Lighting design with LEDs

An investigation of the information that lighting designers require and receive from the LED Supply Chain,
and an empirical study on the implications of lighting design with the use of LEDs.

A thesis submitted to the
Institute for Environmental Design and Engineering (IEDE),
University College London (UCL)
in candidacy for the degree of Doctor of Philosophy

by

PANAGIOTA HATZIEFSTRATIOU

London
2016

I, Panagiota Hatziefstratiou, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Lighting Emitted Diodes (LEDs) are currently being used in advanced lighting designs, mainly in the leisure industry, due to the technological advantages that they offer. Nevertheless, there have been key problems related to the adoption of LEDs in contemporary lighting design schemes. These include the photometry and colorimetry of LEDs, the limited available standards against which to compare and evaluate LEDs, the inadequacy of uniform definitions, and also the lack or inconsistency of data in the LED supply chain. In light of the above, the thesis aims at examining the implications of using LEDs in the illumination of the leisure industry, given the latest technological advancements. To achieve this goal, the thesis defines the Supply Chain of the LED industry. It discusses the flow of information between LED manufacturers, LED module manufacturers, luminaire manufacturers, lighting designers and end users. It analyzes the kind of information that each of these groups expects and receives from the other groups of the Supply Chain, for different kinds of LED applications. The thesis also discusses the importance of data availability to meet different lighting parameters in LED applications. Finally, the thesis notes the necessity for standards that ensure quality, reliable and comparable data. And it also provides guidelines on various issues that need to be taken into account when designing with LEDs.

The thesis adds value to the lighting community by addressing issues not covered by previous research. In fact, it puts the whole “puzzle” of the LED lighting industry together by analyzing its different “pieces”: the market of lighting products, lighting design, standards availability, and end user requirements in the leisure industry. The originality of this research is related to the fact that it discloses the flow of information within the lighting industry and the way that the available knowledge is handled and distributed. The novelty of the thesis is also related to the fact that it reveals how information and data availability influence the adoption of LED technology and the decision making in regard to LED products for different kinds of applications. Through that, the thesis contributes to the lighting community by setting the importance of ‘quality’ lighting parameters when designing with LEDs, and by developing guidelines on how to handle the very fast changing technology of LEDs.

Timetable of thesis

The research started in 2008 and was completed in 2014. In particular, the study of the leisure industry was conducted in 2008. The questionnaire survey was conducted in 2009. The market analysis took place in 2012 and then again at the end of 2013. Similarly, the literature review and research on standards were both conducted late in 2013 (latest standard developments are also presented in Annex 6). Finally, the analysis and discussion were both conducted in 2014. The timeframe of 8 years is significant as the whole LED industry has changed very rapidly during this period. The replies of lighting designers to the questionnaire as presented in Chapter Five, thus may have evolved over time and do not necessarily correspond to the availability of information as presented in the literature review of Chapter One, or to the market research of Chapter Six. Similarly, the analysis and discussion of Chapter Seven was conducted later in the chronologically. To assist the reader more recent developments (in 2014) on the technology of LEDs are presented in the Annexes. In particular, Annex 7 presents the developments in photometry and lifetime, Annex 8 the developments in photometric data, Annex 9 the developments in colorimetry, and Annex 10 the developments in luminaire design. The changes that have taken place from 2008 to 2014 in regard to LED technology are presented in the table that follows.

	Developments of LED technology from 2008 to 2014	
Data/ Year	2008	2014
Definitions	Questions on how to define LEDs, lifetime	Clear definitions
Lumen output (lm)	Up to 500 lm or 2,000lm for COB LEDs, different lumen binning systems	Up to 4,000lm for COB LEDs, easier to compare lumen outputs of different manufacturers
Lumen efficacy (lm/W)	Around 50lm/W	More than 100lm/W
Lifetime (Hrs)	Life of 100,000hrs of operation	Lumen maintenance per 50,000 hours of operation & failure rate (L70B50)
Photometry	Limited data availability with no common standards for measurement and presentation of data	Standards have become available to cover photometric data, which is available by many manufacturers
Colorimetry	Statements on warm/ neutral/ warm white and different colour binning systems	Claims of specific CCTs and MacAdam Ellipses
Luminaire design	Integration of LEDs in architectural lighting fittings for conventional lamps	New designs and product developments
Architectural lighting	Wide use of colours and RGB LEDs	Wide use of white light emitted by LEDs
Standards	Limited number of standards	Increased number of standards and market initiatives

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor Peter Raynham for his continuous support and advice throughout my PhD study and research. His immense knowledge on the field enlightened me with the topic of research and his insightful comments guided me in every moment of the research and writing of the thesis. I would also like to thank him for giving me the opportunity, through the PhD study, to participate in conferences and present part of my work.

My sincere appreciation also goes to my supervisor Dr. Kevin Mansfield for his precious advice and valuable feedback from the beginning of my PhD study to the very end of it. His great experience proved a treasure in completing the writing of the thesis.

I would also like to thank Annabel Brown, Academic Administrative Manager at UCL, for being supportive and extremely helpful throughout the years. Special thanks also go to all three - Peter Raynham, Dr. Kevin Mansfield, and Annabel Brown - for showing a great understanding to the obligations of my parallel role as a working mother of two.

Besides my supervisors, I would like to thank the lighting designers and other individuals that participated in the survey, for their time and effort to complete the Questionnaire. Without their precious contribution it would not be possible to conduct the research.

Last but not least, I would like to thank from the bottom of my hart my father George Hatziefstratiou and my husband Mathios Michelinakis for their endless support and continuous encouragement. Their inspiration and motivation followed my thoughts during the entire period of my PhD study. I would also like to thank my mother Argyro Hatziefstratiou for always being there for me.

To
Iro and Manolis,
my angels

LIST OF FIGURES

LIST OF TABLES

LIST OF PICTURES

Chapter One

Completed by the end of 2013

Literature Review

Chapter One introduces the technology of Light Emitting Diodes (LEDs) and discusses the technological advancements over the years, the latest trends, breakthroughs, and product developments. In addition, Chapter One explains the benefits of LEDs as well as the limitations and problems related to this technology. At the same time, it discusses the available standards and work by technical committees in an effort to establish a common basis in regard to LED definitions, measurements, and marking. In turn, Chapter One defines the LED Supply Chain of the LED industry, and portrays the flow of information between LED manufacturers, LED module manufacturers, LED luminaire manufacturers, lighting designers and end users.

1.1. The technology of LEDs

This section introduces the technology of LEDs and defines LED chips, packages, modules, and luminaires. It also discusses the emission of white light by LEDs.

1.1.1. LEDs, LED Modules, LED Luminaires

A light emitting diode (LED) is a semiconductor device that creates light using solid-state electronics[1]. A "semiconductor"[2] is a material which has electrical conductivity, to a degree between that of a metal (such as copper) and that of an insulator (such as glass). "Solid state electronics"[3] are those circuits or devices build entirely from solid materials and in which the electrons or other charge carriers are confined entirely within the solid material.

In the case of LEDs[4], the conductor material is typically aluminum-gallium-arsenide (AlGaAs), where all of the atoms bond perfectly to their neighbors, leaving no free electrons to conduct electric current. In doped material[5] trace impurity elements such as crystalline (silicon, germanium, etc.) are inserted to alter the electrical or optical properties. Additional atoms change the balance, either by adding free electrons (N- type or cathode) or creating holes (P-type or anode) where electrons can go. Power applied to this p-n junction excites the electrons which are able to recombine with holes within the device, releasing energy in the form of photons. This effect is called electroluminescence[6], and the result is the creation of light[7], as indicated in Figure 1.

[1] http://www3.nd.edu/~leds/how/How.htm 21/7/13
[2] http://en.wikipedia.org/wiki/Semiconductor 21/7/13
[3] https://en.wikipedia.org/wiki/Solid_state_(electronics) 21/7/13
[4] http://electronics.howstuffworks.com/led1.htm 21/7/13
[5] http://en.wikipedia.org/wiki/Dopant 3/10/14
[6] http://en.wikipedia.org/wiki/Light-emitting_diode 21/7/13
[7] http://www3.nd.edu/~leds/how/How.htm 21/7/13

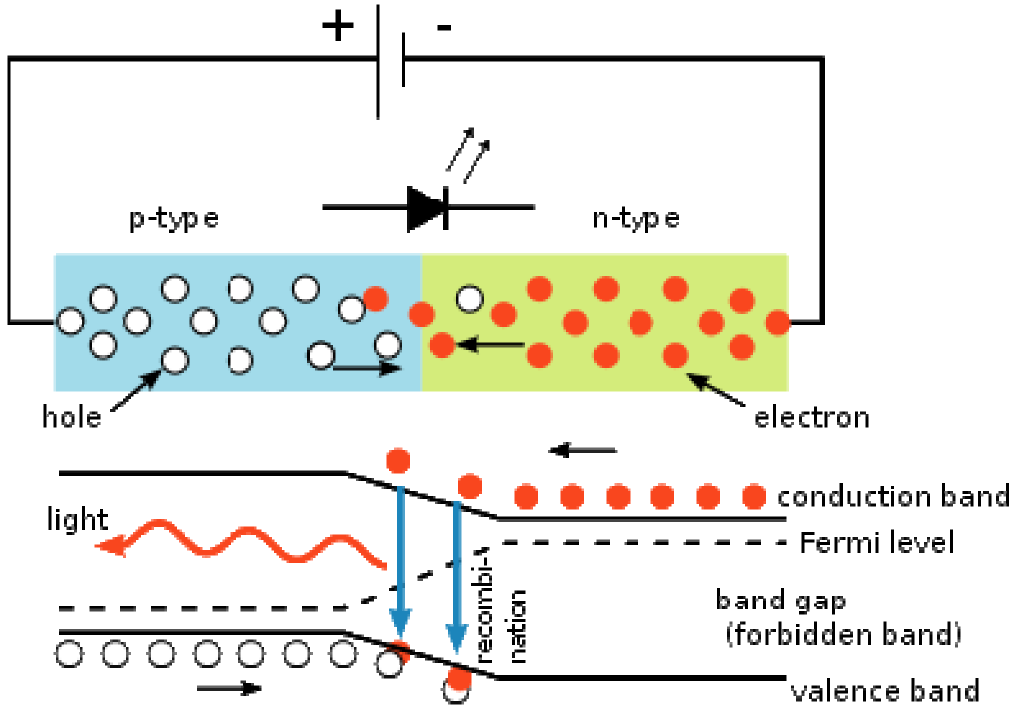

Figure 1.1: Light emitted by LEDs[8]

[8]http://en.wikipedia.org/wiki/Light-emitting_diode 4/10/14

The light produced by LED dies or chips is nearly monochromatic where the colour emitted is dependent upon the material, which is wavelength specific; thus, we see essentially one colour[9]. The terms AlInGaP and InGaN refer to the materials or elements used to create the LED chip. For longer wavelength red, orange or yellow light, combinations of Aluminum (Al), Indium (In), Gallium (Ga) and Phosphorous (P) are typically chosen. For example, Philips Lumileds creates amber with a blue chip and phosphor plates. ButAlInGaP is not the only way to create amber. For shorter wavelength green or blue light, combinations of Indium (In), Gallium (Ga) and Nitrogen (N) are chosen. Examples of LED dies or chips[10] are shown in Figure 1.2.

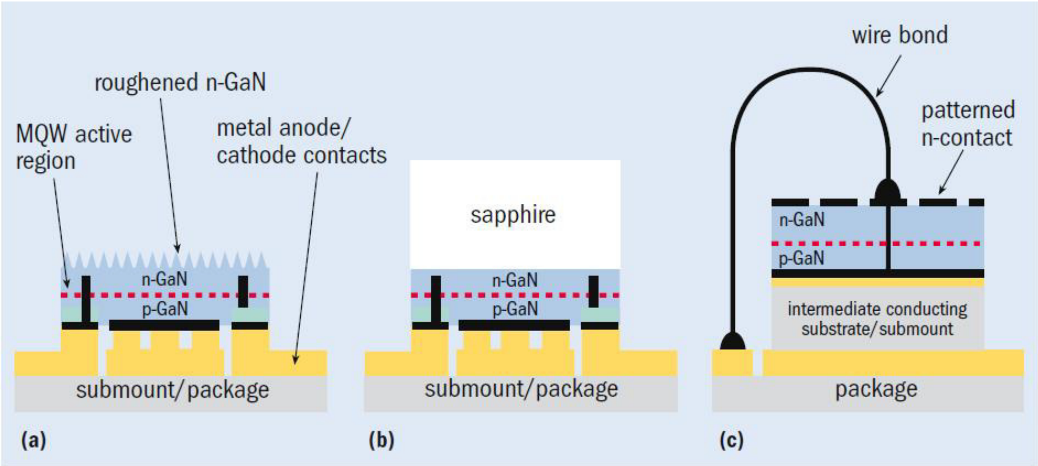

Figure 1.2: Examples of LED Chips, (a) Thin-film-flip chip LED, (b) Flip chip LED, (c) Vertical thin-film chip LED

[9] http://www.hadco.com/Hadco/Upload/Content/downloads/techPapers/Philips_Hadco-Information_Brief_Making_White_Light_with_Blue_LEDs.pdf 4/9/13

[10] DD IEC/PAS 62717:2011,LED modules for general lighting, Performance requirements, p.38

LEDs come in many packages.LED Package is the LED die contained in a suitable package allowing simplified electrical connection or assembly[11]. LED Packages vary from single chip to sophisticated multi-directional aspheric lens designs. Packages may include dies of different size, types, locations, lenses, coloured materials, diffusers and phosphors, all of which can alter the spatial and spectral distribution relative to the basic chip[12]. In addition, the physical characteristics of the materials used to manufacture the chips determine the spectrum of the emitted light, and hence the spectral distribution, the dominant wavelength, the colour etc[13]. Examples of LED Packages[14] are shown inFigure 1.3.

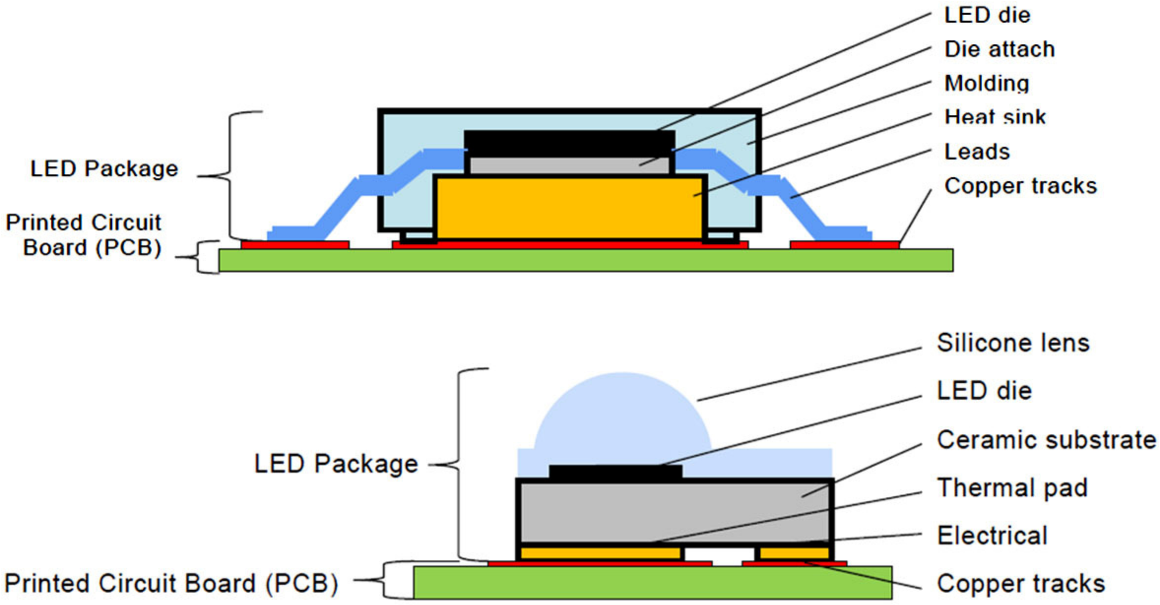

Figure 1.3: LED Packages

[11] Lighting Industry Liaison Group, "A Guide to the Specification of LED Lighting Products 2012", October 2012
[12]YoungRichard, 'LED Measurement Instrumentation', Optronic Laboratories, 2006, p. 3
[13]Instrument Systems, 'Instrument Systems and LEDs: Total measurement solutions', p.6, 2006
[14] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p.39

LED Clusters are composed of many single LEDs and are very small, durable and long lasting, reducing maintenance costs in many applications. They also provide longer lamp life than other sources, they are very energy efficient, and they produce little heat. LED Clusters come in different sizes and shapes. Examples are shown inFigure 1.4.

Figure 1.4: LED Clusters

Some Clusters use LEDs that are constructed in a 5mm diameter, which however are temperature sensitive and suffer from colour variation, low light output and poor lumen maintenance. In turn, High Power LEDs were developed. The large metal “slug” dramatically improves heat transfer characteristics. Also they allow for higher current due to their larger emitting surface, thus they offer higher light output, better thermal management, improved colour control, improved lumen maintenance and luminous efficacy[15]. An example[16] is shown in Figure 1.5.

Figure 1.5: High Power LEDs

[15] www.ies.orgIESNA, ‘The Emergence of LEDs – Luminance to Illumination’, 2006
[16] http://gr.mouser.com/Search/Refine.aspx?Ne=254016&N=1323038+14873455+4292733696 4/10/14

A LED Module is the LED die or chip together with the mechanical and optical components making a replaceable item for use in a luminaire[17]. In addition to one or more LEDs, it may contain further components, e.g. optical, mechanical, electrical and electronic, but excluding the control gear[18]. An example of LED Module is presented in Figure 1.6.

Figure 1.6: Xicato LED module

Modules are classified, according to the method of installation, as built-in, independent, or integral[19].The built-in LED module is generally designed to form a replaceable part built into a luminaire, a box, an enclosure or the like and not intended to be mounted outside a luminaire. The independent LED module is the LED module, designed in such a way that it can be mounted or placed separately from a luminaire, an additional box or enclosure or the like. The integral LED module is the LED module, generally designed to form a non-replaceable part of a luminaire.

LED Modules can be self-ballasted meaning that they are designed for connection to the supply voltage. But usually LED modules run off a low voltage and have to have their current limited. In such cases, electronic control gear is required to operate LEDs. Electronic control gear[20]is the unit inserted between the supply and one or more LED modules which serves to supply the LED module(s) with its (their) rated voltage or rated current. The unit may consist of

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[17] Lighting Industry Liaison Group, "A Guide /to the Specification of LED Lighting Products 2012", October 2012
[18]BS EN 62031: 2008 LED Modules for General Lighting- Safety Specifications, page 6
[19] BS EN 62031: 2008 LED Modules for General Lighting- Safety Specifications, page 7,8
[20] BS EN 61347-2-13:2006, Lamp controlgear, Particular requirements for d.c. or a.c. supplied electronic controlgear for LED modules, p. 10

one or more separate components and may include means for dimming, correcting the power factor and suppressing radio interference.

LED modules are distinguished according to their control gear as LED modules with integral control gear, LED modules with means of control on board but with separate control gear ("semi-ballasted"), and LED modules with complete external control gear[21].Figure 1.7 shows the types of LED Modules based on their control[22].

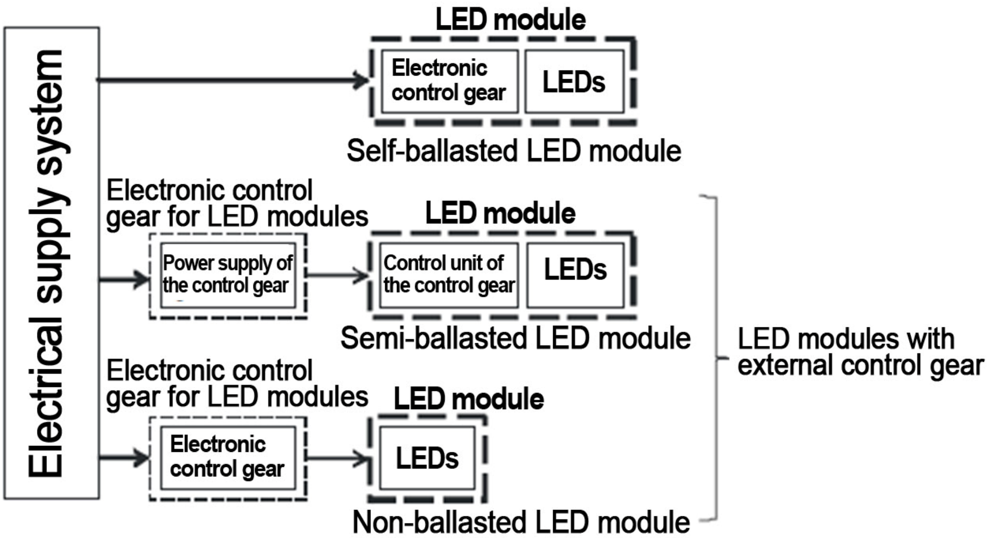

Figure 1.7: Types of LED Modules according to the method of control

LED Luminaires[23] incorporate LED light sources, LED lamps or LED modules. LED Luminaires also incorporate[24] optical systems which can be composed of reflectors, lenses and diffusers. They also incorporate cooling systems which control the operating temperature of the LED and the printed circuit board (PCB) which is the interface between a LED and the heat-sink. Cooling systems control heat dissipation from luminaires, hence the efficiency of the system and its performance characteristics.

[21] DD IEC/PAS 62717:2011,LED modules for general lighting, Performance requirements, p. 6
[22] DD IEC/PAS 62717:2011,LED modules for general lighting, Performance requirements, p. 7
[23] DD IEC/PAS 62722-2-1: 2011, Luminaire performance, Particular requirements for LED luminaires, p.7
[24] Lighting Industry Liaison Group, "A Guide to the Specification of LED Lighting Products 2012", October 2012

The better the electronics of LED luminaires, the better the protection to minimize damage at installation or on power-up of the luminaires. In relation to that, special attention needs to be given to the external control gear which is selected, as this affects the total life and failure rate of LED luminaires. Equally important is the mechanical integrity of LED luminaires, including the positioning and vibration resistance of the heat sink, the IP rating, the need for maintenance and so on.

Over the last couple of years, a great number of companies have been established, specializing in LEDs. Also, many existing LED companies have been acquired by traditional lighting manufacturers. The result is the wide variety of LED luminaires available in the market that covers almost all lighting applications. Examples of LED luminaires are presented in Figure 1.8.

