25	20.00	5.00	20.00	5.00	20.00	5.00
Total		383.77		376.95		374.91	
Sale Price		450.00		450.00		450.00	
Profit Per unit		66.23		73.05		75.09	
Total Profit		\$6 623		\$18 263		\$37 543	

It is difficult to make a clear recommendation as to which of the two production options is best. Clearly the cast option has a much higher aesthetic appeal and will attract customers more strongly for that reason. It however has the exact same lighting performance as the extruded option. Another consideration is the risk for the manufacturer, there is a significant difference between the tooling estimates for the two options (\$40,000 and \$6,000), but this is somewhat reflected in the expected annual profit (\$30,000 and 18,000). Finally, the total cost of each unit (and therefore the sale price) is not significantly different.

While the final choice regard which option to pursue would depend on the risk acceptable to a manufacturer, the higher profit potential and image of the cast option is recommended here.

4 DISCUSSION ON THE RESEARCH & DEVELOPMENT

The research stage of the project showed that SSL technology is very much a niche product, but it has definite traits that make it attractive to particular target groups, such as commercial architectural applications. It also demonstrated that to produce a useful product the established LED advantages must be maintained throughout the design process. It showed that the high component costs typically associated with SSL are almost always reflected in the sale price of LED lighting products.

The research and, in particular, the prototype development have shown that even a small company could potentially take either the cast or extruded options on as a product venture. While tooling is an initial expense, either option predicts reasonable returns even at small sales volumes on a national scale. Larger volumes for overseas markets are obviously possible with shipping and marketing being additional expenses, but not tooling. The testing also showed that the performance is comparable in terms of light output and uniformity to more expensive products from established manufacturers.

Moreover, the development reiterated the fact that useful, efficient LED light and its heatsinking can be compact and aesthetically pleasing. Although, the colour rendering with LEDs is not as high as conventional sources, the development in this project is possibly useful for applications ranging from 12 volt lighting, drainpipe or small space inspection to machine vision.

The working prototype achieved useful average light output of 276 lux with uniform distribution, while maintaining a power consumption of 25W. Visible size and weight are also low at 80mm wide by 169mm below the ceiling and 930g. Finally the expected cost per unit is \$376.95, allowing a low sale price and a worthwhile profit margin. The product is also aesthetically simple and discrete. With the exception of the target output of 300 lux (discussed next), these variables were all above the targets set at the beginning of the project.

Achieving output significantly greater than 300 lux is possible with an increase in drive current. This and possibly moving to an RGBA setup are recommendations for further development for this project. The LEDs are only running at half their rated current and as an RGB system due to the converter presently available. There has been indication from Tridonic Atco that converters with 4 channels and 700mA capacity will become available in the near future. The current mounting profile could be maintained and simply widened for an RGBA setup, while additional heatsink area may be needed for the 700mA upgrade depending on operating environments. However, both of these options will require new or modified tooling, so perhaps any tooling should wait until this time. Given that the product is likely to already be profitable this is a decision that would need to be considered carefully.

5 CONCLUSION

Firstly, the research showed that the development of LEDs for lighting is far from maturity, unlike other light sources. It also showed that they have characteristics which make them desirable for general lighting in the future, in terms of both user benefit and environmental impact. While they do have their downsides, there is little doubt that LEDs will become the standard light source in the future, and several Governments are committed to making this happen.

Commercial consumers of architectural lighting products are suited to be targeted for SSL products as they prefer a high initial/low maintenance cost structure. They also require precise control and variability of their architectural lighting, compact size, appealing form, low energy use and lessened environmental impact at disposal, but perfect colour rendering is not as important. These needs match the characteristics of SSL well, and an LED trend that has recently been observed in this area of the lighting industry.

Following this research and some experimental testing using various ideas and sample products, a working prototype of an LED product to suit the architectural and accent lighting market was built. Also developed was a method of large scale manufacture for this design, and a simpler design that can be produced at a lower cost. The key aim for this development was to build on the unique qualities of LEDs and ensure they are best utilised.

A series of tests was then completed to establish how this new product performs against similar existing models. The key finding here related to the light output, specifically the new design illuminates the target area with an intensity and even distribution that is often better than comparable products. It does this with low power consumption, cost and weight.

This project has shown that a useful and competitive product can be developed by directly building on the inherent strengths of SSL and treating it as an entirely separate technology, rather than applying conventional lighting design techniques

to it. This niche market is allowing consumers to see the benefits of LED technology, and these SSL products that are smaller, simpler and safer for the environment will occupy more and more on the general illumination market.