Figure 1.8: LED Luminaires

1.1.2White light from LEDs

LEDs became available in the 1960s. At that time, LEDs were used primarily in applications such as stop lights on automobiles, indicator lights, traffic lights, display screens, and exit signs. However, nowadays, the term LED die or LED chip is used to describe the fundamental light source[25].

LED structures have rapidly developed over the years and their efficiency and light output have exponentially increased. This is attributed to the parallel development of high-brightness LEDs as well as advances in optics and materials[26]. Given that, LEDs have developed from a glowing indicator lamp to an important light source. As the technology improved, LEDs are now being used in decorative, landscape, road light, marine, emergency, and architectural lighting applications.

White light emitted by LEDs was an important step. White light from LEDs can be made with RGB LEDs[27]. White light can also be made with a blue LED and a phosphor[28].Figure 1.9[29] shows the yellow-based phosphor applied over the blue chip.The yellow phosphor over the blue LED[30] produces cool white light.

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[25] Lighting Industry Liaison Group, "A Guide to the Specification of LED Lighting Products 2012", October 2012

[26]Dadgar, A.; Poschenrieder, M.; BläSing, J.; Fehse, K.; Diez, A.; Krost, A. "Thick, crack-free blue light-emitting diodes on Si(111) using low-temperature AlN interlayers and in situ Si\sub x]N\sub y] masking". Applied Physics Letters 80 (20): 3670, 2002

[27]http://en.wikipedia.org/wiki/RGB_color_model 4/9/13

[28]Ohno Yoshi, 'Optical metrology for LEDs and solid state lighting', National Institute of Standards and Technology, USA, p. 12, 2006

[29]http://www.hadco.com/Hadco/Upload/Content/downloads/techPapers/Philips_Hadco-Information_Brief_Making_White_Light_with_Blue_LEDs.pdf 4/9/13

[30]http://www.hadco.com/Hadco/Upload/Content/downloads/techPapers/Philips_Hadco-Information_Brief_Making_White_Light_with_Blue_LEDs.pdf 4/9/13

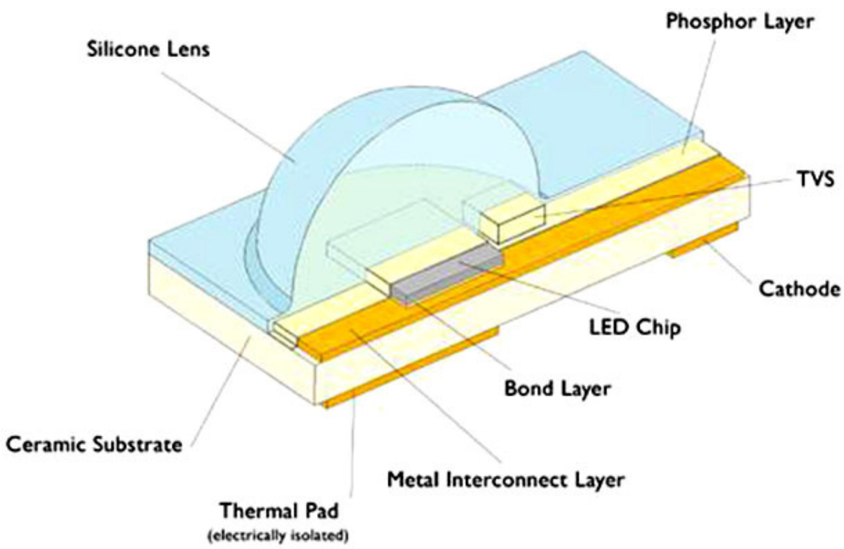

Figure 1.9: Yellow- based phosphor over blue LED chip

The combination of colours makes use of a phenomenon known as metamerism[31] which occurs when our eyes and brain perceive two different but complementary colours as "mixing" to "create" a third complementary colour, which we see as cool white light. If we add red phosphor, the light is down-converted further to warm white light. Figure 1.10presents this on the CIE 1931 Chromaticity Diagram.

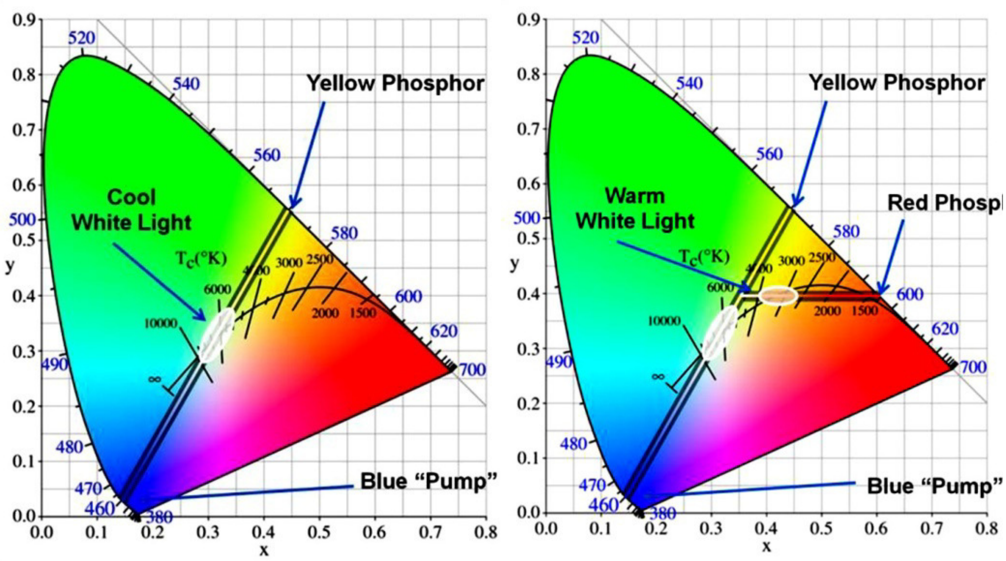

Figure 1.10: Cool and Warm White Light created with phosphors and LEDs

[31] The IES Nomenclature Committee and American National Standards Institute, Nomenclature and Definitions for Illuminating Engineering, ANSI / IES RP-16-10, New York: Illuminating Engineering Society of North America, 2010

Heat degrades phosphor. As the phosphor degrades at different rates in different LEDs the colours of the LEDs in an installation become different. For this reason, companies us the remote phosphor approach, where the phosphor is actually isolated from the actual LED die, keeping it cool throughout the entire life of the module. By keeping the phosphor isolated and cool, colour consistency is maintained over the life of the module[32].Figure 1.11 shows the remote phosphor design used by Xicato.

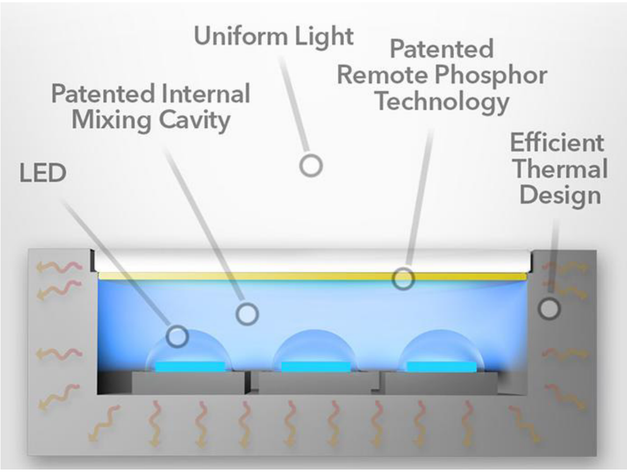

Figure 1.11: White light emitted by LEDs by isolating the phosphor

1.2.Advantages of LEDs

LEDs have developed from a glowing indicator lamp to an important light source. Indeed, LEDs are currently being used in many different applications due to the advantages they offer.

In particular, LEDs are very small in size which makes them ideal for applications where hiding the source is essential or for concealed lighting. Alternatively, the small size of LEDs enables the creation of a variety of luminaire designs. In addition, LEDs are durable and long lasting, providing longer lamp life than other sources. Moreover, LEDs can be energy efficient, thus they may offer energy saving, low power consumption, and reduced maintenance costs in many applications. Thus, LEDs establish a sustainable environment, with a long lifetime.

[32]http://xicato.com/technology/corrected-cold-phosphor-technology® 4/9/13

LEDs produce little heat and no UV / Infrared emissions which makes them suitable for illuminating fragile art works. They are vibration resistant due to the fact that they have no filament and are small size; they also allow cold temperature operation. In general, LEDs have low operating voltage which makes them safer to use, they have low operating temperature and silent operation.

In addition, LEDs are offered in a vast variety of models and are very flexible, allowing lighting designers to use them in a variety of applications. LEDs offer dimming capabilities and allow control of colours and dynamic colour changes, creating different lighting scenes.

1.2. Key issues with LEDs

This section discusses the key issues related to LED technology.

1.3.1. Standards

When LED technology was first developed, there were no guidelines on how to develop LED data, and no standards against which to evaluate and compare LED products. The lack of standards was mainly noted in regard to the photometry and colorimetry of LEDs. This resulted in manufacturers providing different kinds of information for different products. Also, manufacturers often claimed their LED efficacy, life expectancy, and light output based on the testing lab performance of the LED source, not its real-world performance in a complete lighting system[33].

At that time, a prime concern of the LED measurement industry was the high levels of uncertainties and inconsistencies found in measurement results[34]. Moreover, new developments in instrument design opened up new methods of measurement, while new LED structures required some product specific

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[33]Miller L Stephani, The LED Evolution, Architectural Lighting Magazine, 2007http://www.archlighting.com/industry-news.asp?sectionID=1350&articleID=587492. 6/5/09

[34]Optronics, Application Note A16, 2006 http://www.olinet.com/content/library/1223922794A16_ELIMINATING-LED-MEASUREMENT-ERRORS_12-01.pdf. 24/5/09

measurements[35]. Given that, the results from LED measurements needto be compared with the results obtained from the measurement of conventional light sources[36].

The question was to define standards that apply to the testing and measurement of LED modules and LED luminaires, because there was a disconnection between the results produced by LED die manufacturers and the results produced by the LED luminaire manufacturers, because various issues such as thermal management can change the actual performance[37]. Not only that, but changes in LED dies and LED modules have an impact on the luminaire standards and vice versa, due to the behaviour of LEDs. Therefore, a close collaboration of experts on these categories of products was essential to develop performance standards[38].

Following that, research on LED measurements was undertaken at many National Metrology Institutes[39]. The Commission International de L'Eclairage (CIE) maintains an interest in all areas of light measurement, and published the recommended measurement of single LEDs, as described in CIE Publication 127: 1997 Measurement of LEDs[40].

Over the years, many standards have been published, including:

- BS EN 62560 2012: Self- ballasted LED- lamps for general lighting services by voltage >50V- Safety specifications
- DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services- Performance requirements
- BS EN 61347-2-13: 2006 Lamp control gear- Part 2-13: Particular requirements for d.c. or a.c. supplied electronic control gear for LED modules

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[35]CIE Commission Internationale de l'Éclairage. *Measurement of LEDs*. CIE 127:1997, p.1
[36]Krochmann.(2006). Radiometric and Photometric Measuring Systems for LEDs.http://www.prc-krochmann.de/files/Datenbl/Eng/LED_eng.pdf. 7/5/09
[37] 'A Guide to the Specification of LED Lighting Products 2012, Lighting Industry Liaison Group, October 2012
[38] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 6
[39]Godo K., Saito T., Shitomi H., Zama T., and Saito I, *Development of a total luminous flux measurement facility for LEDs at the National Metrology Institute of Japan*, NMIJ/AIST 1-1-4, JAPAN, 2006
[40]http://www.cie.co.at/index.php?i_ca_id=402 8/5/09

- BS EN 62384: 2006+A1: 2009 DC or AC Supplied Electronic Control Gear for LED modules- Performance Requirements
- BS EN 62031: 2008, LED Modules for General Lighting- Safety Specifications
- DD IEC/PAS 62717:2011 LED modules for general lighting- Performance Requirements
- BS EN 60598: 1998 Luminaires Part 1: General Requirements and tests
- DD IEC/PAS 62722-2-1: 2011 Luminaire Performance Part 2-1: Particular Requirements for LED luminaires

At the same time, CIE Technical Committees have been working on the following topics[41].

- TC2-46 CIE/ISO standards on LED intensity measurements
- TC2-50 Measurement of the optical properties of LED clusters and arrays, with the purpose of producing a technical report for the measurement of optical properties of LED assemblies.
- TC2-58 Measurement of the LED radiance and luminance
- TC2-63 Optical measurement of High- Power LEDs, with the purpose of developing a CIE recommendation on methods for the operation of high-power LEDs in DC and in pulse mode, at specified junction temperatures, for optical measurements.
- TC2-64 High speed testing methods for LEDs, with the purpose of preparing a technical report on high speed testing methods for electrical, thermal and optical quantities during the production of LEDs and the conversion of the values to DC operational conditions including the related time dependent functions.

1.3.2. Light emitting diodes

When LEDs were first developed, there was no clear definition of the term "LEDs". LEDs are semi-conductor devices or chips that produce light when an electrical current is applied. Nevertheless, for LEDs to operate, a driver (power supply) and a thermal management system are also required[42]. Therefore, the lighting community had to define what an LED is: a lamp, a luminaire or a

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[41] http://www.cie.co.at/index.php/Technical+Committees, 4/7/13
[42] Philips. (2008). Think LED lighting is complicated? Think again'. www.sll-pocket.indd, 23/5/09

system? Lately, LED dies, LED modules, and LED luminaires have been well distinguished and defined (see 1.1.1).

1.3.3. Light output and Lifetime

Most conventional light sources fail (stop giving out any light at all) after they have been in service for a given time. However, in most cases the light output has only dropped off by 10 or 20% at the time when they fail. LEDs have very long lives and may have lost over 90% of their light output before they fail. Clearly this is not a useful definition of life and so we have to use a definition of life based on lumen depreciation.

Lumen depreciation is the length of time during which a complete LED luminaire or LED lamp[43] provides more than a percentage of the rated luminous flux under standard test conditions. The maintained luminous flux is measured at 25% of rated life time up to a maximum of 6,000 hours. From the measured value the output reduction with time can be extrapolated and expressed as a percentage of the initial value. The maintained value determines the lumen maintenance code. There are three lumen maintenance codes compared to the initial lumen output[44], as indicated in Table 1.1.

Lumen maintenance %	Code
>= 90	9
>= 80	8
>= 70	7

Table 1.1: Categories of lumen maintenance codes

Table 1.1shows that lumen depreciation is the rate and percentage of light loss which is measured as follows: when the light output is greater than 90% of the initial, then the lumen maintenance code is Code 9; when the light output is greater than 80% of the initial, then the lumen maintenance code is Code 8; and when the light output is greater than 70% of the initial, then the lumen maintenance code is Code 7[45].

[43] DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services- Performance requirements, p. 6
[44] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 20
[45] Lighting Industry Liaison Group, “A Guide to the Specification of LED Lighting Products 2012”, October 2012

Accelerated test methods for projecting measurement data beyond limited test time is currently under consideration. In practice, however, leading LED manufacturers test their products for 6,000 hours and then apply extrapolation methodologies and statistical predictions to arrive to lumen maintenance figures, as indicated inFigure 1.12[46].

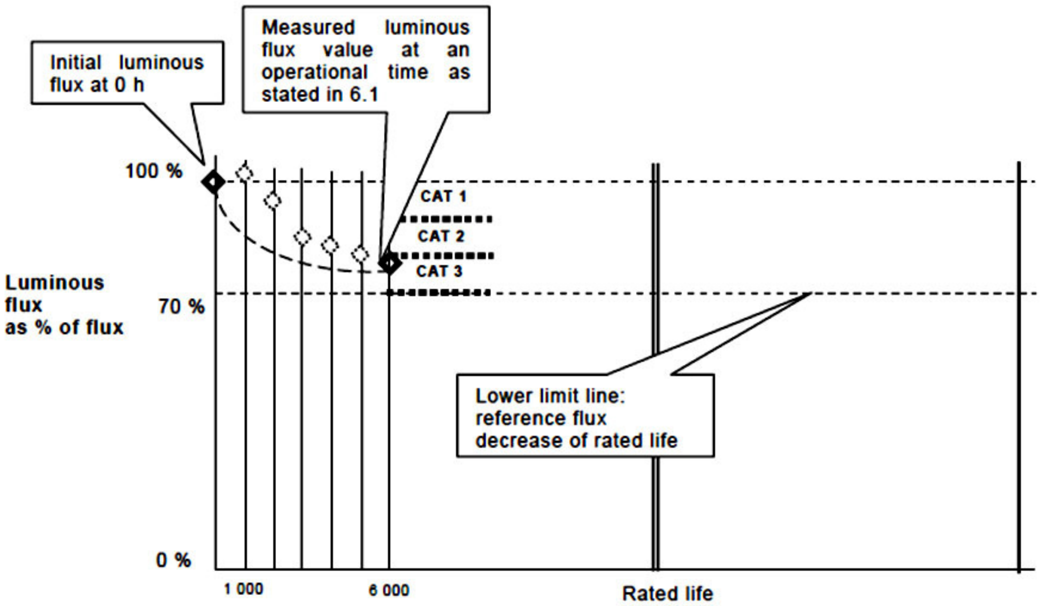

Figure 1.12: Luminous flux depreciation over test time

Lumen maintenance is used to express the length of time during which a complete LED-lamp provides more than 50% or 70% alternatively of the rated luminous flux, under standard test conditions. The LED has reached its end of life when it no longer provides 50% or 70% of the rated luminous flux. It is suggested that for illuminating luminaires the percentage should be greater than 80% indicated as L80, whereas for direct view luminaires the percentage should be greater than 50% indicated as L50[47].

In light of the above, 'lumen maintenance categories' have been defined[48] to express the initial decrease in lumen until 25 % of rated lamp life has elapsed with a maximum duration of 6,000 hours. Depending on the life definition (L50 or

[46] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 22
[47] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p.8
[48]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p.10

L70), there are five (in case of L50) or three (in case of L70) categories each covering an additional 10% of lumen maintenance compared to the initial lumen output at 0 hour, as indicated in Table 1.2.

Luminous flux decrease at 6 000 h as % of 0 h value	Δ φ category
Measured flux decreased by no more than 10 % of rated flux	Cat A
Measured flux decreased by no more than 20 % of rated flux	Cat B
Measured flux decreased by no more than 30 % of rated flux	Cat C
Measured flux decreased by no more than 40 % of rated flux	Cat D
Measured flux decreased by no more than 50 % of rated flux	Cat E

Table 1.2: Categories of lumen maintenance after 6000 hours of operation

Life is published in combination with the failure rate[49], which is the percentage of a number of tested lamps of the same type that have reached the end of their individual lives. More specifically, if the rated life of a product is 50,000 hours and the light loss is L70, then the physical failures are Fx (where x is the percentage number of failures) at the rated life of 50,000 hours. In other words, a value of L70 F10 means that 10% of the lamps have failed when the point of 70% lumen maintenance has been achieved[50]. Note that it should be assumed that the manufacturer has tested to a maximum of 6,000 hours and extrapolated beyond that- unless they explicitly state differently[51]. For self-ballasted LED lamps the failure rate is expressed as a rate of 10% (F10) or 50% (F50).

Failure is further distinguished in two types according to their light output behavior. According to DD IEC/PAS 62717:2011[52], Gradual failure fraction (*B*y) is the percentage y of a number of LED modules of the same type that, at their rated life, designates the percentage (fraction) of failures. This failure fraction expresses only the gradual light output degradation. Abrupt failure fraction (*C*y) is the percentage y of a number of LED modules of the same type that, at their rated life, designates the percentage (fraction) of failures. This failure fraction expresses only the abrupt light output degradation.

[49]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services- Performance requirements, p. 7
[50] IES LM-80-08 Approved Method: Measuring Lumen Maintenance of LED- Light0 Sources- Illuminating Engineering Society of North America, 2008
[51] Lighting Industry Liaison Group, “A Guide to the Specification of LED Lighting Products 2012”, October 2012
[52] DD IEC/PAS 62722-2-1: 2011, Luminaire performance, Particular requirements for LED luminaires, p.15

For purpose of distinctness and comparability, it is recommended to limit the use of possiblevalues for x and y in *L*x*B*y, *L*x*C*y and *L*x*F*y to define life time metrics, as indicated inTable 1.3[53].

	LxBy						**LxCy**		**LxFy**					
x	70		80		90		0		70		80		90	
y	10	50	10	50	10	50	10	50	10	50	10	50	10	50

Table 1.3: Recommended x and y values for life time metrics to be used in life time specification

LED luminaire manufacturers need to take into consideration catastrophic failures of individual LEDs[54] and other failure modes of light output depreciation related to the electronics, the cooling system, the mechanics, and the optics[55]. Finally, manufacturers should remember that there is no validated way to translate the lumen maintenance curve of an individual LED into a curve for a LED luminaire.

1.3.4. Photometry

In regard to the photometry of LEDs, the initial and maintained luminous flux shall be measured after stabilization of the LED module.Research has indicated that different LED clusters achieve stability after different lengths of time[56]. Thus, it is important to make light output measurements of the LED luminaire, and not just the single LED, only after stability has been achieved.

Luminous intensity distribution shall be measured[57] in accordance with CIE 127, IEC/TR 61341, and other related standards. The intensity of light emitted from the LED module in different directions is measured using a goniophotometer. In IEC/ PAS 62717 it says that luminous intensity distribution data shall be

[53] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 33
[54]BS EN 62560: 2012, Self ballasted LED lamps for general lighting services by voltage >50V- Safety specifications, p. 11
[55] Lighting Industry Liaison Group, “A Guide to the Specification of LED Lighting Products 2012”, October 2012
[56]Hatziefstratiou, P.*Photometry and colorimetry of LED Clusters,* UCL, UK, 2005
[57] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements

available for all variations of the LED module and any optical attachments or accessories that the LED module has been specified for use with.

1.3.5. Efficacy

Efficacy of a lighting fixture is the amount of light (lumens) produced by a certain amount of electricity (watts). In IEC/ PAS 62717 it says that LED module efficacy shall be calculated from the measured initial luminous flux of the individual LED module divided by the measured initial input power of the same individual LED module[58].

For luminaire efficacy, it is also important to consider factors that affect the entire LED system and not only the individual LED source. For example, losses in luminaire performance are associated with operating temperature, driver, housing, optical systems, reflectors, and lenses.

The ratio of lumens leaving a fixture to the total flux produced by the light source is the light output ratio (LOR).

1. 3.6.CCT

Correlated Colour Temperature (CCT) is described as the colour impression of a black body radiator at certain temperatures. The higher the colour temperature, the cooler the impression of white light becomes. Colour temperature is expressed in Kelvin.