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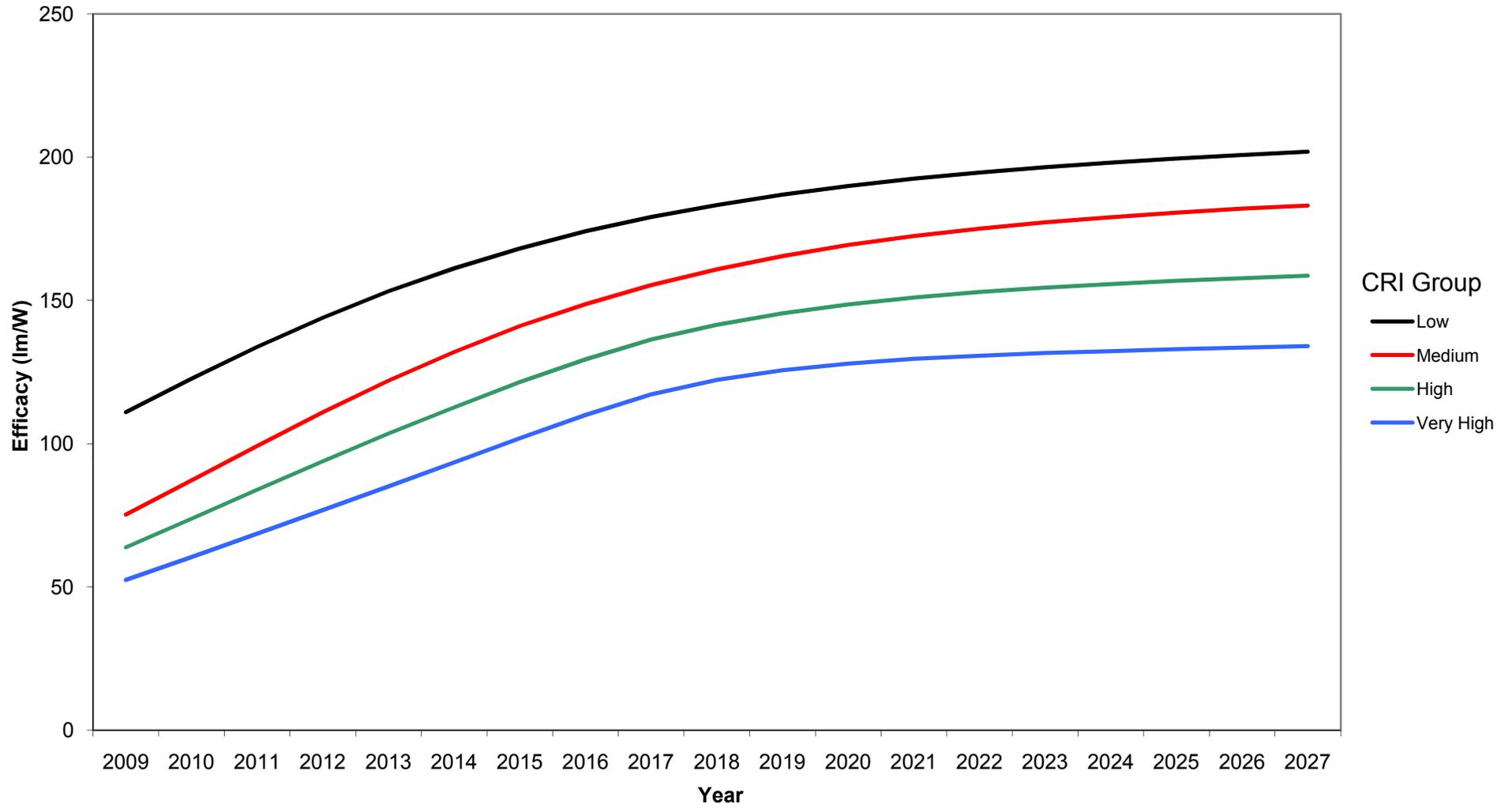
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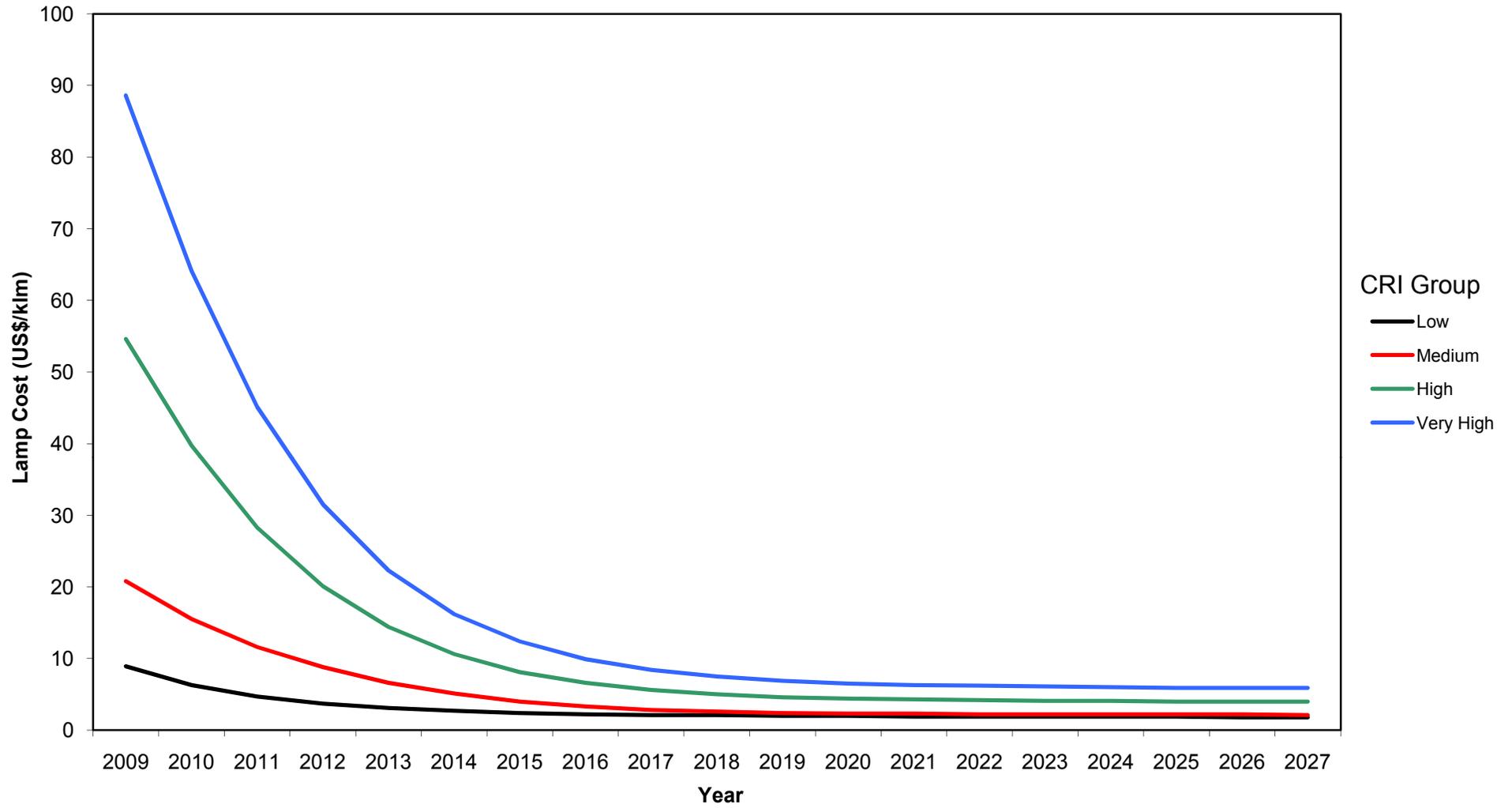
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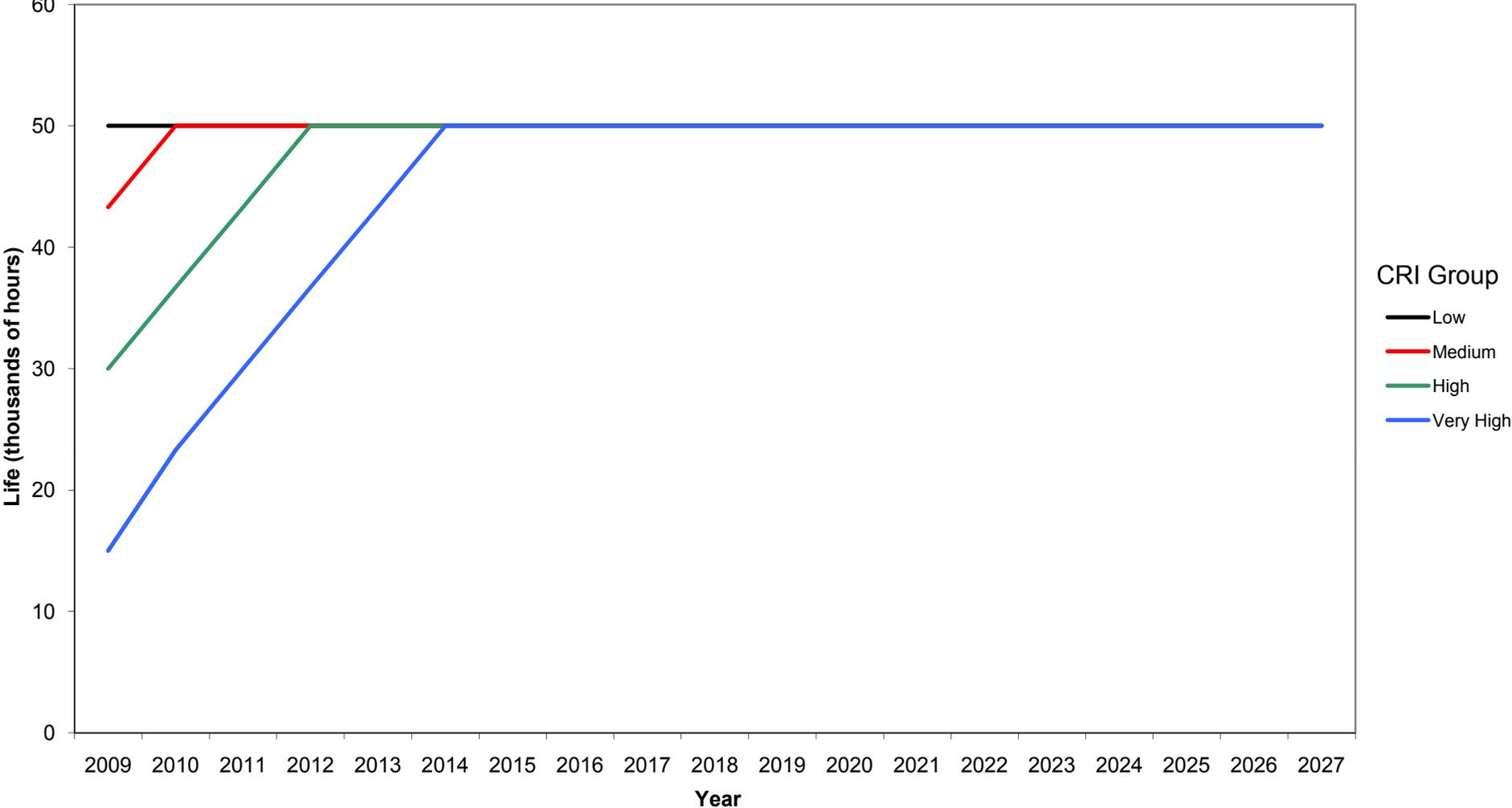
Appendix 1: Predicted LED Efficacy by CRI Group (2009 to 2027)