Colour temperature of LEDs[59]is defined by the initial colour temperature value and the rated colour temperature, usually one of the following six values: 2.700K, 3.000K, 3.500K, 4.000K, 5.000K or 6.500K.For reference purposes, the standardized chromaticity co-ordinates corresponding to these CCT values are given in Table 1.4(IEC 60081, Clause D.2, modified)[60].

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[58] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements

[59]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p. 9, 10

[60]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p.9, 10

ColourIndication	CCT	X	y
F 6500	6400	0,313	0,337
F 5000	5000	0,346	0,359
F 4000	4040	0,380	0,380
F 3500	3450	0,409	0,394
F 3000	2940	0,440	0,403
F 2700	2720	0,463	0,420

Table 1.4: Correlated color temperatures and chromaticity coordinates

The initial CCT of a LED lamp is measured as the value after an operation time of 25% of rated lamp life (with a maximum duration of 6,000 hours). The measured actual CCT values (both initial and at 25% of rated lamp life with a maximum duration of 6,000 hours) are expressed as fitting within one of 8 categories, as indicated in Table 1.5.

MacAdams ellipse type	CCT category
All measured CCT's within a 1-step	ellipse Cat 1
All measured CCT's within a 2-step	ellipse Cat 2
All measured CCT's within a 3-step	ellipse Cat 3
All measured CCT's within a 4-step	ellipse Cat 4
All measured CCT's within a 5-step	ellipse Cat 5
All measured CCT's within a 6 step	ellipse Cat 6
All measured CCT's within a 7 step	ellipse Cat 7
All measured CCT's not within a 8 step	ellipse Cat 8

Table 1.5: Tolerance categories on nominal CCT values

The categories indicated in Table 1.5correspond to a particular MacAdam ellipse around the rated CCT value. The MacAdam ellipse defines a zone in the CIE 1931 chromaticity diagram where the human eye cannot discern colour difference[61]. The size of the ellipse (expressed in n-steps) is a measure for the tolerance/deviation of an individual lamp and LED module[62], because the contour of the ellipse represents the just noticeable differences of the chromaticity. Table 1.6shows that colour is defined as within a 1-step, 3-step, 5-step, 7-step ellipse and greater than a 7-step ellipse.

[61] http://www.photometrictesting.co.uk/File/blog_LED_colour_difference.php 4/10/14
[62] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 19

Size of MacAdam ellipse, centered on the rated colour target	Colour variation category	
	Initial	Maintained
3-step	3	3
5-step	5	5
7-step	7	7
>7- step ellipse	7+	7+

Table 1.6: Tolerance categories on rated chromaticity co-ordinate values

1.3.7. RGB LEDs

The research shows that no standards have been published to define a uniform system for colour measurements of RGB LEDs. Also, no standards have been published to define white light using RGB mixing at full power, or a uniform binning structure against which comparisons will be made[63].

When RGB LEDs operate at full power, the colour point of the source varies with angle. In fact, the colour changes with position in the beam, because the separate colours of RGB clusters do not always have identical photometric distributions.The chromaticity coordinates can be depicted on the CIE Chromaticity Diagram, as indicated in Figure 1.13, in order to define the colour of the emitted light.

The size of the rings round the x, y values for RGB LED Clusters could be used as some form of metric of colour stability across the beam[64]. Thus, the smaller the size of the ring, the more colour stability exists across the beam and more uniform in terms of colour the emitted light is. On the contrary, the bigger the size of the ring, the more unstable the colour is across the beam.

[63] Lighting Industry Liaison Group, “A Guide to the Specification of LED Lighting Products 2012”, October 2012
[64]Hatziefstratiou, P. *Photometry and colorimetry of LED Clusters*.UCL. London, UK, 2005

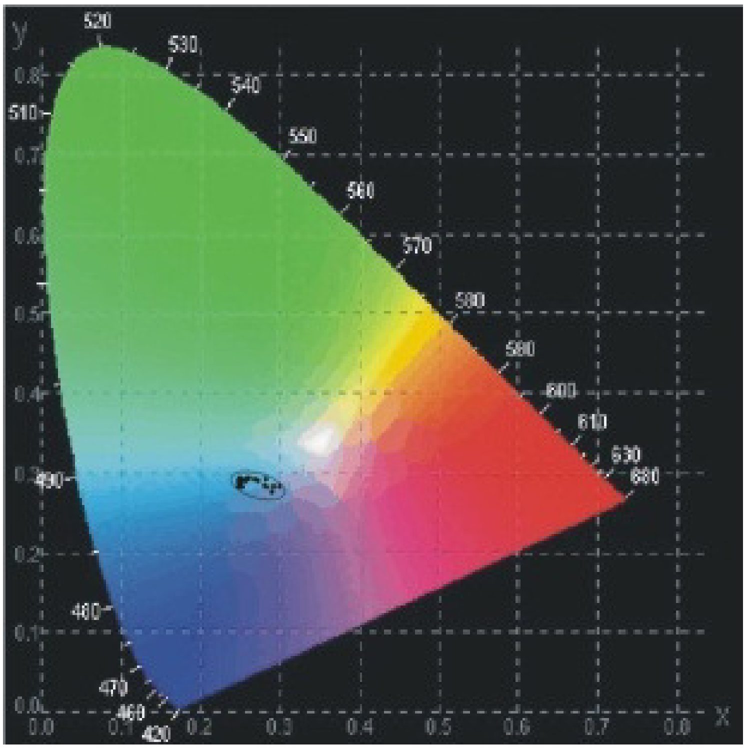

Figure 1.13: Rings of RGB colours

1.3.8. CRI

Colour Rendering index (CRI) is a measure[65] of the ability of a light source to reproduce colours faithfully in comparison with an ideal or natural light source. However, with the new LED technology, with in some cases a narrow spectrum, the CRI index is not in all circumstances giving a fair representation of the colour appearance. Definitions and methods for measuring are under development in CIE.

The initial CRI value classification for the photometric code can be obtained by using the intervals shown in Table 1.7. For LEDs, the initial colour render index (CRI) is measured together with the value after a total operation time of 25% of rated lamp life (with a maximum duration of 6000 hours)[66].

Code	**CRI Range**	**Colour properties**	**Rendering**
6	57-66	Poor	
7	67-76	Moderate	
8	77-86	Good	
9	87-100	Excellent	

Table 1.7: CRI value classification

[65] http://en.wikipedia.org/wiki/Color_rendering_index, 4/7/13
[66] DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services- Performance requirements, p. 10

1.3.9. Definition of code for LEDs

Published standards have proposed codes for defining LEDs[67]. An example of photometric code is the: 830/359, where:

- 8: The initial CRI of e.g. 77
- 30: Initial CCT of 3000K
- 3: initial spread of chromaticity co-ordinates within a 3-step MacAdam ellipse
- 5: maintained spread of chromaticity co-ordinates at 25% of rated life (with a maximum duration of 6000h) within a 5-step MacAdam ellipse
- 9: code of lumen maintenance at 25% of rated life (with a maximum duration of 6000 hours, in this example: >=0% of the 0h value

1.3.10. Ambient Temperature and other conditions

Factors that affect LED performance include the heat that is generated from the LED fixture, the operating temperature, and the environmental conditions of the lighting application. Manufacturers use conductive materials to create heat sinks in their LED products that take heat away from the light source. Indeed, the better the heat sink, the more stable the LED lumen output, colour, and lifetime[68]. Attention should also be given to the drive current, dimming, and aging of LEDs[69] which affect the lumen output and chromaticity properties.

[67] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 34

[68]Miller L, S, The LED Evolution.*Architectural Lighting Magazine*, 2007. http://www.archlighting.com/industry-news.asp?sectionID=1350&articleID=587492. 28/5/09

[69]Protzman J.B, House W.K. (2006). LEDs for General Illumination: The State of the Science, *IESNA Leukos, Vol. 3, No. 2.*, p. 121-142

1.4. Marking

This section presents the marking that LEDs, LED Modules and LED Luminaires should have. Further information on symbols can be found in the BS EN 60598[70].

1.4.1. Marking of LEDs

Table 1.8presents the marking of LEDs.

	Location of marking		
Marking[71]	**PRODUCT**	**PACKAGING**	**DATASHEET**
Rated luminous flux(lm)	x	x	x
Lamp colour code	x	x	x
Rated life and the related lumen maintenance factor (Lx)	x	x	x
Failure rate (Fx), corresponding to the rated life			x
Lumen maintenance category (Cat A to E)			x
Rated correlated colour temperature including tolerance category (Cat 1 to Cat 8)			x
Rated colour render index			x

Table 1.8: Marking of LEDs

1.4.2 Marking of LED Modules

Table 1.9shows the durable and legible mandatory marking for built-in or independent modules.

	Location of Marking		
Marking[72], [73]	**PRODUCT**	**PACKAGING**	**DATASHEET**
Mark of origin (trade mark, manufacturer's name or name of the responsible vendor/supplier)	X		
Model number or type reference of the manufacturer	X		
rated supply voltage(s), or voltage range, supply frequency (when applicable)	X		
rated supply current(s) or current range, supply frequency (when applicable)	X		x

[70] BS EN 60598 2008,Luminaires: General Requirements and tests p.30-35, 117-118 Figure 1 Symbols

[71] DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services- Performance requirements, p.8

[72] BS EN 62031: 2008 LED Modules for General Lighting- Safety Specifications

[73] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements, p. 14

rated input power, or power range	X		
Nominal power	X		X
position and purpose of the connections for safety	X		X
Value of *tc*	X		
eye protection (IEC 62471)	X		X
Built-in modules marked to separate from independent modules	X		X
Availability of Heat sink with module or not			x
Luminous intensity distribution			x
Beam angle			x
Peak Intensity			x
Rated luminous flux (lm)		X	X
Photometric code		X	X
Rated life (h) and the associated lumen maintenance (x)		X	X
Failure fraction (Fy) corresponding to the rated life		X	X
Lumen maintenance code			X
Rated chromaticity coordinate values both initial and maintained			X
Correlated colour temperature			X
Rated Colour Rendering Index			X
tp max of LED module (C)	X		X
Tp-point	x		x
Ageing time (H) if different to 0 h			X
Ambient temperature range			X
Efficacy (lm/W)			X
Dimensions, including dimensional tolerances			X

Table 1.9: Marking of LED Modules

The control gear of LED modules should also have appropriate markings[74][75][76] such as circuit power factor, limits of the permissible temperature range, indication if it has stabilized output voltage or current or if it is suitable for operation with a mains supply dimmer, rated output voltage or rated output current and maximum output voltage, total circuit power, indication of the operation mode, indication if it is suitable for LED modules.

[74] BS EN 62384: 2006 + A1: 2009, DC or AC supplied electronic control gear for LED modules. Performance requirements, p. 6
[75] BS EN 61347-2-13:2006, Lamp control gear, Particular requirements for d.c. or a.c. supplied electronic control gear for LED modules, p. 12
[76] IEC 61347-1: 2007, Lamp control gear – Part 1: General and safety requirements

1.4.3 Marking of LED Luminaires

Table 1.10 shows the marking of LED luminaires.

	Location of Marking		
Marking[77][78][79]	**PRODUCT**	**PACKAGING**	**DATASHEET**
Mark of origin (trade mark, the manufacturer's identification mark or the name of the responsible vendor).	x		
Rated voltage(s) in volts	x		
Rated wattage	x		x
Rated input power (W)			x
Rated current at rated voltage if less than the rated value	x		
Nominal frequency in hertz			
Class of protection Class II or Class III where applicable	x		
Type reference by maker	x		
Terminations marked to identify live, neutral and earth in case of connection of the luminaire to the supply mains	x		
Max number of luminaires that may be interconnected or the max total current that may be drawn by means of couplers provided for looping-in connection to the mains supply	x		x
Symbol for luminaires not suitable for covering with thermally insulated material	x		x
Details to ensure proper installation, use and maintenance	x		x
Operating temperatures and Spacing requirements	x		
A wiring diagram, except where the luminaire is suitable for direct connection to the mains supply.	x		
Special conditions	x		
limitations of use	x		
Power factor and supply current	x		
For luminaires using remote control gear, the range of lamps for which the luminaire is designed	x		
Warning whether they are suitable for direct mounting on normally flammable surfaces or are only suitable for mounting on non-combustible surfaces	x		x
IP number ingress of dust, solid objects and moisture	x		
Information about the intended use, i.e. “For indoor use only”.	x		

[77] BS EN 60598: 2008 Luminaires: General Requirements and tests, p. 30-35
[78]DD IEC/PAS 62722-2-1: 2011, Luminaire performance, Particular requirements for LED luminaires, p. 8-10
[79]DD IEC/PAS 62722-2-1:2011, Luminaire performance, Particular requirements for LED luminaires, p. 9-10

Protective conductor current		x
Means of adjustment (if applicable)	x	
Circumstances of use (normal use or for rough service)		
Photometric code		x
Rated luminous flux (lm)		x
Rated life (in h) of the LED module in the luminaire and the associated rated lumen maintenance (Lx)		x
Failure fraction (Fy) corresponding to the rated life of the LED module in the luminaire		x
Lumen maintenance code		x
Rated chromaticity coordinate values both initial and maintained		x
Correlated colour temperature (CCT in K)		x
Rated colour rendering index (CRI)		x
Ambient temperature (tp) for a luminaire	x	x
LED luminaire efficacy (lm/W)		x
Aging time, if different to 0 h		x
Luminous intensity distribution		
Peak intensity values		
Beam angle		
Chromaticity tolerance initial and maintained		
CRI initial and maintained		
Temperature cycling		
Optical risk		
Risk Group		

Table 1.10: Marking of LED Luminaires

1. 5. LED Supply Chain

For the purposes of this research, the researcher introduces the concept of "LED Supply Chain", in an effort to define the major players of the LED industry. The LED Supply Chain is illustrated in Figure 1.14.

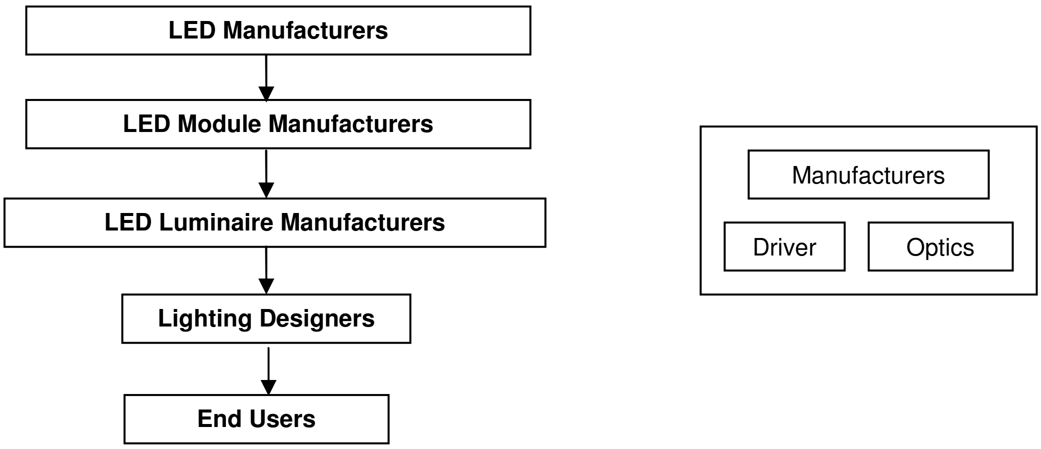

Figure 1.14: LED Supply Chain

The major players in the LED Supply chain are:

- LED manufacturers

LED manufacturers offer a variety of high power, high brightness, and low power LEDs. All companies spend a lot of time, money, and effort in the research and development of new products with improved efficacy, higher lumen output, greater efficiency, and superior LED emitter packages.

One of the leaders is PhilipsLumileds, which is most well-known for its power Luxeon technology. The Luxeon LEDs include the Rebel, the K2, and the Luxeon I, II, III, IV. The new version of Luxeon K2 features the thin film flip chip technology (TFFC), which is offering an improved light output, thermal capability, and optical performance.

Cree is another market-leading innovator and manufacturer of a variety of LED Chips, LED components, materials, power components and wireless devices. From its LED components range, the XLamp LEDs are the brightest and most efficient LED lamps, considered to be the only "lighting-class" LEDs available in the market.

OsramOpto Semiconductors is also one of the major players in the LED market. Indeed, Osram has announced its own high current LED called the Diamond Dragon, which according to the company is the brightest single-chip surface mount LED. Also, Osram deals with organic light-emitting diodes (OLED).

- LED Module manufacturers

Manufacturers use new LED multi-die packages to design clusters or arrays with LEDs. Clusters are usually printed circuit boards with two or more LEDs mounted on the board. Alternatively, retrofits such as an MR16 lamp with 3X1W LEDs are referred to as clusters. In this sense, there are many cluster manufacturers around the world. Cluster manufacturers combine LEDs in such a way so as to achieve high lumen output, consistency of colour over time, long lifespan, and good thermal management.

Module manufacturers use advanced production techniques to combine the LED die or chip together with mechanical and optical components making a replaceable item for use in a luminaire[80]. It may also contain further electrical and electronic components, but not the control gear[81]. Reputable module manufacturers are Xicato, Philips Lumileds, CREE, and Sharp.

- LED luminaire manufacturers

LED luminaire manufacturers are divided in two categories. The first category consists of the companies that come from the entertainment industry. Such companies are Martin Architectural, JB Lighting, Colorkinetics, Pulsar, Tryka, Griven, and Pixelrange. The specific companies have developed a variety of LED fittings, such as LED Parcans, colour changing LEDs, LED matrices.

[80] Lighting Industry Liaison Group, "A Guide /to the Specification of LED Lighting Products 2012", October 2012

[81]BS EN 62031: 2008 LED Modules for General Lighting- Safety Specifications, p. 6

The second category consists of the companies that come from the architectural lighting industry, such as Targetti, Erco, Thorn lighting, Zumtobel, Crescent Lighting, and Bega. These companies have introduced a variety of LED luminaires ideal for architectural lighting applications, including spotlights, and decorative LEDs.

Manufacturers produce new designs or incorporate LEDs in existing fittings. In fact, the great variety of LED fixtures that is nowadays available has contributed to the expansion of the so called “Architainment” where elements of both entertainment and architectural lighting are combined to illuminate a variety of venues, mainly in the leisure industry.

- Lighting designers

Lighting designers may have a background in architecture, decoration, theatrical lighting, and electrical engineering. Lighting designers are expected to bring their knowledge, background, experience, and imagination to design with LEDs.

Lighting designers have a great variety of products to select from. The LED products can be used for concealed lighting, cove lighting, general illumination, highlighting, accent lighting, colour-changing effects. Often, lighting designers work with manufacturers to develop new products according to their own special requirements.

- End users

End users are not very literate about LEDs. Nevertheless, as more and more lighting designs are being developed with LEDs, end users are becoming more familiar with the technology and more confident in regard to the capabilities that LEDs offer. Thus, they become more enthusiastic about using LED technology.

Finally, in the LED supply chain it is important to incorporate other groups such as:

- Driver manufacturers
- Optic manufacturers
- Others whose products are eventually used with LEDs

1.6. Product information that is needed to support applications

Each group of the LED Supply Chain requires specific product information in order to support applications.

To begin with, LED Module Manufacturers are interested to acquire from LED Manufacturers information on:

- Models of LEDs (high power, high brightness, low power)
- Variety of white LEDs
- Colour consistency over time
- Lifespan, lumen maintenance over time
- Electrical current
- Power consumption, stability
- Quality
- Availability

LED luminaire manufacturers require from LED or LED Module manufacturers information on:

- Photometric data, intensity
- Lumen output per watt (lumen efficacy)
- Colorimetric data
- Lumen maintenance
- Colour consistency over time
- Operating voltage

- Power consumption
- Current rating
- Thermal management
- Lifespan
- Optics, lenses

Lighting designers require from LED luminaire manufacturers information on:

- Photometric measurements
- Colorimetric measurements
- Intensity distribution curves
- Lumen per watt
- Lumen maintenance, lifespan
- Colour consistency over time
- Correlated Colour Temperature
- Colour Rendering Index
- Operating voltage
- Power consumption
- Control systems, flexibility
- IP protection
- Accessories

Finally, end users are mainly interested in:

- Lighting results that LED luminaires generate
- Energy consumption
- Operating and maintenance costs
- Consistency of lighting levels and colours
- Lighting effects
- Lifespan, durability, availability
- Control capabilities and ease of use

Besides the direct flow of product information, there is an indirect flow of information within the LED Supply Chain. The information is distributed usually through product presentations, magazines, newsletters, internet, and exhibitions.

Finally, manufacturers of drivers, optics, heat sinks, and other components provide information about their products to the major players of the LED Supply Chain.

Figure 1.15presents the LED supply chain and the flow of information between the major players.

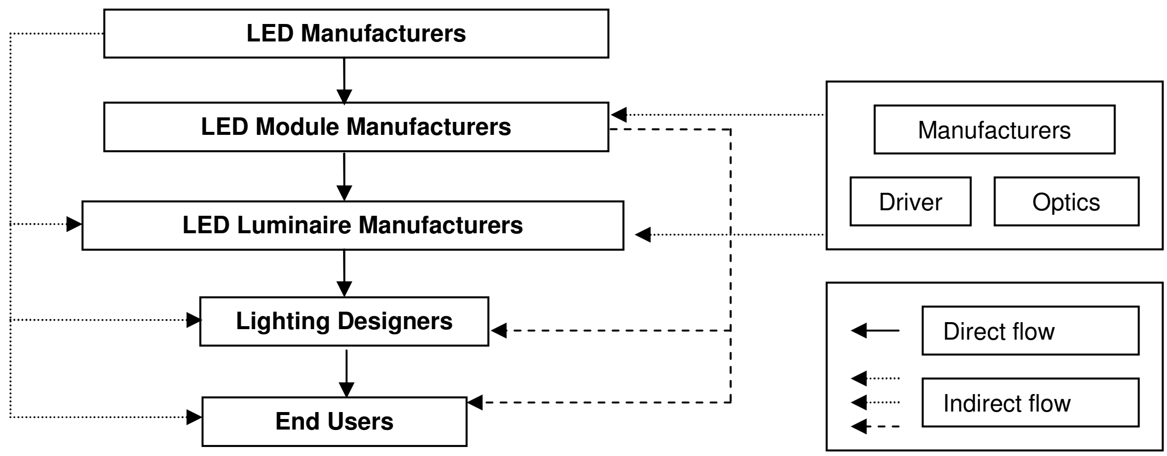

Figure 1.15: LED Supply Chain and flow of information

To sum up, each group of the LED supply chain requires a variety of data from the other groups. The data becomes more or less important depending on the application of LEDs. In fact, because key lighting parameters change depending on the application, the data required vary accordingly.