Appendix 2: Predicted LED Lamp Cost by CRI Group (2009 to 2027)



Appendix 3: Predicted LED Life by CRI Group (2009 - 2027)



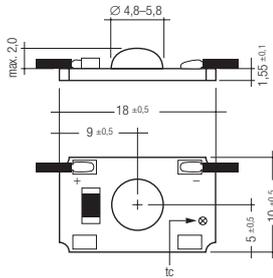
Following pages:

Appendix 4: Tridonic Atco Telex Eos P211-2 RGBA LED datasheet

Appendix 5: Tridonic Atco Telex K350 DALI RGB DALI constant current converter datasheet

TALEXeos P211-2 RGBA
High luminous flux TALEX module – 2nd generation

RoHS



Applications:

- general lighting
- effect and design lighting
- emergency lighting
- spotlights

Highlights:

- high flux TALEX module
- small CCT tolerance band
- compact design
- excellent thermal management ③
- optional accessory: spot lens TALEX(lens O211
- integrated protection against reversed polarity

Properties:

- high-power LED in COB technology
- low thermal resistance $R_{th, j-hs} < 10 K/W$ ③
- 140° light distribution pattern, uniform illumination ④
- fixing: pre-mounted thermal conductive adhesive tape
- connection method: cable 200 mm
- identification of polarity: + red / – black

Notes:

- cooling required. For details please refer to page 2 ③
- none of the components of the TALEXeos module (substrate, LED, electronic components etc.) may be exposed to tensile or compressive stresses
- for further information on installation please refer to the brochure entitled "TALEX installation instructions"

TALEX

type	article number	colour	wavelength nm	light points per module	typ. luminous flux lm ①	luminous intensity cd ④	supply current mA ②	power W ①	ta °C ③	tc °C ③	packing unit
all data for ta = 25 °C, tc = 40 °C, I = 350 mA											
P211-2 R 140°	89600351	red	620–627	1	27	9	350	0.9	-25 → +55	75	20
P211-2 A 140°	89600352	amber	585–592	1	22	8	350	0.9	-25 → +55	75	20
P211-2 G 140°	89600353	green	520–530	1	59	13	350	1.2	-25 → +55	75	20
P211-2 B 140°	89600354	blue	455–465	1	13	2.7	350	1.2	-25 → +55	75	20
all data for ta = 25 °C, tc = 40 °C, I = 700 mA											
P211-2 R 140°	89600351	red	620–627	1	42	15	700	1.8	-25 → +55	75	20
P211-2 A 140°	89600352	amber	585–592	1	38	14	700	1.8	-25 → +55	75	20
P211-2 G 140°	89600353	green	520–530	1	85	22	700	2.4	-25 → +55	75	20
P211-2 B 140°	89600354	blue	455–465	1	21	4.5	700	2.4	-25 → +55	75	20

① Tolerance range for optical and electrical data: ±15 %

② Exceeding the maximum operating current leads to an overload on the TALEXeos module. This may in turn result in a significant reduction in lifetime or even destruction of the TALEXeos module.

③ $R_{th, j-hs}$ = Thermal Resistance (Junction – Heat Sink)
 If the maximum temperature limits are exceeded, the life of the module will be greatly reduced or the module may be damaged. The temperature of the TALEXeos module at the tc point in the thermally stable state by means of a temperature sensor or temperature-sensitive sticker (available for example from www.conrad.com, www.rs-components.com) as per EN60598-1. For the precise position of the tc point see the above diagram. For details please refer to page 2.

④ Typical luminous intensity for 0° central view. For details please refer to page 3.

TALEXeos P211-2 RGBA

Thermal design and heat sink

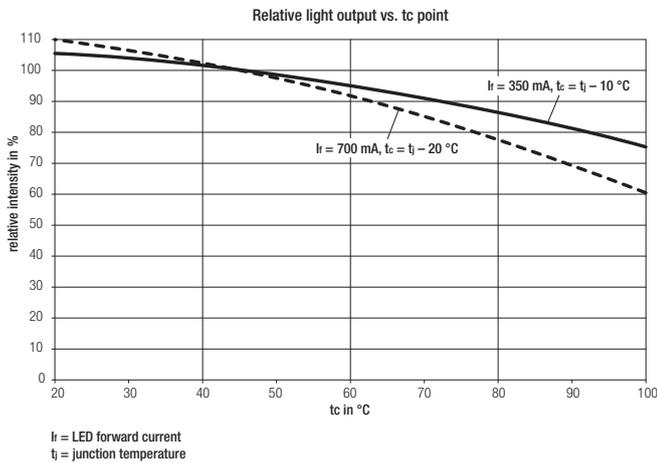
The rated life of TALEX products depends to a large extent on the temperature. If the permissible temperature limits are exceeded, the life of the TALEXeos module will be greatly reduced or the TALEXeos module may be destroyed.

Therefore the TALEXeos P211-2 needs to be mounted onto a heat sink. However, it is allowed to operate the TALEXeos P211-2 without heat sink for a short period of time (30 seconds).

TridonicAtco's excellent thermal design for the TALEXeos products provides the lowest thermal resistance and therefore allowing new compact designs without sacrificing quality, safety and life time.

tc point, ambient temperature ta, temperature and service life

The temperature at tc reference point is crucial for the light output and life time of a TALEX product.



For TALEXeos P211-2 a max. tc temperature of 75 °C is recommended in order to achieve an optimum between heat sink requirements, light output and life time.

Compliance with the maximum permissible reference temperature at the tc point must be checked under operating conditions in a thermally stable state. The maximum value must be determined under worst-case conditions for the relevant application.

Mounting instruction



TALEXeos modules from TridonicAtco which have to be installed on a heat sink are equipped as standard with thermally conductive adhesive tape on the back of the pc board.

These TALEX products must be installed with this adhesive tape. To ensure permanent adhesion the fixing/cooling surface must be cleaned before installing the TALEX modules to remove all dirt, dust and grease.

For further information please refer to the brochure entitled "TALEX installation instructions".