More specifically, in applications where white light is required, the key lighting parameters are mainly CCT, CRI, lumen output, stability characteristics, lumen maintenance, colour consistency and colour stability through life. In such applications, the groups of the supply chain require information as indicated in Figure 1.16.

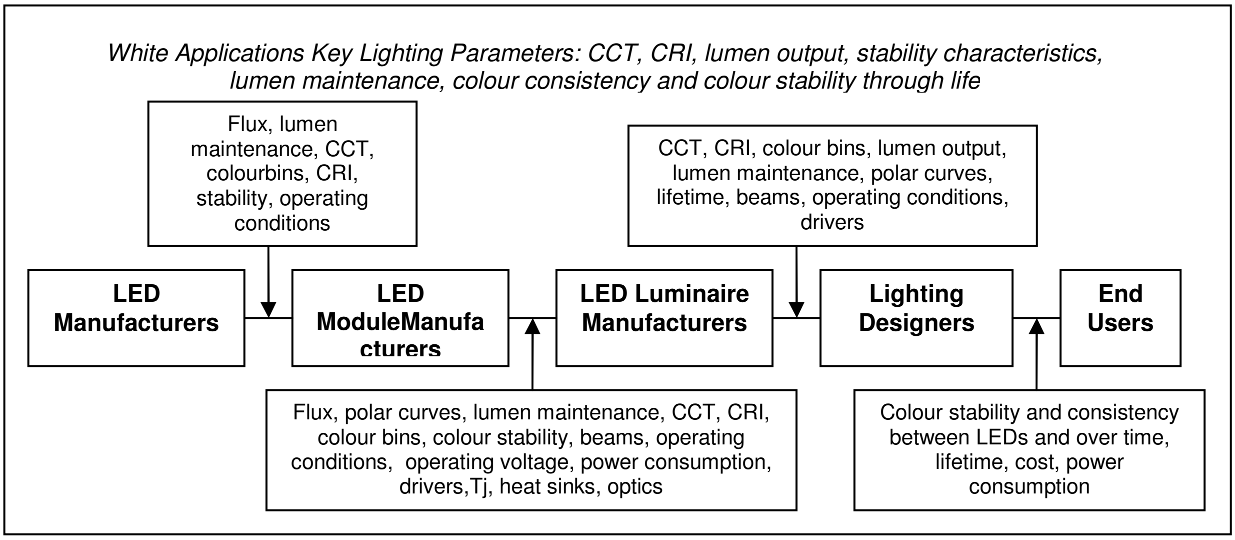

Figure 1.16: White applications- lighting parameters and product information

In applications where coloured light is required (other than white), the key lighting parameters are mainly the colour outcome, lumen output, lifetime, and lumen maintenance. Thus, the different kind of information required from the different groups is as described in Figure 1.17.

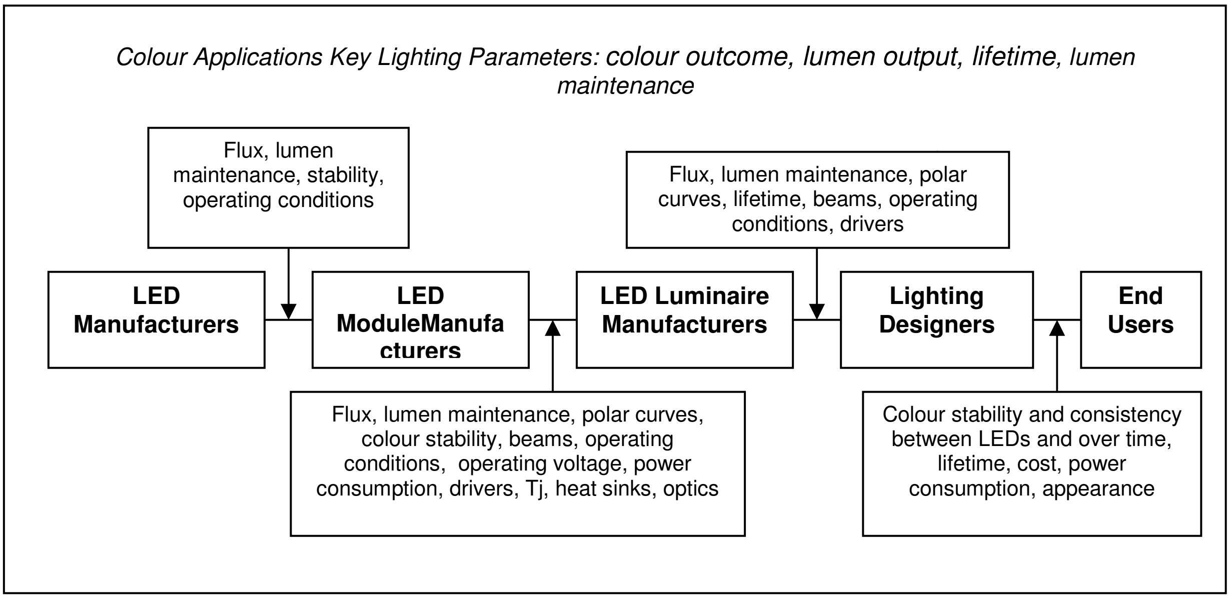

Figure 1.17: Single color applications- lighting parameters and product information

In applications where RGB light is required, the key lighting parameters are mainly the control capabilities, current rating, and operating voltage. Thus, the different kind of information required from the different groups is as described in Figure 1.18.

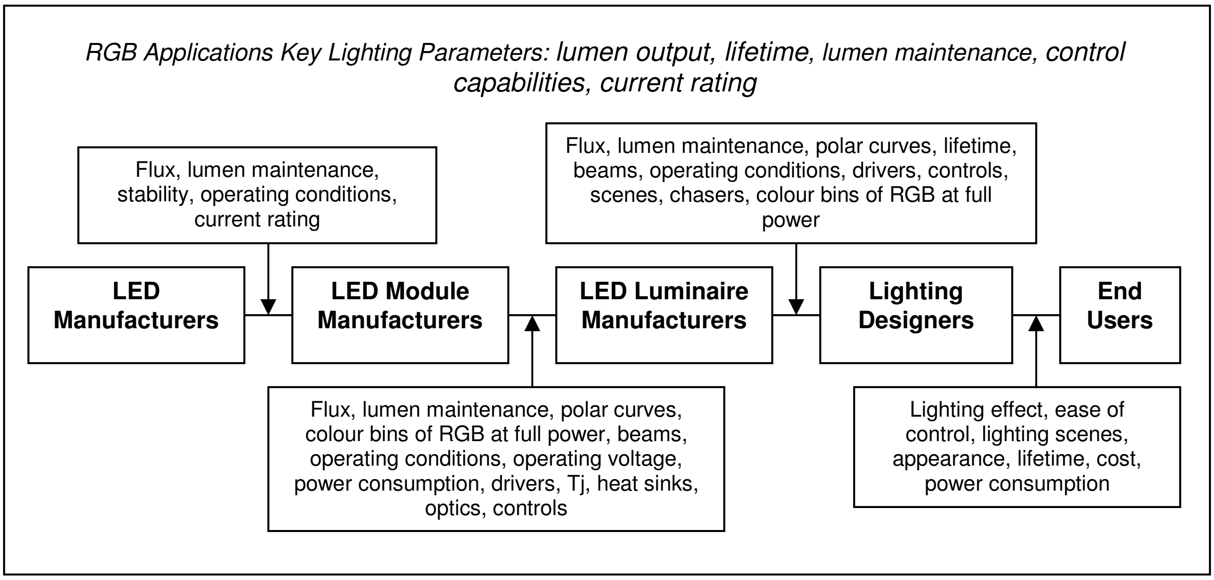

Figure 1.18: RGB applications- lighting parameters and product information

Chapter Two

Completed by the end of 2008

The Leisure Industry

Chapter Twodefines the leisure industry and explains the objectives of lighting in this field. Case studies from around the world are presented to show how lighting objectives can be achieved with the use of LEDs in leisure venues.

2.1. The meaning of Leisure

Watkins and Bond[1] summarise some of the most important studies related to the meaning of Leisure as follows:

One approach to identify the unique and common properties of leisure has compared leisure with non-leisure phenomena. Iso-Ahola[2] defined perceived freedom, intrinsic motivation and a low work orientation as key determinants of leisure definitions. Shaw[3] claimed that three or more of the following five dimensions were required to predict the definition of a situation as leisure: enjoyment; physical, emotional and mental relaxation; freedom of choice; intrinsic motivation; and a lack of self or other evaluation. Gunter[4] explained that the eight properties of pure leisure were: a sense of separation or escape, freedom of choice, intense pleasure, spontaneity/spur of the moment, timelessness, fantasy, adventure and exploration and self-realization. For Mobily[5] leisure was associated with hedonic words (pleasure, fun, enjoyment) and passive activities.

Donald and Havighurst[6] studied leisure in relation to socio-demographic variables. According to them, men frequently defined leisure as change from work, whereas women viewed leisure as being creative. People from upper middle class backgrounds identified leisure with achieving something, whereas those from lower middle class backgrounds emphasized contacts with friends. Kleiber, Caldwell, and Shaw[7] defined leisure with the following five meanings: relaxing/doing nothing, free time, free choice, enjoyment and activities. In particular, their study revealed thatwomen were twice as likely to define leisure as relaxing/doing nothing and free choice, whereasmen were four times more likely to define leisure as enjoyment or activities.

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[1] Watkins, Michael and Bond, Carol, Ways of Experiencing Leisure, Leisure Sciences, 2007, 29:3, p. 287- 307
[2]Iso-Ahola, S. E., Basic dimensions of definitions of leisure, Journal of Leisure Research, 1979, 2(1), p. 28–39
[3] Shaw, S., The meaning of leisure in everyday life, Leisure Sciences, 1984, 7(1), p. 1–24
[4] Gunter, B. G., The leisure experience: Selected properties, Journal of Leisure Research, 1987, 19(2), p. 115–130
[5]Mobily, K., Meanings of recreation and leisure among adolescents. Leisure Sciences, 1989, 8, p. 11–23.
[6] Donald, M. &Havighurst, R., The meanings of leisure, Social Forces, 1959, p. 355–360
[7]Kleiber, D., Caldwell, L., & Shaw, S., Leisure meanings in adolescence, Society and Leisure, 1993, 16(1), p.102

Some researchers employed a more micro-analytic approach to study leisure in relation to the influence of personal and social contexts. Freysinger[8] investigated the meaning of leisure in relation to developmental issues and tasks associated with middle age. Thus, some people described leisure as change in which freedom of choice and control resulted in feelings of enjoyment, relaxation, and rejuvenation; while others defined leisure as social context for developing affiliation with family and friends and a source of personal development through opportunities for self-expression and learning.

Lee, Dattilo, and Howard[9] revealed pleasurable characteristics such as enjoyment, relaxation, and freedom in addition to previously un-reported stressful characteristics such as feelings of apprehension, nervousness, disappointment and guilt. Pleasurable meanings were found to remain in subjects' memories well after experience while stressful meanings faded over time.

To sum up, each of the above studies has given a different definition to 'leisure'. Nevertheless, no matter which of the above studies best explains the meaning of leisure, it should be noted that leisure is an ethnocentric term mostly based on North American and European thinking[10]. Thus, whenever researchers present the term leisure to their study participants, it is not certain that what participants think of leisure is matched with what researchers think of as leisure. In a global and international context, the above is likely to be affected by personal, social, cultural, historical, and political differences across the cultural boundaries.

Thus it can be seen that there are a variety of definitions of leisure. For some people leisure is a relaxing evening, reading a book. However, for most people leisure involves social interaction and is related to activities such as

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[8]Freysinger, V. J., The dialectics of leisure and development of women and men in mid-life:An interpretive study.Journal of Leisure Research, 1995, 27(1), p. 61–84
[9] Lee, Y., Dattilo, J., & Howard, D., The complex and dynamic nature of leisure experience, Journal of Leisure Research, 1994, 26(3), p. 195–212
[10] Yoshitaka Iwasaki a; Hitoshi Nishino b; Tetsuya Onda b; Christopher Bowling ba Temple University, Philadelphia, Pennsylvania, USA b Tokai University, Hiratsuka, Kanagawa, Research Reflections Leisure Research in a Global World: Time to Reverse the Western Domination in Leisure Research, Japan Online Publication Date: 01 January 2007

entertainment, eating, drinking, and traveling.

2.2. The Leisure Industry

In today's competitive and high-pressure environment, people work at least eight-hours a day and have limited free time to relax and enjoy. The leisure industry has arisen to cater for the spending of this spare time[11]. Thus, the leisure industry can be defined as the sector of the economy that includes the following segments: restaurants and hotels; recreation and culture, betting and gambling; sports; health and fitness[12]; entertainment and tourism related products and services[13]. Indeed, some of these segments are large enough to be described as industries on their own[14]. Nevertheless, for the purposes this research, leisure is defined as follows: *hotels, bars, and restaurants*.

The leisure industry is a major part in the economy of many countries. In fact, the leisure industry has been and will always constitute an essential and dynamic component of many economies around the world: Dubai, Hong Kong, Singapore, Bang Kong, London, Athens, Rome, Paris, New York and Las Vegas are such economies.

Take, for instance, the United Kingdom economy. In the UK, the leisure industryemploys more than three million people or 13.5 percent of the UK employees, and accounts for 10 percent of the UK gross domestic product (GDP)[15]. Moreover, according to a report[16] edited in 2003 by the former Mayor of London Ken Livingstone, it is estimated that a quarter of the national leisure economy is in London, and that it has grown by nearly 30 percent from 1995 to 2001.

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[11] Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p.19

[12] http://www.prospects.ac.uk/cms/ShowPage/Home_page/Explore_job_sectors/Sport_and_Leisure/overview/p!ebeeed, 21/7/08

[13] http://en.wikipedia.org/wiki/Leisure_industry, 21/7/08

[14] From Exam Results magazine, Issue 2001/2, Published: 31 January 2002, The Independent Online, July 2008

[15] http://www.prospects.ac.uk/cms/ShowPage/Home_page/Explore_job_sectors/Sport_and_Leisure/overview/p!ebeeed, 21/7/08

[16] Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p. 4, 19, 74-75

Indeed, according to the same report, the leisure sector is one of the fastest growing parts of London's economy. With nearly 300,000 jobs and a consumer market of £9.5 billion, it directly represents around six to eight percent of the whole London economy. The leisure sector is growing rapidly and is likely to make up a substantial part of the 178,000 new jobs in other services' projected by 2016 in the Mayor's London Plan.

The leisure industry is highly sensitive to economic and competitive market conditions and is capital, management, marketing, personnel, energy, maintenance, and technology intensive[17]. Thus, the leisure industry needs to periodically perform market analysis in order to understand consumer preferences, but it also needs to forecast and respond to fashion trends.

In addition, the leisure industry needs to constantly analyse and find ways to respond to the changing composition of population. For instance, research[18]in 2003 indicates that Britain has an ageing population; with 19 per cent aged 55-74 years and 8 per cent over the age of 75, and that by 2010 the number of over 60s will have increased by 3.1 million. The leisure industry needs to find ways to adjust to these social changes.

Similarly, the leisure industry needs to comprehend economic conditions and take into consideration variables such as disposable incomes, changes in consumer demand, inflation and unemployment rates[19]. In addition, the leisure industry needs to take into account severe competition from national and international markets, as well as globalisation trends.

To sum up, the leisure industry is a major component of the economy of various places around the world. It needs to meet the challenges of a diverse population, adjust to changing conditions, adapt new technologies, and ultimately offer recreation, enjoyment and satisfaction to hotel guests and customers.

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[17]http://www.pwc.com/extweb/industry.nsf/docid/A475490CED245E078525675F006C114A, 23/8/08
[18]Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p. 15
[19]www.prospects.ac.uk/cms/ShowPage/Home_page/Explore_job_sectors/Sport_and_Leisure/overview/p!ebeeed, 21/7/08

2.3.Leisure industry: Hotels, Bars, Restaurants

For the purposes of this present research, the leisure industry is defined as "hotels, bars, and restaurants".

Hotels rely on tourism; on people who travel to and stay in places outside their usual environment for leisure, business and other purposes[20]. In 2007 in the UK, there were over 903 million international tourist arrivals, with a growth of 6.6% as compared to 2006. Also, despite the uncertainties in the global economy, arrivals grew at around 5% during the first four months of 2008, almost a similar growth than the same period in 2007[21].

Moreover, according to the study of Ken Livingstone[22], tourism spending was worth £39 billion to the British economy in 2000, according to Visit Britain. Overseas and domestic visitors who stayed at least one night in London spent £10 billion in 2000. Domestic tourism accounts for two-thirds of tourism spending in Britain. However, in London domestic tourists account for only a third of tourist spending, while overseas tourists account for around two-thirds. In London, overseas tourist visits and spending have been growing over the last two decades. In real terms, spending in London has grown by around 47 per cent between 1983 and 2002.

Restaurants and bars also rely on tourism to a great extent. Nevertheless, permanent residents also go out to restaurants and bars. In fact, eating out is a favourite leisure activity. The market for eating out is being shaped by disposable incomes, demand for convenience food and intense competition between restaurants and fast food chains[23]. In London, dinning out employs about 121,000 people and generates sales of up to £4.7 billion. The total value of this industry is forecast to reach £26.04 billion in 2009[24].

London's bars employ 58,000 people and have sales of up to £2.4 billion. The

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[20] http://en.wikipedia.org/wiki/Tourism, 21/7/08
[21] UNWTO World Tourism Barometer June 2008,Volume 6 No. 2, 21/7/08
[22] Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p.20-21
[23] Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p. 6-7.
[24] www.prospects.ac.uk/cms/ShowPage/Home_page/Explore_job_sectors/Sport_and_Leisure/overview/p!ebeeed, 21/7/08

biggest spenders in bars are people aged 18-35 and London has a higher percentage of this group than Britain as a whole. Rapid growth has been driven by the expansion of branded high street pubs[25].

In general, the World Tourism Organization (UNWTO) forecasts that international tourism will continue growing at the average annual rate of 4 %. By 2020 Europe will remain the most popular destination. Long-haul travel will grow slightly faster than intraregional travel and by 2020 its share will increase from 18% in 1995 to 24%[26]. This suggests that leisure industry will be growing significantly and that there will be increased demand for more leisure services in the future.

2.4. Lighting in the Leisure Industry

Given the worldwide tourism and the fact that we live in a very competitive and high-pressure environment, there is an increasing demand both for leisure pursuits and for venues in which to relax and have a nice time. This implies that the creation of the right ambience and atmosphere is important in the leisure industry. Nevertheless, this is not always easy, given the wide variety of activities that take place in such venues. Moreover, the leisure venues need to be used in security and comfortas well as with functionality, which suggests that the entire infrastructure must be planned in such a way so as to make spaces work in the best possible way, by using the appropriate plans, designs and products[27].

In fact, the above issues have become a pivotal concern for the leisure industry worldwide[28]. For this reason, different groups of professionals are involved in the design and development of leisure venues, including lighting designers. Lighting is a crucial and fundamental factor in establishing the appropriate ambience in leisure venues. In addition, a visually stimulating environment of adequate illumination can make building users feel more comfortable, delighted and

[25]Livingstone Ken, Mayor of London, Spending Time: London's Leisure Economy, Published by Greater London Authority, City Hall, November 2003, p.7
[26]http://en.wikipedia.org/wiki/Tourism#Leisure_travel, 23/8/08
[27]http://www.halsion.com/leisure.html, 23/8/08
[28] Morten Heidea, KirstiLaerdal, Kjell Gronhaug The design and management of ambience— Implications for hotel architecture and service, Tourism Management 28, Science Direct, 2007, p. 1315–1325

relaxed. Moreover, lighting can enhance architecture and reinforce ornamental design work.

A successful lighting installation in the leisure industry that is tailored to the needs and requirements of the building users can contribute greatly to the commercial success and increase of sales[29]. In other words, investing in a lighting system can actually lead to increase in both customers and corporate revenues. Thus, lighting is one of the most vital parameters to consider in the leisure industry. Indeed, some say lighting is the difference between success and failure[30].

Given the above, the research will define the objectives of lighting in the leisure industry, and more specifically in hotels, bars and restaurants. In turn, the goal is to critically evaluate the functional effectiveness and visual impact of artificial lighting in general, and LED lighting in particular, as well as to analyse lighting design in different installations around the word.

2.5. Objectives of Lighting in the Leisure Industry

The fundamental objectives of Lighting in hotels, bars and restaurants are the following:

- To attract attention.

In order to attract the attention of visitors or passers-by, it is important to make the building stand out from its surroundings as a preferred location. For this reason, exterior lighting requires not only the most durable and sophisticated outdoor lighting equipment, but it also requires an advanced knowledge of landscaping and architecture[31]. No matter what, the goal is to illuminate the building in such a way so as to distinguish from the nearby constructions.

[29] FordergemeinschaftGutesLicht, Good lighting for hotels and restaurants, 1990, p. 1
[30] http://www.hotelmanagement-network.com/features/feature459/, 24/8/08
[31] http://www.illuminationslighting.com/hotel_lighting.htm, 24/8/08

- To guide visitors to the building and to certain points.

Lighting should guide the way for visitors towards the building or to certain points within the venue. One approach to achieve this is by illuminating at higher levels or in different colours the specific point as compared to the adjacent areas. For example, in a hotel lobby the reception could be illuminated at a higher level as compared to the lounge area. Similarly, the bar of a restaurant could be illuminated in an eye-catching way as compared to the sitting area.

- To make a good first impression.

Lighting often creates the vital first impression when a visitor arrives at a venue. Lighting also contributes to the creation of a feeling of positive sensation throughout a stay, making people want to be in the space and ultimately come back to the venue. How to make a good first impression is a matter of lighting design. Nevertheless, some techniques to achieve that include the balance of illumination levels within the space, the creation of a colourful atmosphere, and dynamic colour effects.

- To establish the character of the venue.

As Pr Jan Ejhed says[32] "*It's probably true to say that lighting helps form the basic character of a hotel… Our role as designers is to help find the basic concept of a hotel and use lighting to enhance this. It's always the concept that comes first and from that comes good lighting*". Indeed, lighting contributes to the establishment of the character of a hotel, bar, or restaurant, which can be modern, classic, minimal, or traditional.

- To create the appropriate ambience.

Ross de Alessi Lighting Design (RDLD) explains[33] that "*…projects run the gamut from highly thematic to the more traditional, and can be seen on some of the most successful and impressive establishments worldwide. The creative opportunities afforded on these projects are challenging. We understand that guests expect more than just good food and fluffy pillows; we know it is the*

[32] http://www.hotelmanagement-network.com/features/feature459/, 24/8/08
[33] http://www.dealessi.com/leisure/leisure.html, 9/8/08

quality atmosphere that helps make anyone a loyal guest. Whether your location is exotic or rustic, great lighting can help create the right ambience for those looking to do business or get away from it all".

- To think of aesthetics and reinforce the emotions of building users.

Lighting should contribute to the aesthetics of the space. Lighting should add to the sense of what people consider beautiful or appropriate for the specific venue. Moreover, lighting should reinforce the emotions of building users. Nevertheless, the emotions must be balanced with the aesthetics of the space. In all cases, lighting should create a feeling of security and facilitate the amenities and night-time activities that occur in the venue[34].

- To create distinct changes in atmosphere and mood to suit the different occasions.

Especially in the leisure industry, it is essential to create changes within different areas of the same venue or to alter the mood and atmosphere between spaces and through time. In particular, each area has a different function, so the localised lighting can help distinguish between the areas and alter mood between each area[35]. For example, the reception area should be bright for generating a welcome atmosphere, while the bar could be much darker to generate a relaxed atmosphere. Similarly, a restaurant could alter lighting scenarios throughout the day and night so as to generate a friendly and cosy environment.

- To generate visual comfort and visual interest.

Lighting affects the degree of visual satisfaction, thus it should make building users feel comfortable and pleased within the space. Not only that, but lighting can enrich the visual environment by creating points of visual interest. A point of visual interest can be a table with flowers in a hotel lobby or a statue in the entrance of a restaurant. The illumination of such focal points of visual interest should always complement the interior architecture and facilitate the different functions in the given area.

[34] http://www.illuminationslighting.com/hotel_lighting.htm, 24/8/08
[35] http://www.lightingdesigninternational.com/, Storey S, 24/8/08

- To be integrated and in balance with the architecture and interior decoration.

Lighting should enhance the architecture and reinforce the interior design of the venue. Thus, lighting should create a subtle combination of effects while emphasising the exterior and interior style of the space[36]. In addition, lighting should reveal the form, the colour and the ornamental design work. To do so, accent lighting should highlight balconies, flagpoles, and window design[37]. Alternatively, layers of light should reveal the architectural constructions and expose decorative elements. To achieve that in the best possible way implies that lighting design should be integrated in the design process from the early stages of the building construction.

- To create a consistent and unite whole.

Lighting should emphasize the individuality of the venue and should promote the image of the establishment, but at the same time it should make the entire structure unite and consistent. As the lighting designer Storey Sally[38] (LDI) points out *"A hotel is almost like a small town in one building with so many different zones including restaurants, bars, meeting rooms, spas; each has its own function and each requires a different atmosphere"*. Lighting should blend everything together in such a way so as to create a consistent and harmonious whole.

- To offer more than just lighting.

The goal of lighting design should be to find the appropriate lighting solution in every situation. Nevertheless, lighting design in the leisure industry should do more than that; it should offer more than just lighting; it should create magic, drama, enthusiasm, passion, interest... Thus, depending on the venue, the perfect lighting solution may be to install indirect concealed lighting to generate a feeling of magic, or to highlight features in a way that creates drama[39], or to

[36] http://www.lightingdesigninternational.com/, Storey S, 24/8/08
[37] http://www.illuminationslighting.com/hotel_lighting.htm, 24/8/08
[38] http://www.lightingdesigninternational.com/, Storey S, 24/8/08
[39] http://www.lightingdesigninternational.com/, Storey S, 24/8/08

make colourful scenes that change over time so as to maintain interest, or to design an impressive luminaire that becomes the focal point and generates enthusiasm.

- To provide good visual conditions for building users.

Providing appropriate illumination and adequate visibility should be a principal consideration in the lighting design process. Every lighting installation should take care of providing adequate levels of illumination that facilitate movement and enable visibility for task accomplishment. The lighting designer should start from the basic concept and work from there taking into account the ergonomics of a space[40]. Thus, the lighting designer should consider the needs of employees, such as convenience, practicability, ease of task accomplishment, and maintenance; the needs of hotel guests, such as feelings of enjoyment, relaxation, and rejuvenation; the needs of bar/restaurant customers, such as affiliation with friends, pleasure. In general, it is important to take into account how different building users visually interact with the lighting scheme while maintaining functionality[41].

- To provide security and personal safety.

In today's environment, it is essential to comply with health and safety regulations in buildings. Thus, the lighting installation should incorporate the necessary exit signs and back-up lighting in case of emergency, given the relative laws that apply to every country. Moreover, as Halsion[42] Lighting Design points out, in every installation there should be suitable exterior lighting for those visiting outside daylight hours. For example, there should be appropriate lighting in parking garages that eliminates shadows and create a brightly lit and glare free atmosphere. The goal is to make building users feel safe and secure and to make it easier for security personnel and security cameras to view[43].

[40] http://www.hotelmanagement-network.com/features/feature459/, 24/8/08
[41] http://www.hotelmanagement-network.com/contractors/lighting/kevan-shaw/, 24/8/08
[42] http://www.halsion.com/leisure.html, 23/8/08
[43] http://www.illuminationslighting.com/hotel_lighting.htm, 24/8/08

- To establish a sustainable environment.

Functionality and maintainability are essential to ensure that the integrity of the lighting design remains throughout the life of the project. As Pr. Ejhed[44] explains *"Designers today have to be appreciative of the financial and ecological arguments and they must be dedicated to finding realistic solutions…If you don't build in sensible energy efficiency measures from the start, the hotel*(or other venue) *may just switch off the lights and you will lose the character of the design you've worked so hard to create."* In all cases, the lighting installation should comply with regulatory legislation and guidelines such as Part L: 2006[45]and should apply new technologies, such as LEDs, to achieve low lighting operating and maintenance costs.

2.6.LED Lighting Applications in the Leisure Industry

The lighting applications presented in this section illustrate the wide use of LEDsin the leisure industry, the immense capabilities offered by LED Technology, as well as the variety of lighting designs that can be developed with the application of LEDs. The specific case studies are only a few examples of the vast number of installations which currently use LED Technology. Nevertheless, they were selected by the researcher amongst other projects due to their diversity, impressive lighting design schemes, and integration with the architecture. The goal is to present a variety of case studies in the leisure industry from around the world.

[44]http://www.hotelmanagement-network.com/features/feature459/, 24/8/08
[45]http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved 4/10/14

- **Semiramis Hotel, Athens, Greece**

  Owner: Dakis Ioannou, A.X.E.K
  Interior designer: Karim Rashid Inc., New York City
  Lighting designer: Paul Gregory, Focus Lighting, New York City
  Manufacturers: Fiber Pro Solutions, Ghidini Neo, Unilamp
  IALD Awards of Merit 2005

The interior of the Semiramis Hotel was designed by Karim Rashid, while the lighting design was developed by Focus Lighting. The goal was to combine the architectural design with colourful and innovative lighting solutions to create one of Europe's most exciting new hotels[46]. Indeed, coloured glass and light combine to create a great hotel experience at the Semiramis Hotel.

As explained by Focus Lighting[47], the stairs of glass at the entry of the hotel are backlit with white LEDs, while the yellow-green glass balconies above are rear-illuminated by 9W fluorescent lamps. This is illustrated in Picture 2.1.

Picture 2.1: Exterior view of Semiramis Hotel

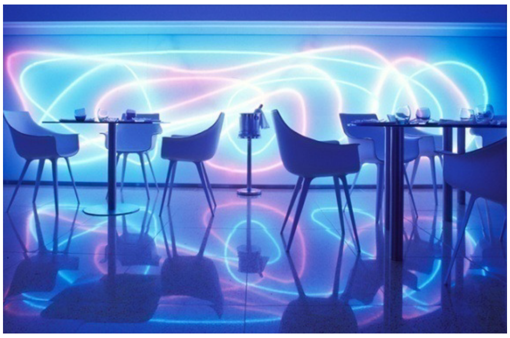
The hotel lobby, as illustrated in Picture 2.2, is a dramatically changing environment where colour changing LEDs are used for linear concealed lighting. In the reception area, LEDs are used for backlighting the pink coloured frosted glass wall of the front desk. The colours of these LEDs rotate through a colour cycle as does the general concealed LED lighting across the lobby. As the

[46]http://www.iesny.org/NewsArticle.aspx?newsId=14776, 8/11/08
[47]http://focuslighting.com/portfolios/semiramis-hotel, 8/11/08

lighting designer Paul Gregory says *"These are soft, beautiful colours, they are the colours of sunset when the sun is coming through at a low angle and everyone has a warm, rich glow. People look good because of all the pink"*[48].

Picture 2.2: The hotel lobby of Semiramis hotel

Similarly, LEDs are installed on the four floors creating a distinctive colour for each one of them: lime, pink, orange and white. In addition, in every room messages such as "Do not disturb" signs appear on LED-lit boards. The restaurant area, as illustrated in Picture 2.3, is a colourful alliance of glass and light, providing an impressive lighting effect and a distinctive image.



Picture 2.3: The restaurant of Semiramis hotel

Paul Gregory explains that *"the lighting design at Semiramis is obviously inclined toward LEDs, but this is because the technology was 'right' for the reality of the project. The LED presence is strong, but not just for the purpose of having LEDs"*[49].He explains that fluorescent tubes could not be used because there was not enough space on the ceiling and shadows would be eventually

[48]http://www.archlighting.com/industry-news.asp?articleID=454030, 8/11/08
[49]http://www.archlighting.com/industry-news.asp?articleID=454030, 8/11/08

created. Not only that but the decision to use LEDs, was also made due to maintenance factors.

Given the above, it is evident that the Semiramis Hotel has blended together the different zones in a unique way and impressive manner, with LED Technology well embedded into the architecture and interior design. As Paul Gregory explains *"The Semiramis Hotel is successful because of the early collaboration. We worked with Rashid to create a visual image that was so wonderful the client could treasure it as a memory forever"*[50].

- **Hard Rock Hotel, Las Vegas, USA**

  Owner: Morgans Hotel Group and equity partner DLJ Merchant Banking Partners
  Lighting Design: Warwick Stone, 4Wall Entertainment, Alios
  Manufacturer: Colorkinetics
  2004

The Hard Rock Hotel & Casino, Las Vegas is a premier destination entertainment resort, originally built in 1995[51]. The resort offers a unique entertainment and gaming experience with the services and amenities associated with a luxury resort hotel. Features of the property currently include an 11-story Hard Rock Hotel tower with 647 guest rooms.

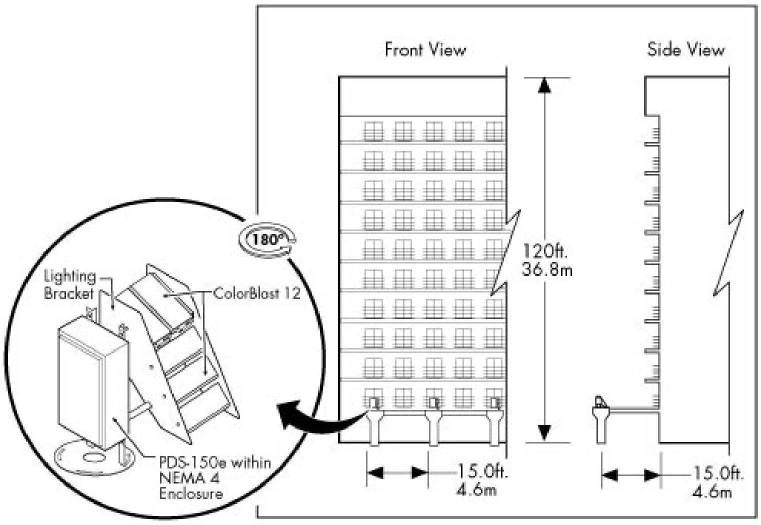
In its previous ten year old exterior lighting system, the exterior façade was illuminated by metal halide-based fixtures, which allowed for single-colour columns of light with dichroic filters. Nevertheless, the Hard Rock lighting designer Warwick Stone together with the full service entertainment company 4Wall Entertainment, have created an eye-catching, remarkable exterior by using the latest LED technology.

In particular, Warwick Stone and 4Wall Entertainment have designed a grand-scale colour changing design for illuminating the 120-foot facade with high output and colour saturation. To achieve this, 4Wall assembled custom fixtures with Colorkinetics LED products; the bottom units with frosted lenses to cast a

[50] http://www.archlighting.com/industry-news.asp?articleID=454030, 8/11/08
[51] http://www.hardrockhotel.com/about.cfm, 8/11/08

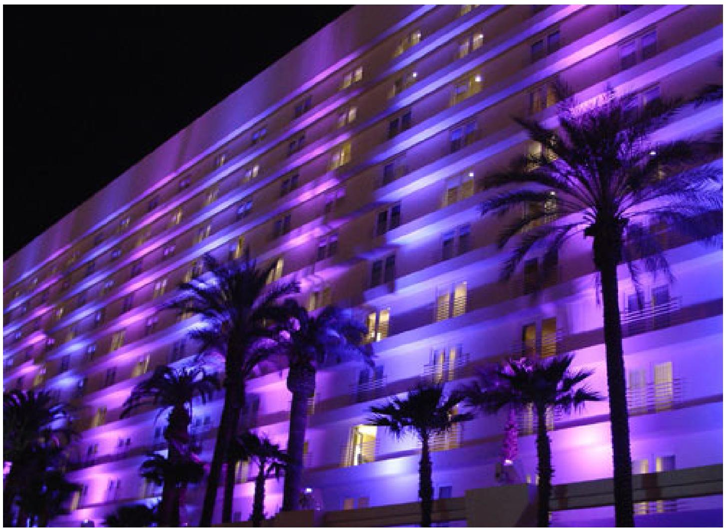
wide beam angle and the top units with clear lenses to maximize upward throw. A total of 300 such units were installed in this fashion to wash the façade with vibrant, dynamic colour[52] and to generate a host of multi-colour chases within columns of light[53]. In addition, the DMX-512 control system of the LEDs provided the opportunity to program and run customized light shows from special events, attractions and holidays.

Installation information is presented inPicture 2.4. The lighting design is shown in Picture 2.5 and Picture 2.6.



Picture 2.4: Installation data of lighting fixtures in Hard Rock Hotel

[52]http://www.colorkinetics.com/showcase/installs/eyecandy/ 8/11/08
[53]http://livedesignonline.com/news/show_business_lightfair_color_kinetics/ , 8/11/08



Picture 2.5: Exterior lighting Hard Rock Hotel

Picture 2.6: Exterior lighting, side view, Hard Rock Hotel

Not only is the lighting design impressive, attracting the attention of visitors, guests and passers-by, but the LED installation also offers ease of maintenance and energy conservation. In fact, it is estimated that the LED fixtures draw approximately $1,900 in electricity per year, while the previous metal halide-based fixtures drew approximately $18,000 annually. The estimated yearly maintenance expense for the LED-based units is $600, while the yearly expense for the previous fixtures was roughly $25,000, without considering the additional costs of replacing the dichroic filters and ballasts on a periodic basis[54]. In total, it

[54]http://www.colorkinetics.com/showcase/installs/eyecandy/ 8/11/08

was estimated that the LED lighting installation will net approximately $41,000 per year in operational savings[55].

Thus, the LED lighting design scheme at the exterior façade of the Hard Rock Hotel, improved the aesthetics of the resort and promoted the image of the hotel in a unique and special way. In addition, it offered energy consumption, lower maintenance and operational costs.

- **L2 Lounge Bar, Washington, USA**

  Design Team: Lehman Smith McLeish, Washington, D.C. (architect and interior designer)
  Lighting Design: MCLA Architectural Lighting Design, Washington, D.C. (lighting designer)
  Manufacturers: Birchwood Lighting, Color Kinetics, Lutron, ProLume, USA Illumination, Times Square Lighting
  2008

The L2 Lounge Bar[56] is located in Washington. It is a member's only lounge of outstanding design, but other customers can enter occasionally. The lounge is made of materials such as brick, stone walls, and concrete floors, generating the feeling that the exterior surrounding is also transferred in the interior of the venue[57]. Moreover, the venue is equipped with audiovisual effects, around the distinctive areas.

The lighting goal, according to the lighting designer Maureen Moran, was to make the lounge dark enough, to establish low levels of light, to create a unique atmosphere and to deal with the high reflectance levels, due to the white ceiling, white lacquer panels, and backlit glass of the space.

To achieve the lighting goal, the lighting designer Maureen Moran decided to primarily use LEDs throughout the venue. In the narrow entryway, the

[55] http://www.colorkinetics.com/showcase/installs/eyecandy/ 8/11/08
[56] www.l2lounge.com, 8/11/08
[57] http://www.archlighting.com/industry-news.asp?articleID=782803&sectionID=1330 , 8/11/08

customers find themselves between one wall of colour changing LED laminate glass panels, and another wall of white lacquer panels. The LEDs located at the rear of the panels are the only source of illumination in the space. They are individually controlled, providing a variety of colour combinations. As the lighting designer claims *“additional lighting was not necessary in this area because the lighting creates the illusion that both walls are backlit, filling the entire space by light’*[58]. This is illustrated in Picture 2.7.

Picture 2.7: The entry way of L2 Lounge Bar

Inside the main venue area, video screens are located on different walls. To offset the video screens from the wall, strips of warm white LEDs are used as concealed lighting to frame the video screens, as illustrated in Picture 2.8.

[58]http://www.archlighting.com/industry-news.asp?articleID=782803&sectionID=1330 , 8/11/08

Picture 2.8: Wall lighting in L2 Lounge Bar

Also, the bar which is composed of glass panels is backlit with colour changing LEDs, reinforcing the atmosphere and design. This is illustrated in Picture 2.9.

Picture 2.9: The bar of L2 Lounge Bar

Indeed, MCLA[59] worked closely with the architect and client to develop a lighting scheme primarily with LEDs that is completely dimmable, and captures the underground feel of the space. In fact, 80% of the installation is LED Technology which can be totally controlled and dimmed[60]. The design team created a classy lounge-appropriate lighting scheme by using LED technology as the main light source, while at the same time achieving the sophistication, ambiance, and quality sought after by the client[61].

[59] http://www.mcla-inc.com, 8/11/08
[60] http://www.archlighting.com/industry-news.asp?articleID=782803&sectionID=1330 , 8/11/08
[61] http://www.archlighting.com/industry-news.asp?articleID=782803&sectionID=1330 , 8/11/08

- **Nando Restaurant, Oxford, UK**

  Owner: Nando chain of restaurants
  Lighting design: Light Projects, Kate Wilkins Lighting Design
  Architect: Michaelis Boyd

Nando[62] was first established in 1987 in South Africa. Since 1992 it has launched more restaurants in the UK. Today, Nando is spreading around the world. Indeed, the Nando chain of restaurants can now be found all around the five continents.

For the Nando restaurant in Oxford, Light Projects[63] collaborated with Kate Wilkins[64]Lighting Designer to create and manufacture a dramatic lighting fitting. In particular, Kate Wilkins wanted to create a lighting scheme that would fit in well with the design of the architect Michaelis Boyd. Thus, it was decided to create 'a glass bottle wave' as the central decorative element within the restaurant, as illustrated in Picture 2.10.

Picture 2.10: The Glass bottle wave of Nando restaurant

The 'glass bottle wave' was composed of Nando's own sauce bottles to create a stunning and unique visual spectacle running along the entire length of the restaurant. The lighting goal was to be clean, fresh, innovative and exciting, with

[62] http://www.nandos.co.uk, 21/11/08
[63] http://www.lightprojects.co.uk, 21/11/08
[64] http://katewilkins.com, 21/11/08

a strong emphasis on sustainability and recycling[65]. To illuminate the 'glass bottle wave', LED technology was used. More specifically, warm white LEDs were incorporated into specially designed caps which are fixed onto the bottles. Nevertheless, not every single bottle from the total of 1,500 was illuminated by LEDs. On the contrary, some bottles were not illuminated at all, in order to create a contrast and pattern within the wave. For this reason, smaller lighting fittings made of clusters of three or four bottles were used to provide additional illumination in individual tables.

The lighting design of Nando restaurant in Oxford is unique and creative. The 'glass bottle wave' luminaire is a very original design, which generates a feeling of warmth and welcoming. The atmosphere is very cosy and generates a positive mood. The lighting design also adds to the aesthetics and reinforces the general architecture of the venue. At the same time, the luminaire is very practical, useful and effective, while the use of LEDs allows for reduced energy consumption and long lifetime of the lamps, which further suggests reduced maintenance and operational costs.

The overall lighting design in Nando Oxford is an exceptional custom-made lighting design. It is an impressive floating glass fitting which is visually very appealing from every angle[66]. It is a 'saucy' lighting scheme which offers energy efficiency and sustainability.

- **Fire nightclub, London, UK**

  Owner: Craig Elder
  Lighting Design: Yan Guenancia of Halo Lighting
  Manufacturers: Colorkinetics and others
  2006

Fire nightclub was redesigned at the end of 2006 when the owner of the club Craig Elder assigned lighting designer Yan Guenancia of Halo Lighting to create an impressive lighting scheme in two months time. The concept was inspired by a Justin Timberlake video, thus it required the conversion of the curved railway

[65] http://www.ledsmagazine.com/casestudies/17291, 21/11/08
[66] http://www.ledsmagazine.com/casestudies/17291, 21/11/08

arch into a video screen. To achieve this, a lot of detailed work, designs and CAD mock-ups were required.

LED Technology was chosen to line the arched ceiling and walls. The first major issue was to decide on the spacing between the LED nodes. It was important to keep the nodes close enough to produce a decent resolution, while also considering budget restrictions. The designers determined that they needed 48 prefabricated panels, each lined withiColor FlexSL[67]strings that were sandwiched between two plywood sheets[68]. Finally, the LED nodes were spaced 100mm apart and were individually controlled.

In turn, a team of four people had to drill for two weeks thousands of holes in order to accommodate thousands of nodes and associated wiring. The panels were then lifted into place[69]. In the end, each string was connected back to the drivers based in the control room, using an 18-way multi-core cable. A Video System Manager converts video signals from a media server and streams the content to the LED nodes, essentially reproducing the video-based imagery against the grid of lights[70]. The installation is shown in Picture 2.11 and Picture 2.12.

Picture 2.11: LED installation in Fire nightclub

[67]http://www.colorkinetics.com/ls/rgb/flex/, 8/12/08
[68]http://www.colorkinetics.com/showcase/installs/fire/, 21/11/08
[69]Brewis, P, Night Magazine, May 2007 Issue, http://www.halo.co.uk/company/clients/fire.html, 21/11/08
[70]http://www.colorkinetics.com/showcase/installs/fire/, 21/11/08

Picture 2.12: LED pixel display in Fire nightclub

The lighting scheme was very difficult to realise in such a small period of time. But as the lighting designer Guenancia explains "*Although some projects are plagued with problems, this one was blessed as all components and design solutions seem to appear at the right time as the project powered on*[71]".