Recommended heat sink surface

P211-2, 350 mA	ta	tc	Rth, hs-a	heat sink surface
red/amber	25 °C	75 °C	40 K/W	17 cm ²
	35 °C	75 °C	32 K/W	21 cm ²
	45 °C	75 °C	23 K/W	29 cm ²
	55 °C	75 °C	14 K/W	47 cm ²
green/blue	25 °C	75 °C	34 K/W	20 cm ²
	35 °C	75 °C	27 K/W	25 cm ²
	45 °C	75 °C	19 K/W	35 cm ²
	55 °C	75 °C	12 K/W	55 cm ²

P211-2, 700 mA	ta	tc	Rth, hs-a	heat sink surface
red/amber	25 °C	75 °C	21 K/W	32 cm ²
	35 °C	75 °C	17 K/W	40 cm ²
	45 °C	75 °C	12 K/W	56 cm ²
	55 °C	75 °C	7 K/W	89 cm ²
green/blue	25 °C	75 °C	16 K/W	42 cm ²
	35 °C	75 °C	13 K/W	53 cm ²
	45 °C	75 °C	9 K/W	73 cm ²
	55 °C	75 °C	6 K/W	118 cm ²

Notes

Values valid for: natural convection, heat sink material: aluminium ≥ 1 mm thick, Rth, hs-a = required thermal resistance of heat sink

Absolute maximum ratings P211-2 *

Parameter	Value
storage temperature, ts	-25 → +80 °C
ambient temperature, ta	-25 → +80 °C
max. reference point temperature, tc	+100 °C
max. junction temperature tj	+125 °C
max. forward current Ir	1000 mA
forward voltage Uf (700 mA)	2,0 → 2,6V red/amber 3,0 → 3,8V green/blue

* it is allowed to operate TALEXeos P211-2 without heat sink only for a short period of time (30 seconds).

Electrical supply/choice of converter

TALEXeos modules from TridonicAtco are not protected against overvoltages, overcurrents, overloads or short-circuit currents. Safe and reliable operation can only be guaranteed in conjunction with a converter which complies with the relevant standards. The use of TALEX converters from TridonicAtco in combination with TALEXeos modules guarantees the necessary protection for safe and reliable operation.

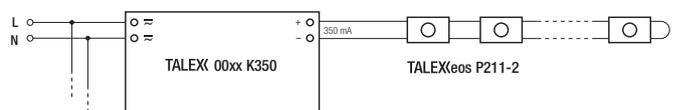
If a converter other than TridonicAtco TALEXconverter is used, it must provide the following protection:

- SELV
- Short-circuit protection
- Overload protection
- Overtemperature protection



TALEXeos P211-2 must be supplied by a constant current converter. Operation with a constant voltage converter will lead to an irreversible damage of the module. The TALEXeos modules P211-2 are protected against reversed polarity.

Wiring example



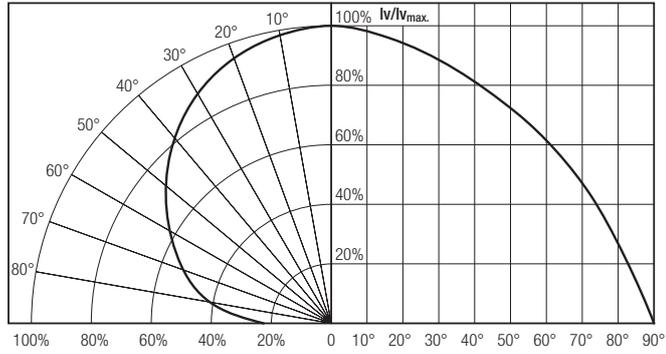
TALEXeos P211-2 must be wired in series connection to the constant current converter TALEXconverter 00xx K350/TALEXconverter 00xx K700.

TALEXeos P211-2 RGBA

Optical characteristics TALEXeos P211-2

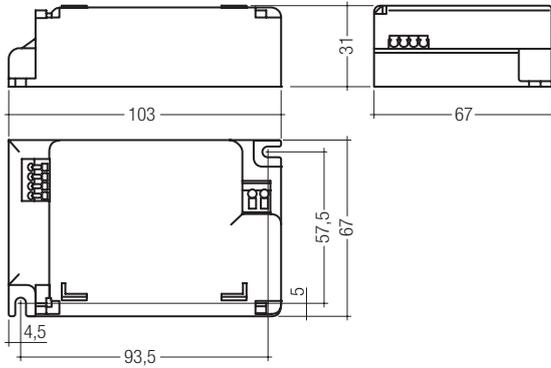
The optical design of the TALEXeos lens system ensures an optimum of homogeneity for the light distribution.

TALEXeos P211-2 140°: Light distribution $I_v/I_{v_{max}}$.



Colour temperature	$I_{v_{max}}$ (cd) 350 mA
red	9.0
amber	8.0
green	13.0
blue	2.7

TALEXconverter 0018 K350 DALI RGB
DALI constant current converter



Highlights:

- 3-channel DALI dimming converter for 350 mA TALEXeos modules
- dimming: 0.1-100 %
- exact load balancing per output channel
- compact housing for luminaire installation
- integrated stand-alone sequencer (default setting: deactivated)
- for programming the free software "TALEX sequence programming software" is available at www.tridonicatco.com

Properties:

- DALI digital control input
- 3 addressable output channels
- 350 mA current-PWM output signal
- overtemperature protection
- suitable for DC supply
- primary connection cable: H03VV-F, H05VV-F, cross section max. 2.5 mm²
- 6-pole ribbon cable terminal secondary, 1 m ribbon cable included in delivery

Packaging:
 box of 20

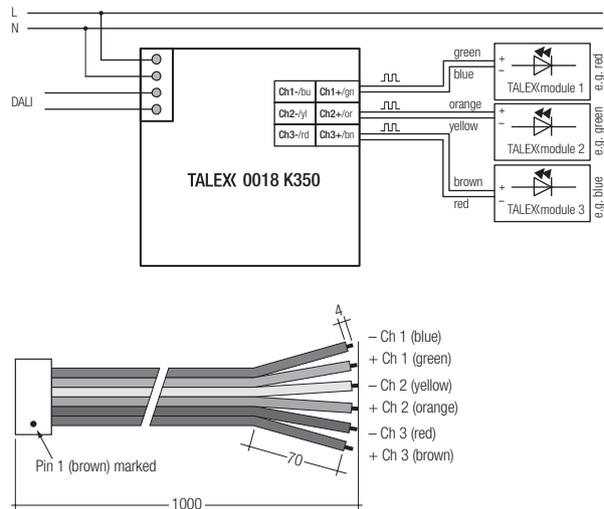
Designed according to:
 EN 55015
 EN 61000-3-2
 EN 61000-3-3
 EN 61347-1
 EN 61347-2-13
 EN 61547
 EN 62384

type		TALEXconverter 0018 K350 DALI RGB
article number		86458276
primary voltage	V _{AC}	230
primary voltage range	V _{AC}	198-254
primary voltage range	V _{DC}	200-240 (160 ①)
frequency	Hz	0/50/60
efficiency	%	> 82
output current	mA	350
PWM frequency	Hz	120
output power	W	18 (max. 5 LED / channel)
max. cable length	m	20
dimming signal	-	DALI
ambient temperature t _a	°C	-20 → +45
max. case temperature t _c	°C	75
weight	kg	0.15
dimensions LxWxH	mm	103x67x31
fixing centres (D)	mm	91.5-95.5

① after power up with higher voltage, the device will work with a reduced voltage as specified above.