At the end of the day, the LED panels follow the curvature of the arches and place the dancers in a unique environment[72]. The LED pixel display is animated with graphics and changing colours, creating an impressive lighting design scheme and a notable atmosphere in the club. This is definitely a modern lighting design scheme and installation that explore the uses of LED light in the leisure industry.

- **Park Hyatt Hotel, Dubai, UAE**

  Owner: Park Hyatt Hotel
  Lighting design: Project Lighting Design Singapore

In a fast growing tourist destination such as Dubai, the Park Hyatt Hotel aimed at establishing a pleasant and cheerful atmosphere inside its restaurant. Indeed, the lighting goal was to create a blend of colour and light that would create a warm and exotic atmosphere throughout the restaurant.

The lighting designer Stephen Gough of Project Lighting Design decided to use LED technology. In particular, the ceiling was made of the Barrisol diffuser. This

[71] http://www.architainment.co.uk/Portfolio/Sub%20Portfolio%20pages/Sub%20Pages/Fire%20Nightclub/sub_fire.html, 21/11/08
[72] http://www.ledsmagazine.com/news/5/4/32, 21/11/08

material allows the diffusion of light, thus when combined with LEDs can create a uniform single colour or colour-changing ceiling. Behind the Barrisol diffuser more than 67m of iColor Cove NXT[73]were recessed into the ceiling, approximately 30 cm behind theBarrisol diffuser. The specific fittings have a wide angle of 120 degrees, thus they were suitable for floodlighting the ceiling. In particular, the fittings were installed end-to-end in linear runs across the entire ceiling, and spaced apart in 90 cm increments[74].

In turn, a Light System Manager was used to author and control a series of ethereal, colour-changing effects. These include a chasing rainbow that completes a cycle of colours in 30 seconds, and a cross-fade that displays specific colours for 30-second intervals[75].

The final lighting design scheme is very impressive, as illustrated in Picture 2.13. The Barrisol material allows for the diffusion of colourful light in a uniform way, while colour mixing is achieved in a harmonious mode.

Picture 2.13: Ceiling illumination in Park Hyatt Hotel

In addition, the ceiling seems to be illuminated from within, generating the feeling of a glowing ceiling, as illustrated in Picture 2.14. Finally, the whole environment creates a positive atmosphere and promotes the feelings of affiliation and socialization.

[73]http://www.colorkinetics.com/ls/rgb/cove_nxt/, 8/12/08
[74]http://colorkinetics.com/showcase/installs/parkhyatt/, 23/11/08
[75]http://colorkinetics.com/showcase/installs/parkhyatt/, 23/11/08

Picture 2.14: Glowing ceiling in Hyatt Hotel

- **Grand Lisboa Hotel & Resort, Macau, China**

  Owner: Sociedade de Jogos De Macau (SJM)
  Manufacturer & Installer: Daktronics, Keyframe
  2007

Located in Macau Special Administrative Region in China, which is known for its dazzling lights and extravagant structures that remind one of Las Vegas, the Grand Lisboa Hotel & Casino had to establish an impressive lighting scheme that would attract the attention of visitors and passers-by. LED technology was used in the building façade in order to create a display that shows custom text messages, graphics, animations and video images.

The bottom of the building, where the installation is made, is egg-shaped. The egg-shaped podium measures 56 meters high and 189 meters wide with an area of approximately 10,609 square meters. For its illumination, over 59,000 ProPixel LED lighting elements from Daktronics[76] were installed. Each circular ProPixel is individually addressable and contains 20 LEDs (8 red, 6 green and 6 blue). In addition, the podium is made up of 12,000 triangles of different coloured triangle-shaped glass, thus ProPixel fittings were installed so as to custom fit the spaces between the pieces of glass. The technology used is

[76]http://www.daktronics.com/Company/NewsReleases/Pages/The-Americana-at-Brand.aspx, 8/12/08

actually a video display system with true video processing capable of displaying millions of colours[77], as illustrated in Picture 2.15.

Picture 2.15: Exterior lighting of Grand Lisboa hotel & resort

Indeed, the installation is composed by an intelligent LED lighting system, which creates spectacular effects, and displays words, images and animations that attract the attention of people from a distance, as illustrated in Picture 2.16. Not only that, but the lighting scheme also offers the benefits of superior brightness, long lifetime, low power consumption, and unique visual effects.

Picture 2.16: Intelligent LED display in Grand Lisboa hotel & resort

[77] http://www.ledsmagazine.com/news/4/7/12, 23/11/08

2.7. LEDs in the Leisure Industry

Developing an interesting lighting design and an effective lighting scheme with LEDs requires the close cooperation from the very beginning of lighting designers with other groups of people, including architects, interior decorators, electrical engineers, owners and building users. The lighting designer needs to be integrated from the very start in the design process, and should not be treated in isolation. The goal for the lighting designer is to understand the general architecture of the space, and to appreciate the decorative structures and ornamental design work, so as to develop an appropriate lighting design scheme that enhances these elements.

In addition, when the lighting designer is integrated in the design process from the beginning, it is more likely for him/her to comprehend the needs of the space and create the appropriate atmosphere and generate the suitable mood. In short, when the lighting designer is involved at the beginning of the project until the end, the venue is most likely to be properly lit, rather than becoming the outcome of bad communication between all parties involved[78]. Nevertheless, to achieve the above, the lighting designer needs to have experience, imagination, technical expertise, and knowledge of the new lighting technologies.

LED lighting technology is developing very rapidly, offering new capabilities to the leisure industry. Not only that, but because the leisure industry (and especially hotels) operate 24 hours a day, seven days a week, hotels and bar/ restaurants have tended to be in the lead in the use of new lighting control techniques and new lighting sources[79], such as LEDs. Thus, LEDs are commonly used in the leisure industry because of the benefits they offer, including energy efficiency, low maintenance costs, low operational costs, long lifetime, and low levels of heat emission.

As indicated in the case study of Hard Rock Hotel in Las Vegas (see 2.6), it is estimated that the LED fixtures used approximately $1,900 in electricity per year, while the previous metal halide-based fixtures used approximately $18,000 annually. In addition, the estimated yearly maintenance expense for the LED-

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[78] http://www.lightingdesigninternational.com/, Stonley, 24/8/08
[79] Simpson S Robert, Lighting Control: technology and applications, Focal Press, p.459, 2003

based units is $600, while the yearly expense for the previous fixtures was roughly $25,000[80]. In total, it is estimated that the LED lighting installation will net approximately $41,000 per year in operational savings[81].

The case studies of section 2.6 demonstrate that lighting designers use LED technology primarily to realise the lighting goals they have set. In particular, LEDs contribute to the creation of the appropriate ambience while, at the same time, they enhance the architecture and they reinforce the decorative ornamental works in the space. For example, the use of LEDs in the Semiramis hotel allows the creation of a dramatically changing environment through concealed lighting, while reinforcing the modern architecture and enhancing the decorative elements. Similarly, in the L2 Lounge Bar, the use of LEDs contributes to the creation of a dark environment and to the exposure of construction materials such as brick, stone wall, concrete floors and glass panels.

In addition, LEDs offer colour and dynamic colour changing capabilities as compared to conventional lighting (RGB as well as tuneable white light), which allows for different lighting scenarios through time. This is evident, in the Semiramis Hotel where LEDs reproduce the soft and beautiful colours of the sunset, and in the Park Hyatt Hotel where LEDs replicate the colours of the rainbow. In this way, colours contribute to the general aesthetics of the venues. Furthermore, the blending of colours in the L2 lounge bar, for instance, generates the sophistication, ambiance, and quality that the client wanted.

Also LEDs and colour changing can also reinforce the emotions of building users, and create changes in the atmosphere and mood to suit the different occasions. In the Park Hyatt Hotel the changing colours generate warmth and an exotic atmosphere. In the Fire nightclub LEDs create an impressive lighting design scheme and an extraordinary dancing experience.

In addition, the colour changing scenarios also help attract attention from a distance. In the Hard Rock Hotel, colour changing LEDs installed in the façade make an eye-catching, remarkable exterior, which attracts the attention of visitors and passers-by. Also, LEDs can help guide visitors in the building and to

[80] http://www.colorkinetics.com/showcase/installs/eyecandy/ 8/11/08
[81] http://www.colorkinetics.com/showcase/installs/eyecandy/ 8/11/08

certain points. In the Semiramis Hotel, LEDs backlight the glass stairs and highlight the reception desk, leading the way into the building and towards the reception area.

LEDs can help establish the character of the venue and help promote the image of the building. The LED exterior illumination of the Grand Lisboa makes visitors understand that this is a hotel and casino establishment. In fact, the graphics and texts and images of the LED display provide information to the visitors of the kind of leisure activities people can enjoy within the establishment.

Likewise, LEDs can influence the first impression of visitors. Thus, in the narrow entryway of the L2 Lounge Bar customers find themselves, between one wall of colour changing LED laminate glass panels and another wall of white lacquer panels, which makes them curious to walk towards the rest of the venue.

Furthermore, LEDs are used due to their small size, which makes them ideal for applications where hiding the source is essential. This is the case in the Semiramis Hotel, where there was not enough space to place fluorescent lamps on the ceiling. Similarly, in the Park Hyatt Hotel, the floating ceiling was realized by installing LEDs at a short distance from the Barrisol diffuser.

The small size of LEDs enables the creation of a variety of luminaire designs. One such luminaire is established in the Nando restaurant in Oxford. LEDs are incorporated in the saucy glass bottles to create a custom-made luminaire which also constitutes the main decorative element of the space. The glass wave becomes the main point of visual interest.

Also, LEDs are used due to their extraordinary design flexibility in control and dimming. They have low power consumption, they operate at low-voltage which is necessary in some places such as outdoor lighting, and they offer the capability to connect in parallel or daisy chain many fixtures with low voltage connectors. The specific advantages of LEDs were actually taken into consideration when making the installation in the Fire nightclub. The specific installation required a great number of LEDs as well as advanced control and video management systems. The same is evident in the exterior illumination of the Grand Lisboa Hotel where the LED matrix displays graphics, images and text.

To sum up, as illustrated from the case studies, LEDs are primarily used in the leisure industry due to a variety of advantages that they offer. Most importantly, LEDs help lighting designers to achieve the lighting goals that they have set. In turn, LEDs can create the appropriate ambience, strengthen the aesthetics, and reinforce the emotions of building users. In addition, LEDs help change the general atmosphere and alter the emotions during day and night depending on the occasions, by controlling intensity levels or colours, in such a way so as to maintain functionality and visual comfort.

Furthermore, LEDs can help attract the attention of visitors and passers-by, as well as guide visitors to the building and to certain points. In turn, LEDs can influence the first impression that a venue makes to its visitors and customers. This also suggests that LEDs help establish and promote the character of the space as well as the image of the establishment.

Moreover, LEDs can enhance the architecture and reinforce the decorative ornamental works. In turn, LEDs can generate points of visual interest, such as a floating ceiling or a custom-made luminaire. Thus, LEDs can offer more than just lighting; they can create impressive lighting design schemes in a consistent and unique way. This is facilitated due to the immense control capabilities of LEDs which allow the creation of matrices and the projection of images, texts, and graphics.

In addition, LEDs establish a sustainable environment, offering low operating and maintenance costs, long lifetime and energy efficiency. Finally, they offer higher efficiency when compared with other sources, no UV radiation which makes them suitable for illuminating light sensitive works of art, they are vibration resistant due to the fact that they have no filament and are small in size, and they allow cold temperature operation.

Due to all the above factors, LEDs can be found in a great variety of architectural applications in the leisure industry. In fact, the case studies verify the latest trend of ‘architainment’ which means that elements of both architectural and entertainment lighting are combined to illuminate leisure venues.

Chapter Three

Research Question

Chapter Three sets the scene of LED technology in the leisure industry and lists the fundamental issues set out in this thesis, while focusing on what is understood as a knowledge gap, and thus worth investigating. In turn, it sets the research question of this research, and discusses its value and how it covers the gap and contributes to further knowledge.

3.1. Setting the scene

LEDs are being used for the illumination in the leisure industry due to the advantages they offer, including long lifetime, small size, energy efficiency, and low power consumption. LEDs are being used not only in simple applications but also in advanced lighting designs due to their extraordinary design flexibility and advanced characteristics, as compared to conventional sources.

However, there have been some key barriers related to the further adoption of LEDs in contemporary lighting design schemes. These are mainly associated with the photometry and colorimetry of LEDs. Other problems related to LEDs include the lack of uniform definitions, the inconsistency in data availability, and the limited published standards against which to evaluate and compare LEDs.

Over the years, the technological advancements in LED technology have been immense, allowing manufacturers to overcome many of the problems related to the photometry and colorimetry of LEDs. Also, standards have been published and technical committees have been working on related issues, with reputable manufacturers using many of the proposed methods and definitions.

Despite the above developments, there is a limited amount of reliable information about the use of LEDs in the illumination of the leisure industry and the implications of that in contemporary lighting design schemes. Also, no research has been performed to investigate the information that lighting designers require when designing with LEDs, and the information they actually get from the market. Finally, no research has been performed to examine how published standards affect the availability of data in the market, the way lighting design decisions are made, and the way selection of products is realized.

3.2. Research Question

Given the gap in the literature of the lighting community between the wider use of LEDs in the leisure industry and the lack of research in related issues, this thesis aims to answer the following question:

What is the impact of LED technology in the illumination of the leisure industry? What kind of information is needed in order to do lighting designs with LEDs in the leisure industry, and is this information available? What are the implications of this in regard to contemporary lighting designs with LEDs?

In an effort to answer the above questions, this thesis defines the key drivers for using LED technology in the leisure industry, and the barriers to its further adoption. Also, the thesis presents the standards that have been published in relation to LEDs. Moreover, it defines the LED Supply Chain and its major players.

In addition, the thesis investigates the information that different groups of the LED Supply Chain require from the rest of the groups, in regard to three lighting applications: applications that require white light; applications that require monochromatic light other than white; and applications that require RGB light. The thesis aims to analyze the information that is required for each application and the information that is actually available in the market. The thesis also examines the flow of information and looks at how the available knowledge is handled and distributed.

3.3 Objectives

The objective of the present research is to discuss lighting design with the use of LED technology in the leisure industry. To do that, the research aims to compare the information that lighting designers need and the information that lighting designers get from manufacturers for different applications. Also, the thesis investigates how published standards affect the way data is defined and presented, and it examines the way that data availability affects decision making and product selection. In turn, it aims at understanding why different groups of the LED Supply Chain, do things the way they do.

Furthermore, the thesis discusses the main issues that need to be taken into account when designing with LEDs. It also addresses the necessity for standards that may provide a framework for comparing and evaluating products. In addition, the research discusses the design impacts and implications and provides guidelines on how to use LEDs in contemporary lighting designs.

The thesis adds value to the lighting community by addressing issues not covered by previous research. In fact, the originality of this research will be related to the fact that it reveals how information and data availability influence the adoption of LED technology and the decision making in regard to LED products. The present research will help by providing guidelines on how to design with LEDs and by introducing 'quality' lighting parameters that should be taken into consideration. Therefore, the findings will be of interest to lighting designers, to manufacturers, and to all users of LED technology. The findings of the research will propose areas of interest that require further research.

Chapter Four

Completed beginning of 2014

Methodology

Chapter Four discusses the methodology of the thesis.

4.1. Primary Research

The primary research was designed within the qualitative paradigm. It has been suggested[1] that the features of qualitative research are as follows: The research is conducted through contact within a 'field'; the researcher's role is to gain a holistic overview of the context under study and attempts to capture data on the perceptions of local actors 'from the inside'; and most analysis is done with words instead of the use of standardized instrumentation.

The main qualitative method used was the questionnaire. The questionnaire was developed in order to examine participant's perceptions about LED technology and the leisure industry, and many related issues. This was considered the most appropriate method, as it allows for all the participants to respond to exactly the same set of questions[2].

A first questionnaire was developed by the researcher. This is shown in Annex 1. The questionnaire was distributed to some lighting designers and was used as a pilot study. More particularly, lighting designers were asked not only to provide answers to the questionnaire but also to provide their comments in regard to the questionnaire itself and the questions posed.

The researcher received three completed questionnaires. The feedback was then used to assess the quality of the questions and evaluate the validity of what has been asked. It was found that some of the questions were not clear, while others were difficult to understand or did not make a lot of sense to the participants. In turn, the researcher had to revise the questionnaire, re-develop it and improve it. The revised questionnaire, together with the relevant cover letter, is shown in Annex 2. The revised questionnaire was divided in four parts.

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[1] Miles, M B and Huberman, A M, Qualitative Data Analysis: an Expanded Sourcebook, 2nd edition, 1994, Thousand Oaks

[2] Saunders, M; Lewis, P; and Thornhill, A Research Methods for Business students, 2nd edition, 2000, Prentice Hill

The first part of the questionnaire involved general questions on LED technology, as follows.

1. *Do you use LED technology and if yes in which kinds of applications?*
2. *What do you think of the use of LEDs in today's environment?*
3. *What do you think is the future of LED technology?*
4. *How literate do you think are different groups of people in regard to LEDs?*
5. *How do you learn about the available LEDs, LED Luminaires and the latest LED developments?*
6. *What are the major criteria when selecting a LED luminaire?*
7. *What are the major criteria when selecting a LED luminaire manufacturer?*
8. *What kind of information do you require from LED Manufacturers and how much do you value this information?*

In particular, participants were asked if they use LED technology and in which kinds of applications, what they think of the use of LEDs in today's environment and in the future. Moreover, participants were asked how literate they think different groups of people are in relation to LEDs. In addition, they were asked how they learn about LEDs, and what their major criteria are when selecting a LED luminaire and a manufacturer. Finally, participants were asked to value the information that they require from manufacturers.

The second part of the questionnaire aimed at investigating lighting design in the leisure industry.

9. *If the leisure industry is defined as hotels, bars and restaurants, what are the objectives of lighting in the leisure industry?*
10. *What important issues should be considered when generating lighting design schemes in the leisure industry?*
11. *What are the End User requirements and expectations in the leisure industry in terms of lighting and lighting design?*
12. *According to your personal view, please refer to some good lighting design schemes in the leisure industry.*

In particular, participants were asked to set the objectives of lighting design in the leisure industry, and to determine the issues that should be considered when generating lighting design schemes in the field. Moreover, participants were asked about the end user requirements and expectations. Finally, they were also asked to give examples of good lighting design schemes in the leisure industry.

The third part of the questionnaire focused on the use of LEDs in the leisure industry.

13. *Do you use LEDs in lighting designs in the leisure industry?*
14. *What kind of LED products do you use?*
15. *In which applications do you use LEDs?*
16. *What capabilities are offered by LEDs?*
17. *What are the limitations of LEDs today?*
18. *What are the barriers for the further adoption of LEDs?*
19. *How do you take decisions on which LEDs to use?*
20. *How confident do you feel about using LED Technology in your designs and why?*
21. *What important considerations should be taken into account when using LEDs in the leisure industry in the following applications?*
22. *What lighting goals should be achieved when using LEDs in the following applications?*
23. *According to your personal view, please refer to some good LED lighting design schemes in the leisure industry?*

Participants were asked whether or not they use LEDs in lighting designs in the leisure industry, for what reasons, and in which applications. In turn, participants were asked to define the kind of LED products they use for different applications. Moreover, participants were asked to describe the capabilities that are offered by LEDs, the limitation of LEDs, as well as the barriers for the further adoption of LEDs. In relation to that, participants were asked to explain how they take decisions on which LEDs to use and how confident they are when they do use LEDs.

Participants were asked to express the key considerations when using LEDs in various applications in the leisure industry. They were also asked to explain the lighting goals that should be achieved when using LEDs in various applications.

Finally, they were asked to give examples of good LED lighting design schemes in the leisure industry.

The fourth part of the questionnaire involved some general questions.

24. What kind of projects do you handle?
25. In which countries or areas have you worked?
26. Please select your gender.
27. Please select your age group.
28. Please write in your background.
29. Please indicate your job title.
30. Please write in your name if you like (but not necessarily).
31. Please write in the name of your office/ company and your email (but not necessarily).

Participants were asked to explain the projects they handle and in which countries. Also, they were asked to define their gender, their age group, their background, and their job title. Lastly, people were kindly asked to provide their names and company name if they wished.

The majority of the questions of the questionnaires were text open questions so that people could answer freely and without limit the questions posed. Nevertheless, some questions (Question 4, 8, 14, 15) required specific answers (use of x in the appropriate boxes). The questionnaire was developed this way in order to gather both quantitative and qualitative data. The quantitative analysis allowed the researcher to make generalizations of a large sample. The qualitative analysis allowed for an investigation of the participants' beliefs in regard to LEDs, and a detailed description of their opinions.

The Questionnaire was sent to about 600 lighting designers by email. Their contact details were found after investigation in the internet and lighting designers' associations, mainly the International Association of Lighting Designers (IALD[3]). Nevertheless, several emails were returned to the researcher as undelivered, which suggests that some emails were not valid at the time of research. Similarly, the researcher received a few automatic responses that the recipient of the email was out of office for some time, and so

[3]http://www.iald.org 1/1/12

on. Additionally, some participants wished the researcher good luck with the research but explained that they had no time to participate in the survey. Given the above, the researcher received 61 completed questionnaires, which corresponds to approximately 10% feedback.

Once the 61 completed questionnaires were collected, a datasheet was prepared in order to handle all information. The datasheet was prepared in an Access file. In turn, depending on the question the researcher developed and designed a form in Access so that the replies of the questions could be easily entered. This is shown in Annex 3.

4.2. Secondary Research

The secondary research involved the analysis of the leisure Industry, the investigation of LED technology, the study of available standards, and the market research in order to identify the LED products available.

More specifically, the researcher investigated the different meanings of leisure, and defined the meaning of the leisure industry for the purposes of this present research as *hotels, bars and restaurants*. Moreover, the researcher has investigated the significance of lighting in the leisure industry and defined the main objectives of lighting in the field. Furthermore, the researcher studied different installations from the leisure industry around the world, in an effort to investigate where and why LEDs are being applied.

In addition, the secondary research included the study of the technology of LEDs, the technological advancements over the years, the latest trends, breakthroughs, and product developments. In addition, it involved an investigation of the benefits of LEDs as well as the limitations and problems related to this technology. At the same time, it involved the study of the available standards and current work by technical committees in an effort to investigate LED definitions, measurements, and markings.

In turn, the researcher defined the LED Supply Chain and its major players. The researcher also investigated the flow of information required from and between the different groups of the supply chain for various applications.

Finally, the secondary research involved the market analysis of products and product data availability by LED manufacturers. This was realized through a thorough study of the literature of different manufacturers and a detailed internet search. The market research focused on the three major categories of LEDs available: LED Chips, LED Modules, and LED luminaires. The aim was to define the information that different manufacturers offer to the LED Supply Chain. To better achieve this, several products were analyzed per company. In turn, tables and graphs were developed in order to summarize the most important information available from manufacturers in terms of various parameters, as well as to define the differences in the definitions and binning systems between manufacturers.

Chapter Five

Completed in April 2009

Findings of initial survey

Chapter Five presents the findings of the initial research that was conducted in 2009 with the Questionnaire of Annex 2. The replies to the Questionnaire are included in Annex 3. Chapter Five also presents results from analysing the findings.

5.1. Questionnaire

This section presents the answers to the open-text questions of the Questionnaire. It also presents statistical data deriving from the questions that required a specific closed answer.

5.1.1. First Part of the Questionnaire

The first part of the Questionnaire referred to LED Technology.

Question 1: Do you use LED technology and if yes in which kinds of applications?

From amongst the 61 participants, 58 replied to the question. This means that the sample size that responded to Question 1 is 95%.

Question 1 revealed that all 58 participants use LED Technology in various applications. All of the participants use LEDs in both interior and exterior applications, cove lighting, concealed lighting, under-cabinet and under-counter lighting, decorative lighting, indirect lighting, accent lighting, indication lighting, as well as ambient lighting. They also use LEDs in applications that require back illumination, special effects, colour changing effects, dynamic changes, as well as in applications where display panels are needed for video projection. Moreover, many participants use LEDs in special constructions that require small sized fittings.

In regard to architectural installations, most of the participants use LEDs for façade lighting, linear lighting, downlighting and spotlighting, display and showcase lighting, step and path lighting, exit and emergency lighting, task lighting, fountain and under-water lighting, as well as linear lighting. Moreover, many participants use LEDs in installations that require low illumination levels and energy efficiency.

LEDs are used in the leisure industry and more particularly in hotels, bars, restaurants and coffee shops. Moreover, LEDs are used in the retail industry, and more specifically in shops and showcases. Furthermore, LEDs are used in the hospitality and healthcare industry, such as in hospital MRI rooms. Finally, LEDs are used to reinforce urban and landscape architecture, while they are also used in residential spaces to enhance decoration.

Question 2: What do you think of the use of LEDs in today's environment?

From amongst the 61 participants, 58 replied to the question. This means that the sample size that responded to Question 2 is 95%.

Question 2 revealed the belief that LEDs are a very powerful tool, a viable alternative source, offering endless possibilities to lighting design schemes. LEDs are used by the majority of participants, in today's environment, mainly because they are energy efficient, environmental friendly, long lasting and small in size, low power consuming, maintenance-free and sustainable.

Question 2 also reported some worries about LEDs being hyped up too much and over-rated. It revealed the belief that LEDs are only a tool in a whole array of tools that cannot be used in every situation. LEDs cannot replace conventional lamps in terms of light output, colour, and price, in applications such as general lighting. Thus, according to many participants, LEDs need to be further improved.

Moreover, Question 2 revealed that the available knowledge in regard to LEDs is not clear. One participant said "… *it is still the wild west*". Another participant explained that "*We are finally moving past the early adapter stage, but one must be very careful with so many claims and poorly made products*". The above statements express the belief of some participants that LED technology is a very new technology that still has far to go, thus it needs to be used with care. At the same time, it implies the need for further research on the field.

Question 3: What do you think is the future of LED Technology?

From amongst the 61 participants, 59 replied to the question. This means that the sample size that responded to Question 3 is 97%.

Question 3 revealed that some participants are optimistic about the future of LED technology. These participants actually believe that LED technology *is* the future in lighting, and that as the dust settles there will be some good products and applications to use them. More specifically, these participants claimed that as the colour, colour rendering index, and the efficiency improve, while the cost comes down, there will be more and wider use of LEDs. These improvements will lead to the extended use of high power white LEDs in applications such as general downlighting, cove lighting, display lighting; replacing traditional lamps and older lighting technologies. In addition, LEDs will continue to expand into broader areas, ensuring a tremendous future of the technology. One example is the OLED (Organic LED) technology that allows new applications, such as the creation of self-illuminated surfaces in commercial applications.

At the same time, other participants believe that the future of LED technology is questionable and debatable, with too many promises made today that do not look like they will come to realization. These participants explain that there is still a long way to go and several issues need to be dealt with, such as: heat dissipation, new optics, colour stability, CRI, light output, lumen maintenance, and drivers that will last as long as the LEDs. Participants also noted the need to stabilize development. LED technology is growing rapidly, and this causes problems with keeping up on the technology. Therefore, it is possible that when LEDs eventually fail there might not be an equivalent LED replacement in the future. Other participants claimed that most R&D investments will someday yield and a new technology will come up.

At the same time, many participants pointed out the need of defining means of testing as well as the *"… need of more accurate technical and photometric values given by manufacturing companies*". In addition, some participants noted the "…*need to find consistency in colour and intensity of LEDs, and a standard methodology of testing for their photometric performance*". Finally, a few participants noted the importance of defining "white" colour of LEDs.

Question 4: How literate do you think are different groups of people in regard to LEDs?

Figures 5.1-5.6 show how literate participants think that lighting designers, architects, decorators (interior designers), electrical engineers, contractors and end users are in regard to LED technology.

In particular, Figure 5.1 reveals that 61% of the participants think that lighting designers are familiar with LED technology. In addition, 30% of the participants believe that lighting designers have moderate knowledge on LED technology, while 3% think that lighting designers have little knowledge. 7% of the participants did not reply to Question 4.1.

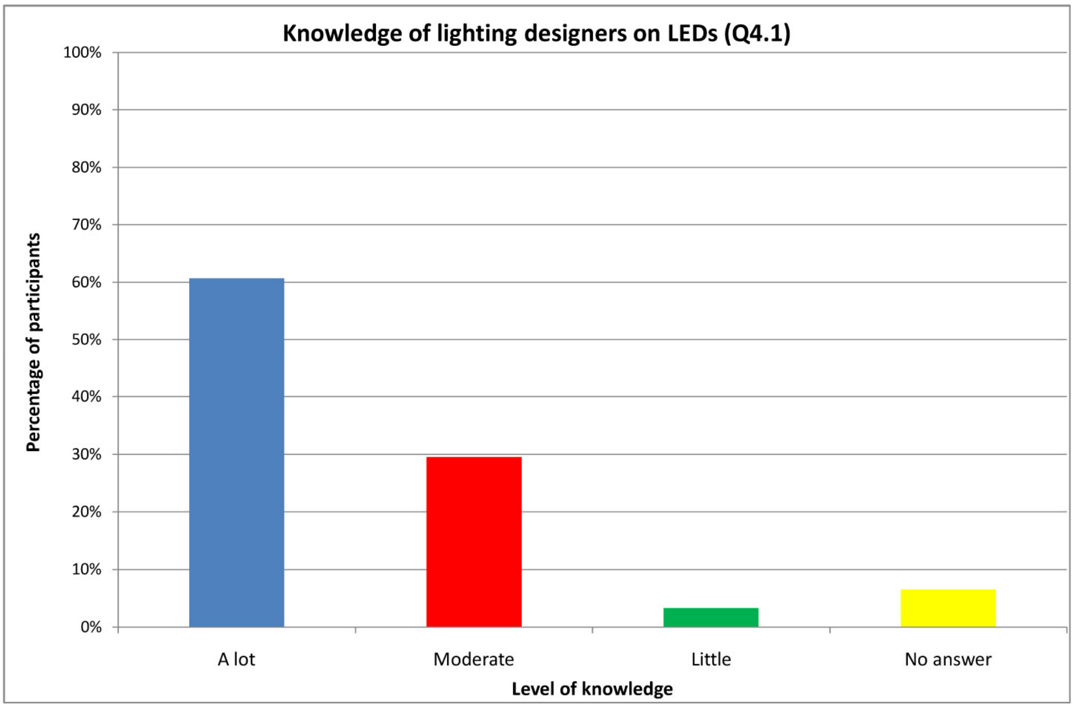


Figure 5.1: Degree of knowledge of Lighting Designers on LEDs (Q4.1)

Figure 5.2 indicates that none of the participants (0%) believe that architects know a lot about LEDs. On the contrary, 49% of the participants claimed that architects have moderate knowledge on LEDs. 46% of the participants claimed that architects have little knowledge on LEDs. Finally, 5% of the participants did not reply to Question 4.2.

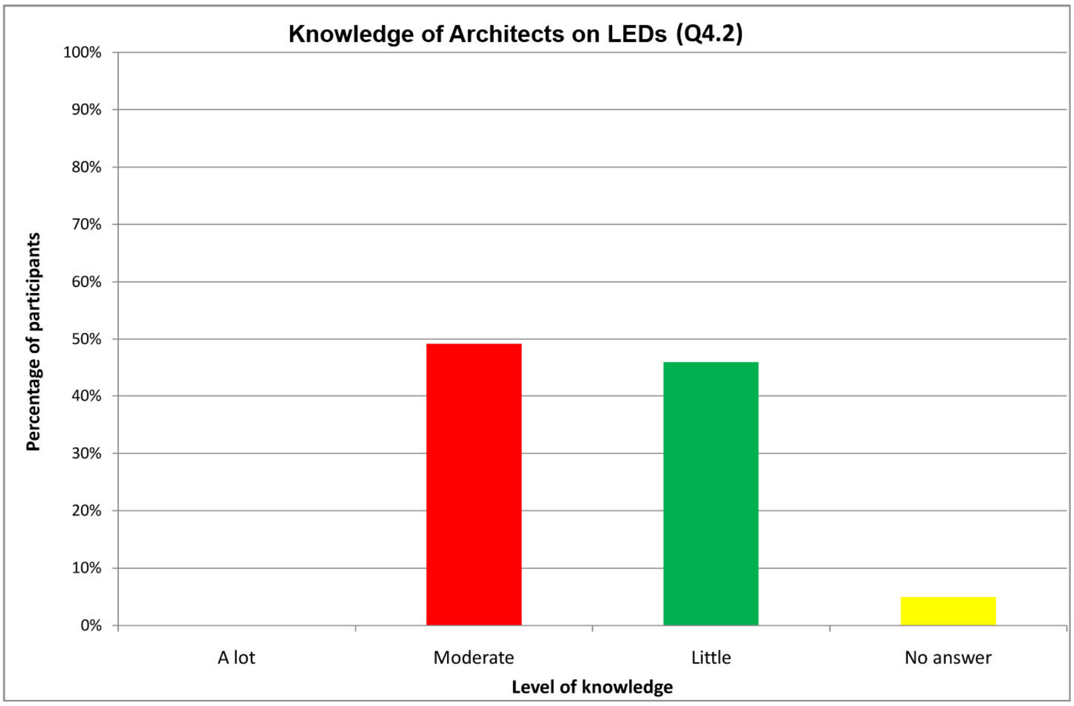


Figure 5.2: Degree of knowledge of Architects on LEDs (Q4.2)

Figure 5.3 indicates that only 2% of the participants believe that decorators/ interior designers have a lot of knowledge on LEDs, while 11% think that decorators have moderate knowledge on LEDs. On the contrary, the vast majority of 82% of the participants claimed that decorators have little knowledge on LEDs. Finally, 5% of the participants did not reply to Question 4.3.

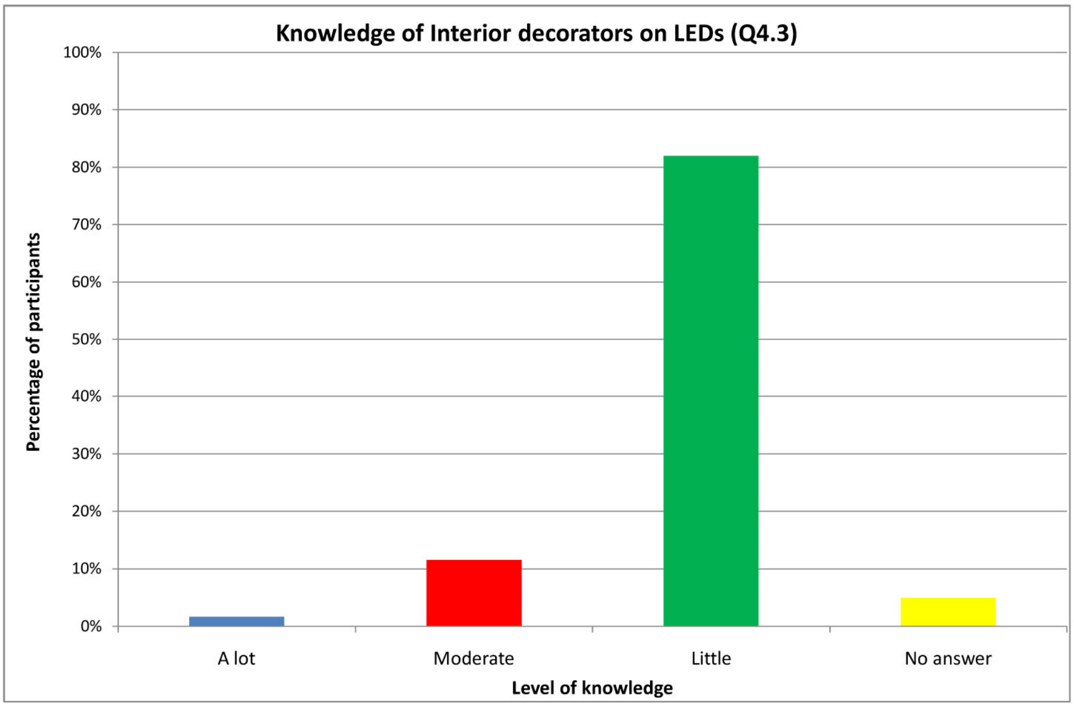


Figure 5.3: Degree of knowledge of interior designers on LEDs (Q4.3)

Figure 5.4 indicates that 18% of the participants believe that electrical engineers have a lot of knowledge on LEDs. The majority of 51% of the participants claimed that electrical engineers have moderate knowledge on LEDs. Furthermore, 26% of the participants claimed that electrical engineers have little knowledge on LED technology. 5% of the participants did not reply to Question 4.4.

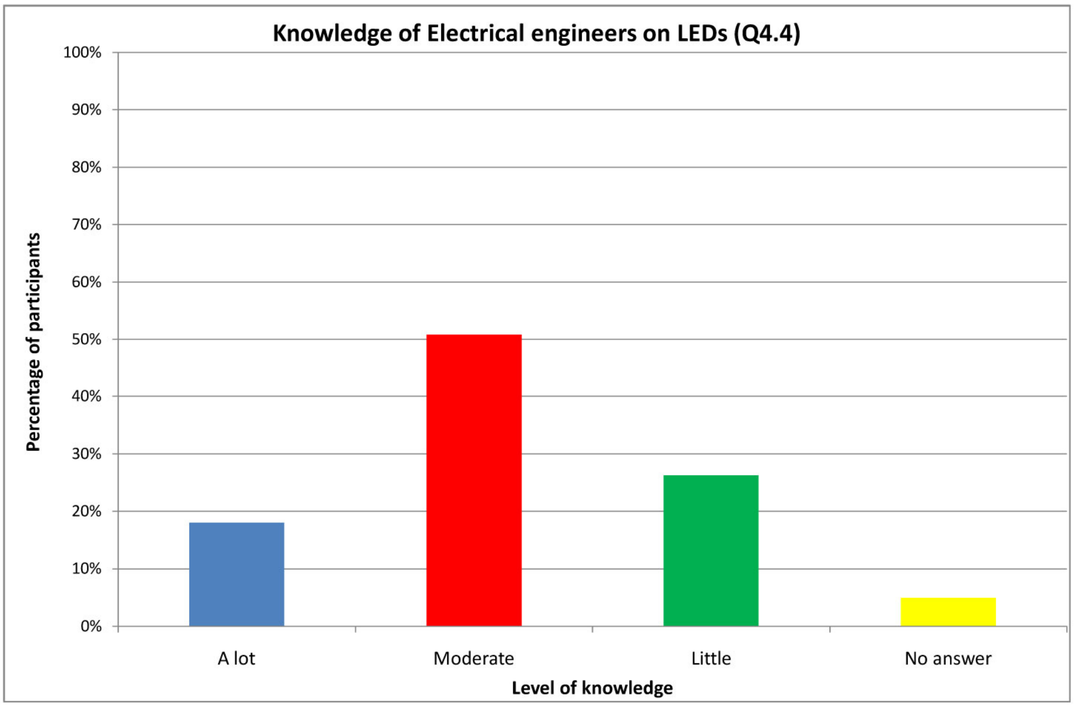


Figure 5.4: Degree of knowledge of Electrical Engineers on LEDs (Q4.4)

Figure 5.5 reveals that only 3% of the participants think that contractors have a lot of knowledge, while 21% claimed that contractors have moderate knowledge on LEDs. The vast majority expressed by 70% of the participants believe that contractors have little knowledge on LED technology. Finally, 5% of the participants did not reply to Question 4.5. Note that the results are rounded to the correct value.

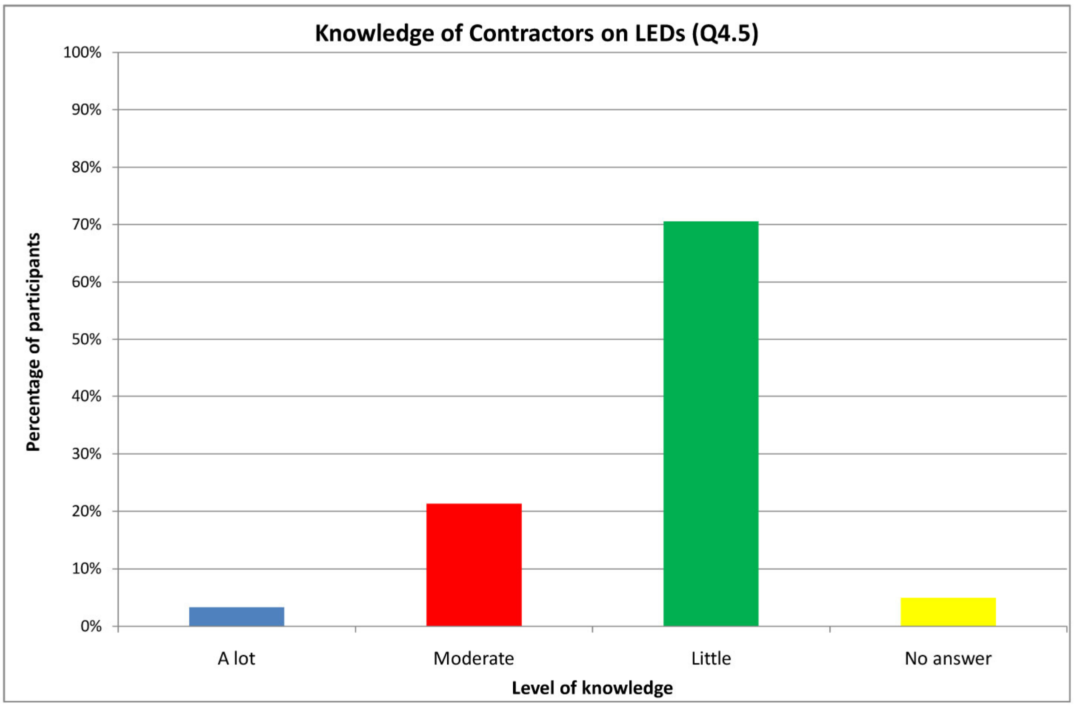


Figure 5.5: Degree of knowledge of Contractors on LEDs (Q4.5)

Figure 5.6 suggests that 89% of the participants believe that end users have little knowledge on LEDs. None of the participants claimed that end users have a lot of knowledge, while only 3% of the participants said that end users have moderate knowledge on LEDs. Finally, 8% of the participants did not reply to Question 4.6.

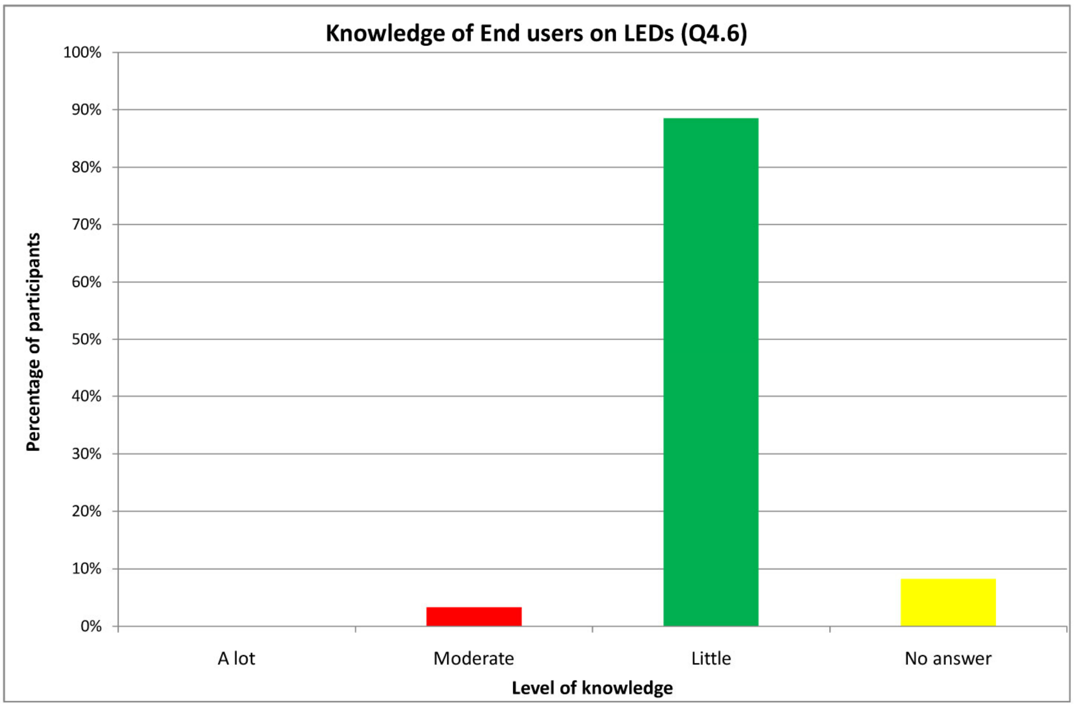


Figure 5.6: Degree of knowledge of End Users on LEDs (Q4.6)

Question 5: How do you learn about the available LEDs, LED luminaires and the latest LED developments?

From amongst the 61 participants, 58 replied to the question. This means that the sample size that responded to Question 5 is 95%.