Number of TALEXeos modules on TALEXconverter 0018 K350 DALI RGB per channel

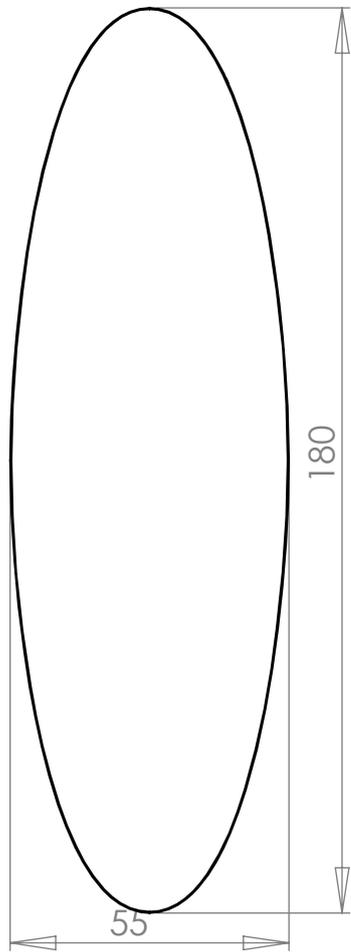
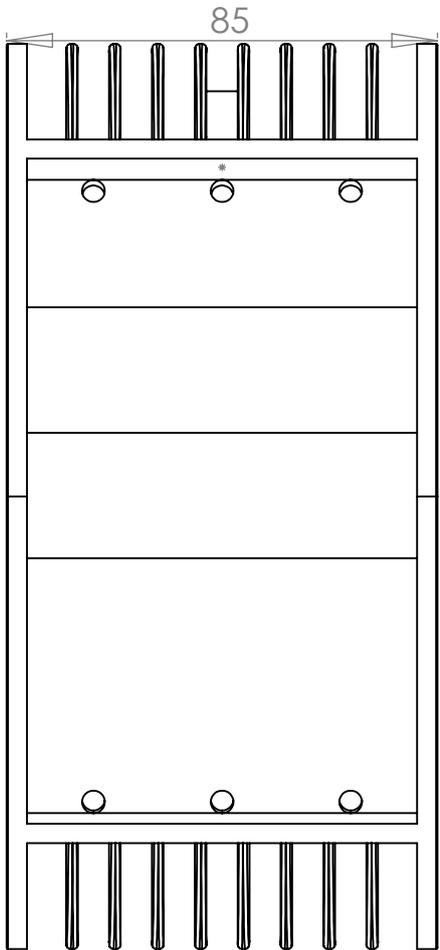
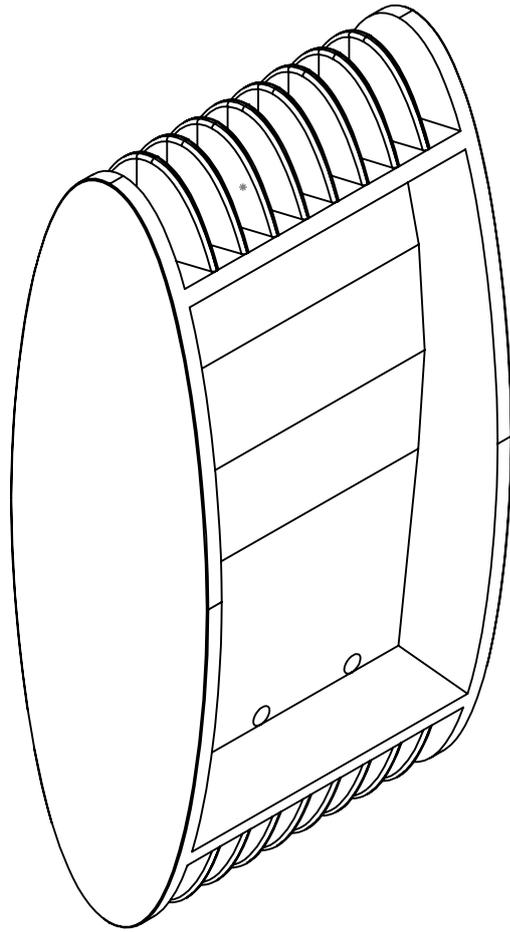
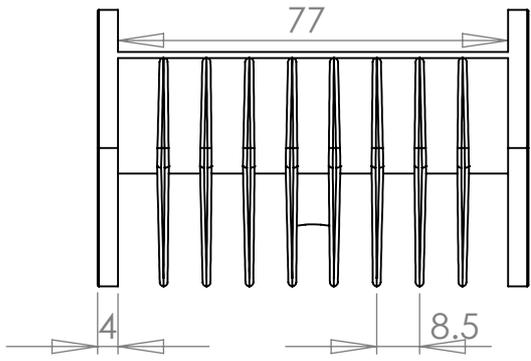
colour	TALEX P211
red,amber	0-5
green, blue,white	0-5



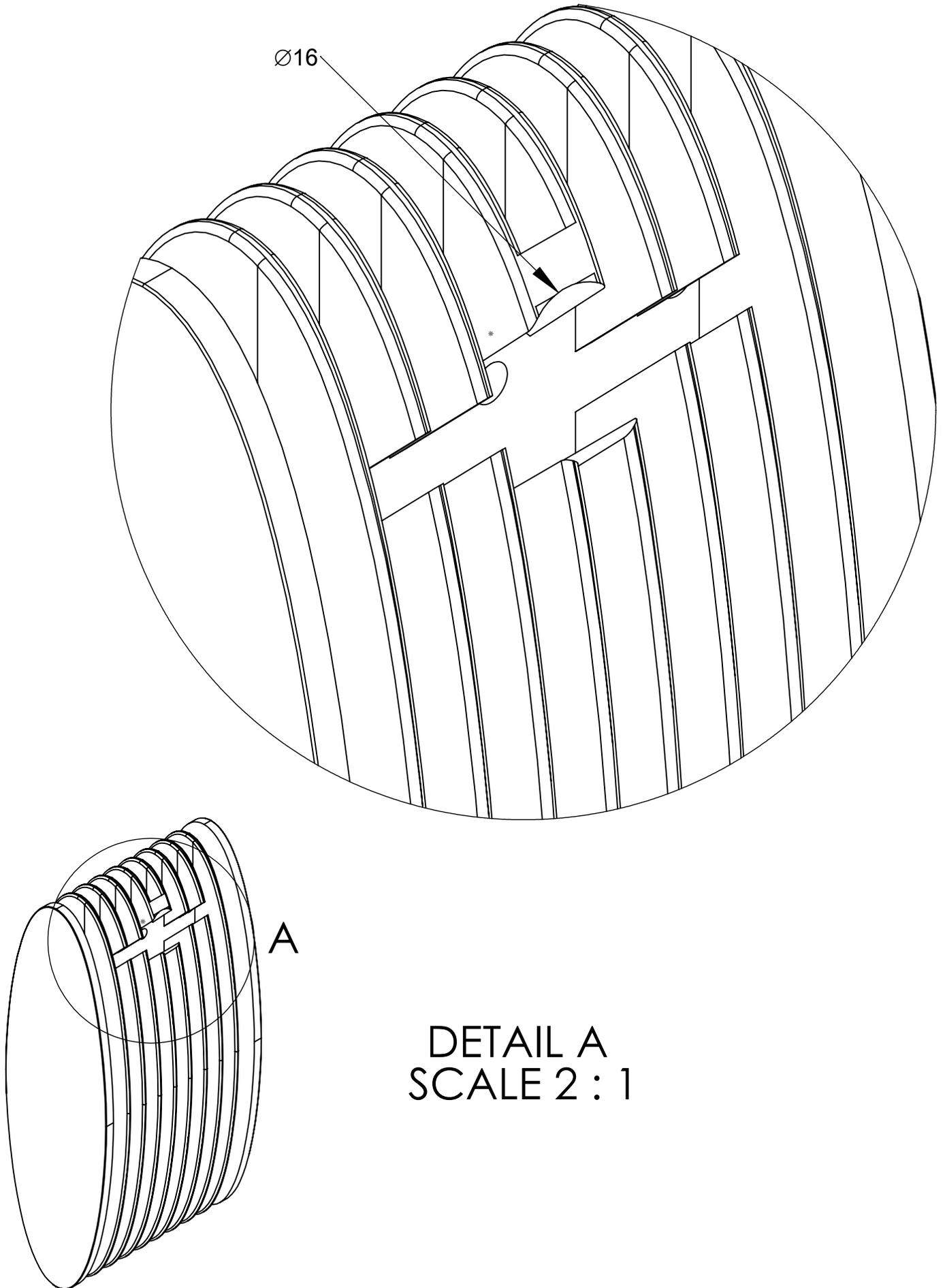
secondary terminals:

ribbon cable (AWG26) with 6 pole multipoint socket connector (DIN41651) included in delivery – plus signal leads can be connected together behind end terminal block.

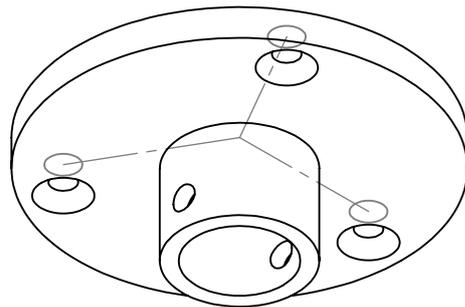
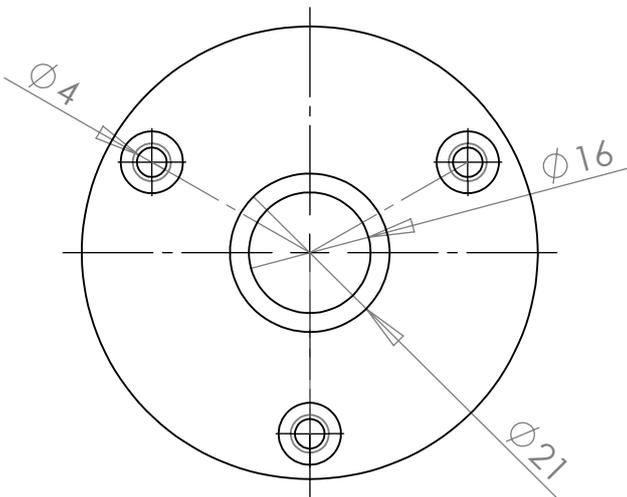
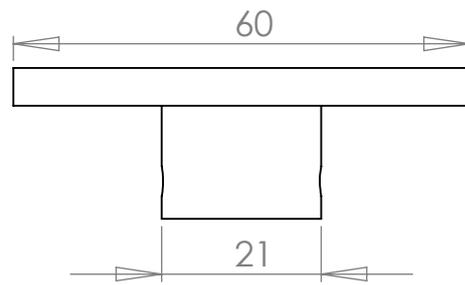
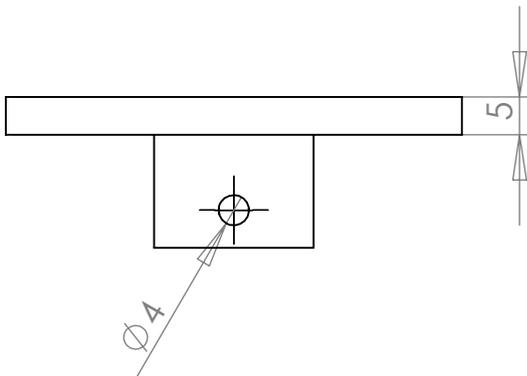
Appendix 6 - Main Body



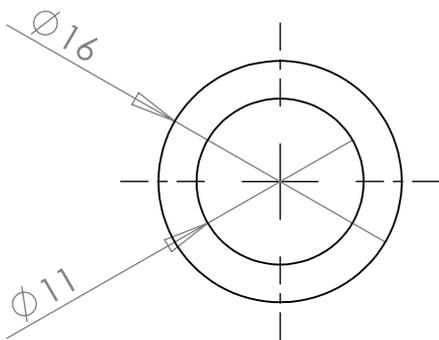
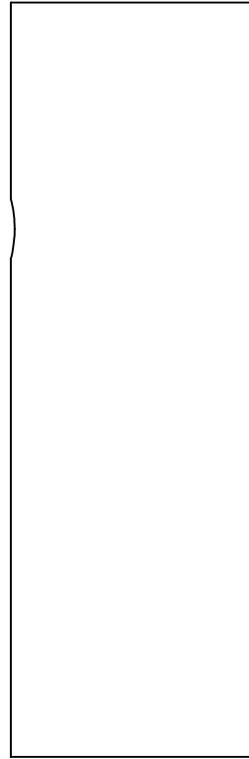
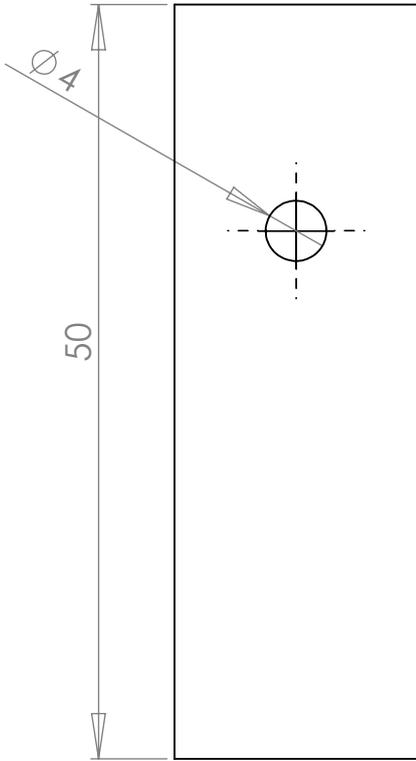
Appendix 7 - Main Body Rear Detail



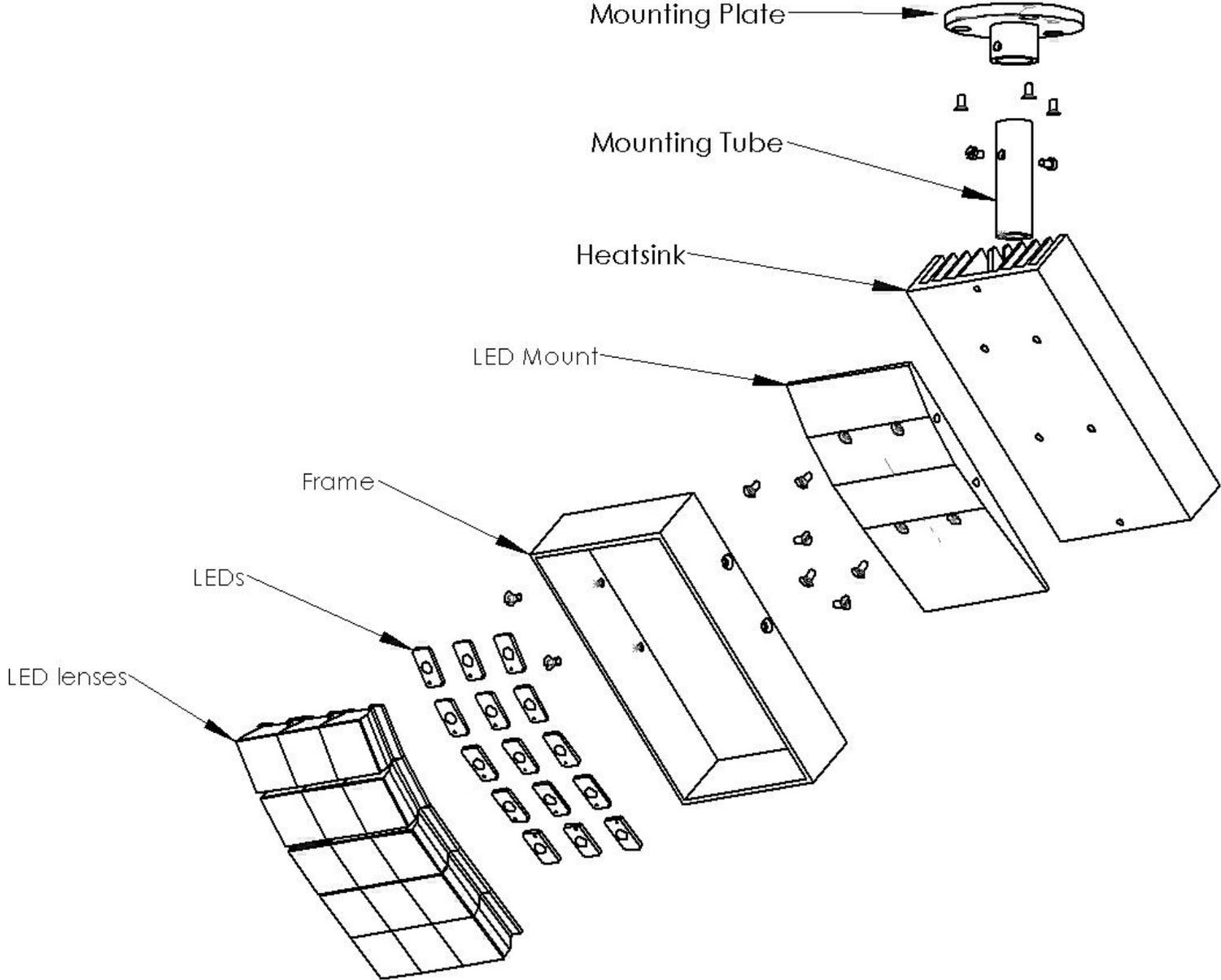
Appendix 8 - Mounting Plate



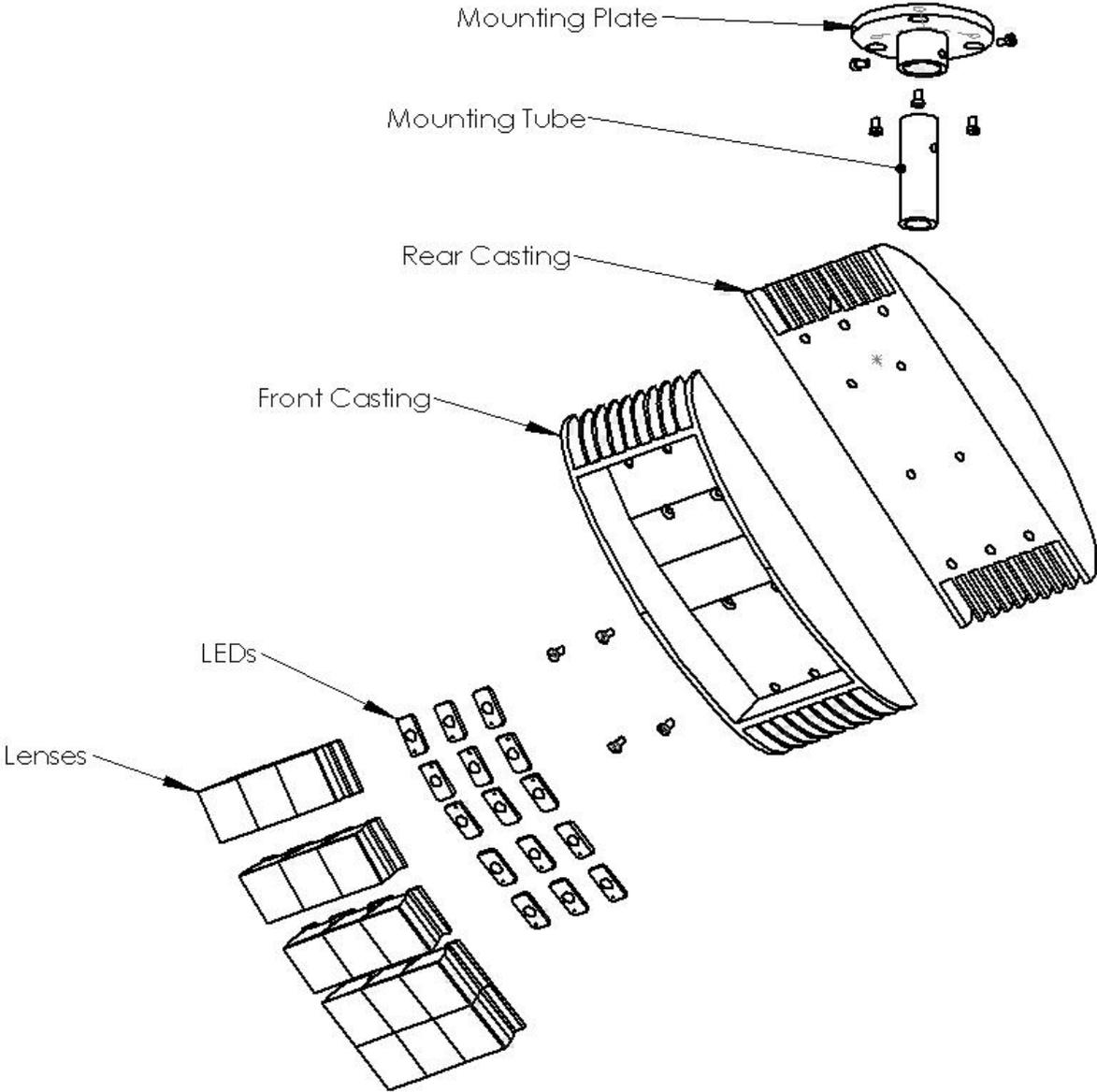
Appendix 9 - Mounting Tube



Appendix 10: Exploded view of extruded production option



Appendix 11: Exploded view of cast production option



Appendix 12: Intensity distribution of competitor products

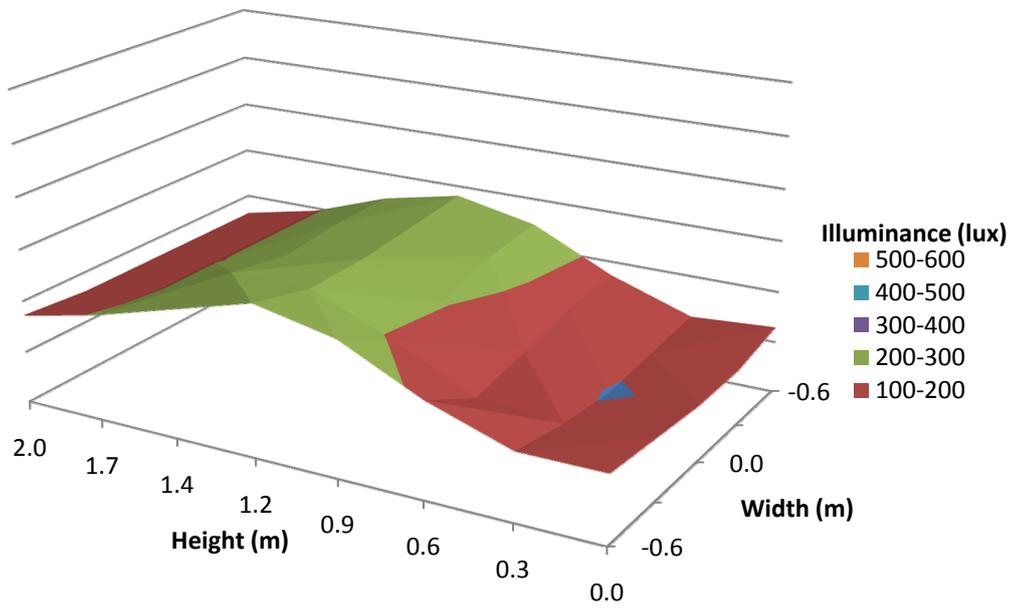


Figure 1 TIR Destiny CW - 1.2m setback, \$2500, 70W

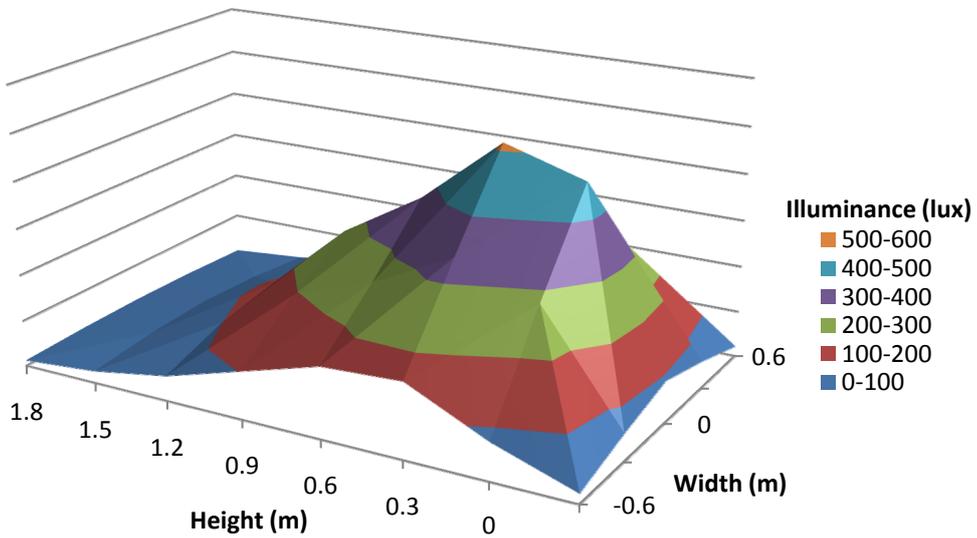


Figure 2 TIR Destiny CG - 1.2m setback, 45° optics, 35W

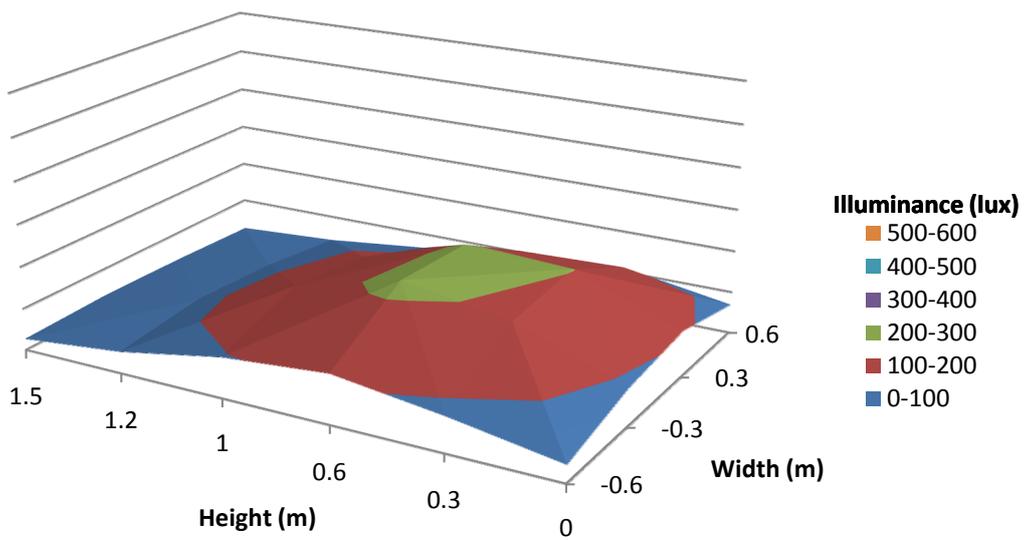


Figure 3 ColorKinetics Colorblast6 - 1m setback, 22° optics, 25W

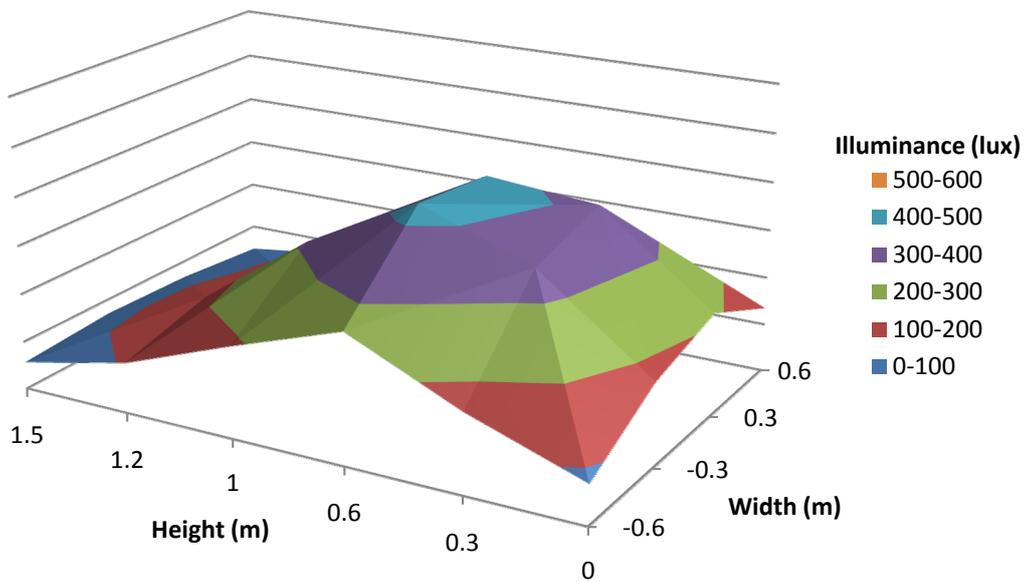


Figure 4 ColorKinetics ColorBlast12 - 1m setback, 23° optics, 50W

GLOSSARY

Chromaticity: the x,y coordinates that give the position of visible light in a chromacity diagram. Chromacity is essentially the colour of the light, regardless of the brightness.

Colour Rendering Index: (CRI) This is a number (from 1 to 100), and is a property of a light source. It describes how well colours are perceived when illuminated by that light source.

Correlated Colour Temperature: measured in Kelvins. The CCT is the temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions. This is used to describe white light in terms of “hot” (reddish) or “cold” (bluish).

Die: The core of an LED, where the p and n regions are located.

Gamut: The range of colours that is achievable by a cluster of LEDs.

Illumination: measured in lux (lx), this is the amount of light incident on a surface.

Luminance: measured in candela per square metre (Cd/m^2), this is the amount of light emanating from a surface.

Luminous Efficacy: measured in lumens per watts. Often called simply “efficacy” or “wall plug efficiency”. This important measurement shows the amount of electrical power that is converted to visible light. It also considers the sensitivity of the human eye to different wavelengths.

Luminous Flux: measured in lumens (lm). This is the total light emitted by a source.

Luminous Intensity: measured in candella (cd). This is the total light emitted by a source that is directed in a particular (useful) solid angle.

Materials: the compounds used in the manufacture of LEDs. Most are aluminium based.

Packaging: the plastic (or other material) encapsulate protecting the LED chip and acting as an optic.

Solid state lighting: refers to the use of both organic and inorganic devices (OLED's and LEDs), when used for illumination as opposed to indication or display. Generally only LEDs are used for this purpose at this time.