The replies revealed that most of the participants learn about the available LEDs, luminaires and developments, mainly through trade shows and exhibitions. Indeed, this is a good way to become aware of the great variety of products that are available in the market by different manufacturers, to get informed about the new trends in lighting, and to be introduced to the latest technological advancements. Moreover, trade shows and exhibitions are places where the lighting community comes together thus lighting designers, manufacturers, architects, electrical engineers and others can directly discuss and exchange ideas and information.

Moreover, many participants claimed that they learn about LED technology and products directly through manufacturers and/ or their sales representatives in each country. Thus, manufacturers may organize product presentations so as to introduce LEDs and discuss about case studies where specific products have been installed. Alternatively, manufacturers may organize seminars and/ or workshops and/ or sessions on LED technology and products, in order to acquaint participants both with the technology and the product variety that they offer.

It is also often the case that participants familiarize with LED technology and products through manufacturers' product demonstrations, which take place even at the participants' offices. Moreover, many participants often get samples from manufacturers in order to explore the technical characteristics of products through trial and error and to investigate their capabilities in real installations.

In addition, some participants become aware of what is new through manufacturers' newsletters, brochures, and publications. Moreover, they get informed through the press, and more particularly through lighting magazines, trade journals, technical articles, research papers, and other literature. Many participants explained that they also do research on the internet, where information is available for everyone to use.

A few participants claimed that they also receive information directly from colleagues who have already used LED products in the past and have experience and knowledge to share. In such case, participants noted also the importance of 'word of mouth' which suggests that they value whatever information comes to their attention. In relation to that, some participants said they also learn by observation of case studies and by studying project awards.

Finally, some participants suggested that they get informed through community forums and lighting conferences. Also, they become aware of the latest developments through lighting associations such as IALD (International Association of Lighting Designers),IES (Illuminating Engineering Society), PLDA (Professional Lighting Designers' Association), and SLL (Society of Light & Lighting), as well as through government organizations such as DOE(USA Department of Energy) and other national committees involved in the innovation and progress of the industry. Lastly, a few participants explained that they also learn about LEDs through postgraduate studies and other educational programs.

Question 6: What are the major criteria when selecting a LED luminaire?

From amongst the 61 participants, 58 replied to the question. This means that the sample size that responded to Question 6 is 95%.

Most of the participants explained that they take into consideration a variety of criteria when selecting a LED luminaire. To begin with, these participants give a lot of importance to criteria related to colour and more particularly to colour consistency (especially for white), Correlated Colour Temperature (CCT), Colour Rendering (CRI), and binning of the LEDs.

Moreover, important criteria are the overall performance of the LED luminaire, and in particular the light output, the brightness, the efficacy of the fixture. Also, significant criteria are the power consumption, the energy efficiency and the lifetime of the LEDs. In relation to all the above, most participants expressed the importance of having photometric data for the LED luminaires.

In regard to the construction and engineering of a LED luminaire, many participants explained the importance of various factors when making a selection, such as the operating temperature, heat dissipation and thermal management. Important factors are also the optical systems, the beam control, the glare protection, and the driving and dimming capabilities.

Additionally, the luminaire design and appearance are important criteria as they need to be in consistence with the architectural and ornamental characteristics of the space. Likewise, dimensions, size, mounting capabilities, ease of maintenance, functionality, and cost seem to also be significant criteria when selecting a LED luminaire. Of course, LED luminaires need to have the appropriate certificates such as CE and UL, depending on the country where the products are to be installed.

Nevertheless, regardless of the above mentioned criteria, some participants claimed that because there is a vast variety of LEDs in the market, they select luminaires only after testing them. However, this is not always feasible, which is why most participants value a lot the reputation and reliability of both the luminaire and the LED manufacturer.

Indeed, many participants claimed that a major criterion when selecting a LED luminaire is the 'quality' of manufacturer. By this, participants refer to the ability of a manufacturer to understand LEDs and answer technical questions relating to the design life, operating temperature, wiring connections, and so on. Also, they refer to the ability of a manufacturer to follow through if any problems come up in an installation and to demonstrate ability to trace the LED components used.

Finally, some participants value the warranty of the luminaire and expect at least three or five year warrantee, to assure themselves about the quality of the product and the spare parts availability in the future.

Question 7: What are the major criteria when selecting a LED luminaire manufacturer?

From amongst the 61 participants, 58 replied to the question. This means that the sample size that responded to Question 7 is 95%.

Most of the participants value a lot the reputation of manufacturers. These participants trust manufacturers who are well established and have a promising future. They also trust manufacturers with high credibility and reliability. In addition, most of the participants explain that although some manufacturers may be very good in conventional fixtures, they may be poor in LEDs. Therefore, they prefer to cooperate with manufacturers who specialize on LEDs. Therefore, they want to know if manufacturers manufacture LED products or assemble luminaires; if manufacturers have their own in-house technical support; and if manufacturers have a Research & Development department.

Moreover, many participants select LED luminaire manufacturers based on their ability to provide quality information and well-documented data in relation to their products; to present technical specifications; to give technical guidelines and installation advice; to offer adequate after-sales service through their representatives; and to solve any kind of problems that may arise. In addition, some participants select manufacturers based on the warrantee that they offer, and on claims of future product and components availability.

Most of the participants select manufacturers based on their ability to replace products during the life-cycle of the building, which could be 20-30 years; to customize fixtures for specific applications; to provide competitive price; to offer simple installation and ease of use; to be compatible with CE, UL and other standards.

Finally, all of the participants select manufacturers that provide quality products. For that reason, participants often request samples and test product characteristics. Participants also value the reputation of the LED chip/ module manufacturer. Thus, the quality of the LED module itself is also important.

Question 8: What kind of information do you require from LED manufacturers and how much do you value this information?

Figures 7-20illustrate the kind of information that participants require from LED manufacturers, as well as the level of importance that participants give toeachlighting parameter, in a scale ranging from very high, high, and moderate importance to low and very low importance.

Figure 5.7shows that 54% of the sample values colour range availability (Q8.1) with very high importance, 25% with high importance, 15% with moderate importance, and 2% with low importance. None of the participants replied that colour availability is of very low importance, whereas 5% of the sample did not reply to the question.

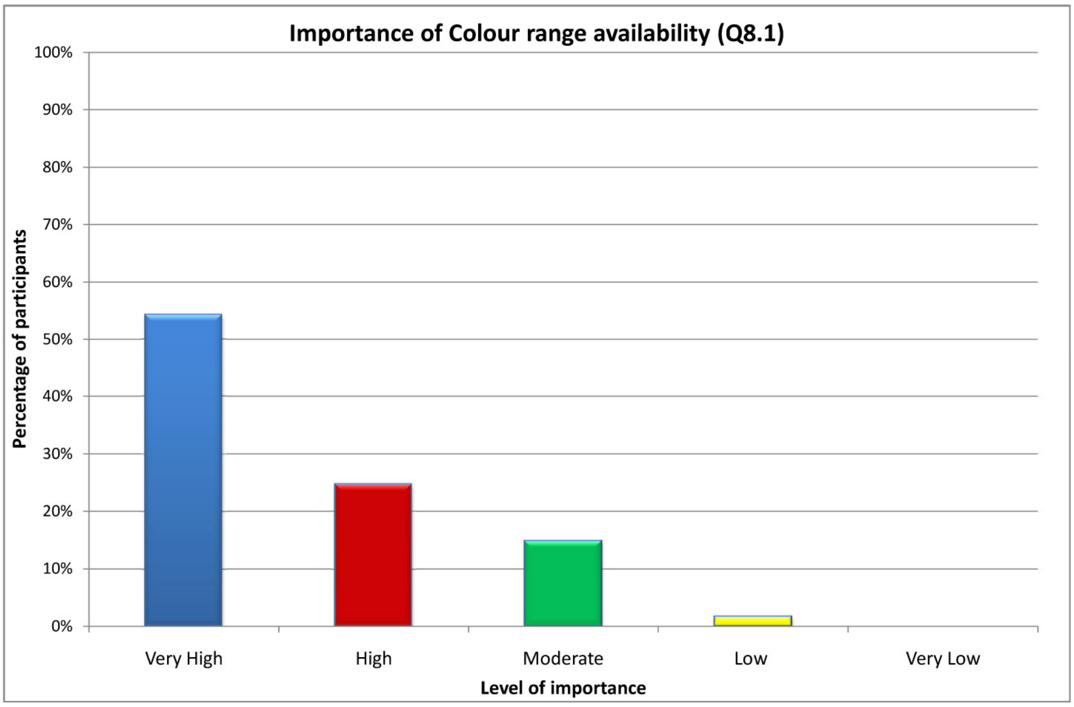


Figure 5.7: Importance of Colour range availability (Q8.1)

Figure 5.8illustrates that 59% of the participants value lumen output (Q8.2) with very high importance, 30% with high importance, and 7% with moderate importance. No participant claimed that lumen output is of low or very low importance, while 5% of the participants did not reply to the question. Note that the results are rounded to the correct value.

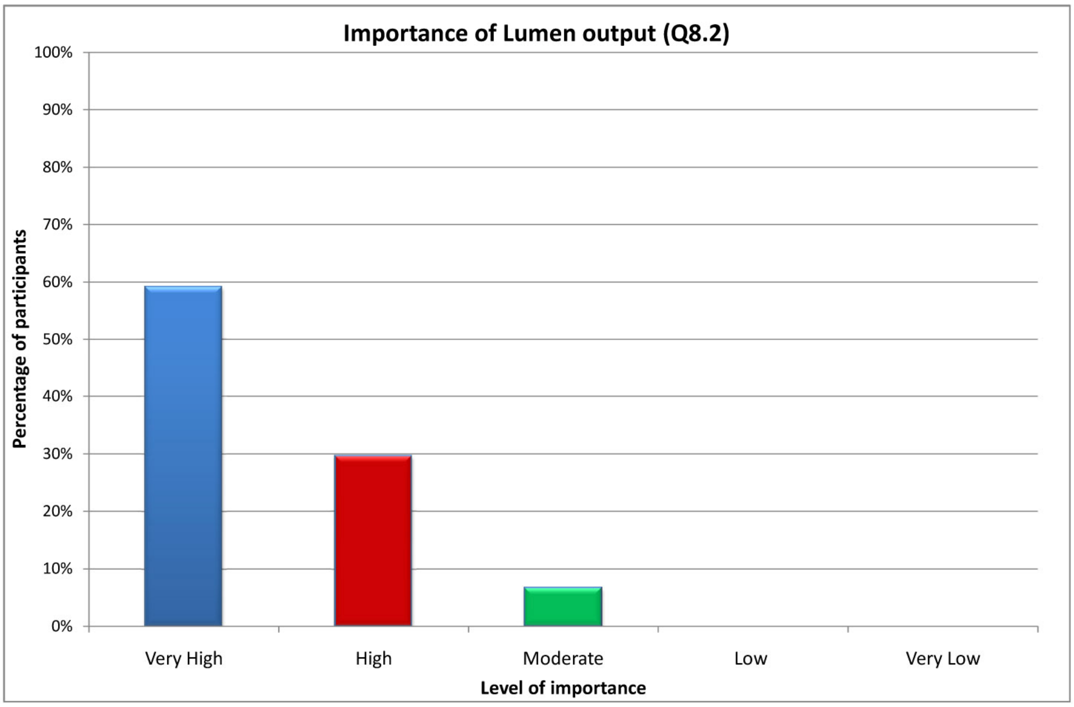


Figure 5.8: Importance of Lumen output (Q8.2)

Figure 5.9presents that 69% of the sample values colour consistency (Q8.3) with very high importance, 21% with high importance, 3% with moderate importance, and 2% with low importance. None of the participants claimed that colour consistency is of very low importance, while 5% of the participants did not reply to the question.

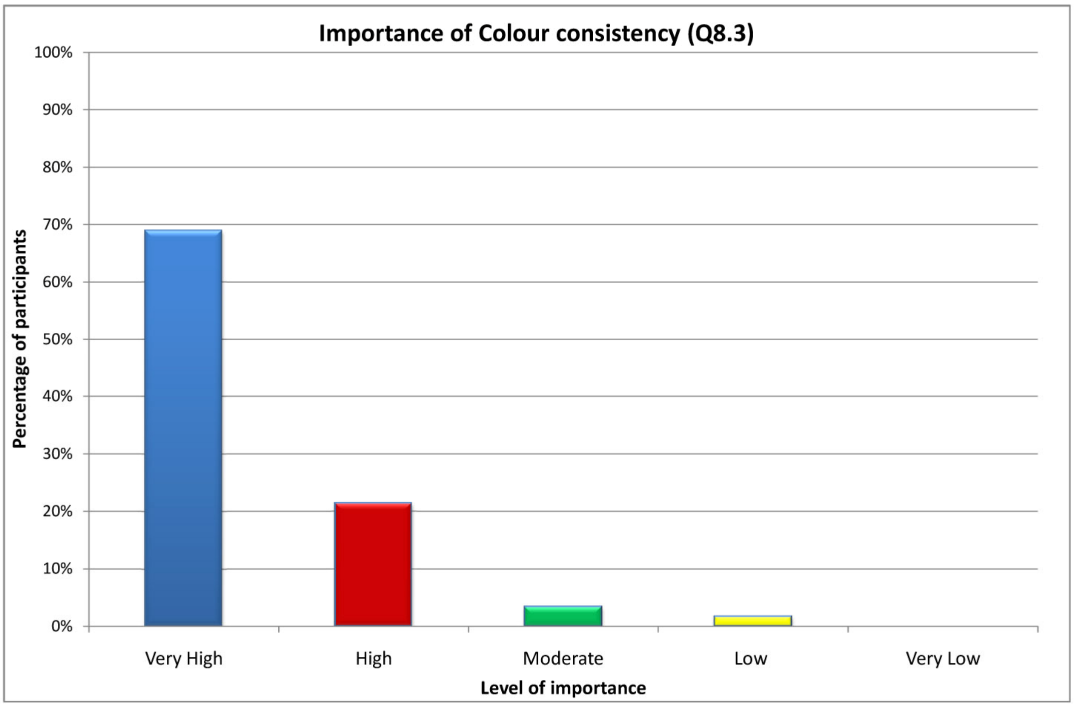


Figure 5.9: Importance of Colour consistency (Q8.3)

Figure 5.10 shows that 43% of the sample values lumen maintenance (Q8.4) with very high importance, 38% with high importance, 10% with moderate importance, and 5% with low importance. At the same time, no participant claimed that lumen maintenance is of very low importance, while 5% did not reply to the question. Note that the results are rounded to the correct value.

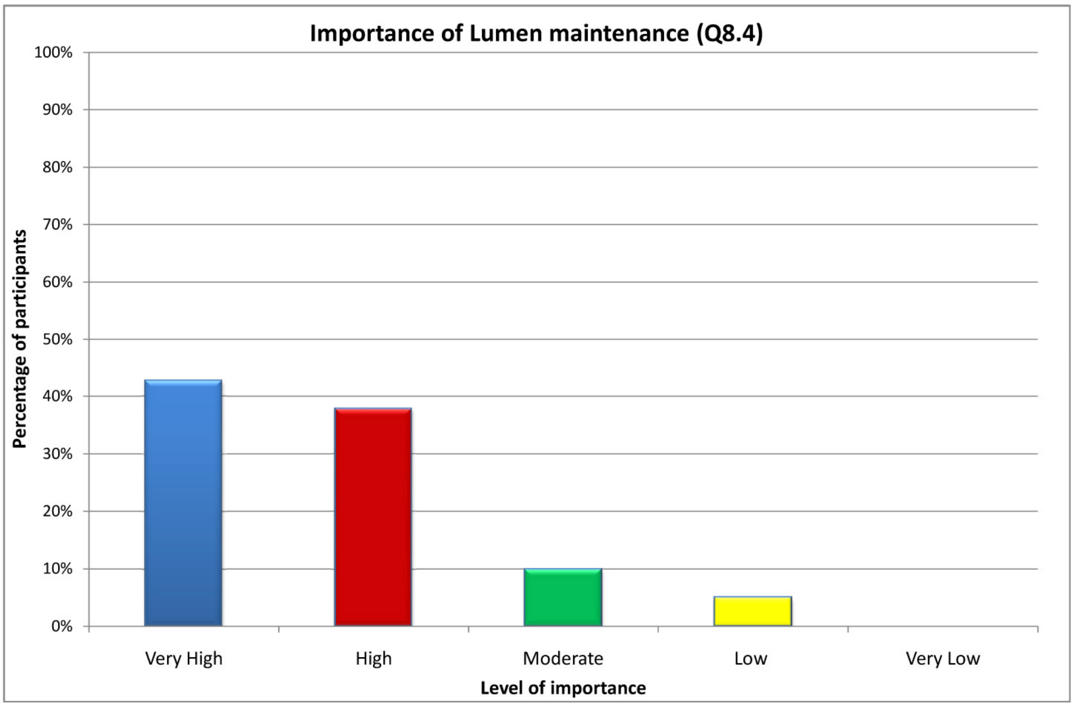


Figure 5.10: Importance of Lumen maintenance (Q8.4)

Figure 5.11 illustrates that 49% of the sample values stability (Q8.5) with very high importance, 36% with high importance, 7% with moderate importance, and 2% with low importance. None of the participants said that stability is information of very low importance, while 7% did not reply to this question. Note that the results, rounded to the correct value.

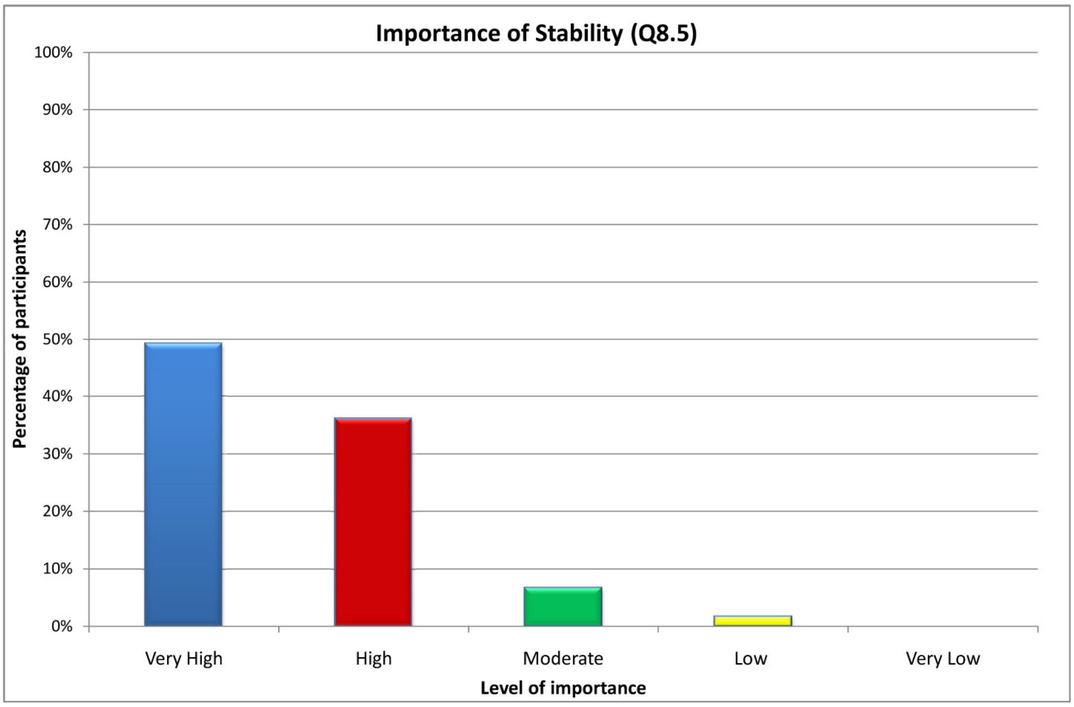


Figure 5.11: Importance of Stability (Q8.5)

Figure 5.12 indicates that 39% of the participants value, control capabilities (Q8.6) with very high importance, 43% with high importance, and 13% with moderate importance. No participant said that control capabilities are either of low or of very low importance. Finally, 5% of the sample did not reply to the question.

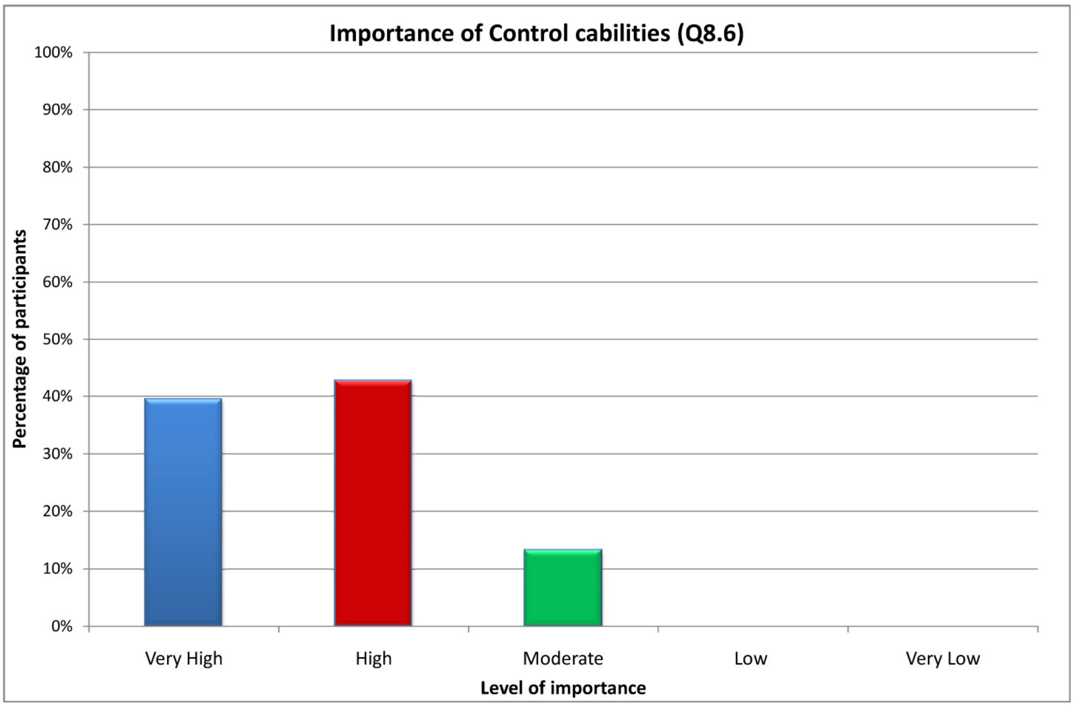


Figure 5.12: Importance of Control capabilities (Q8.6)

Figure 5.13 illustrates that 36% of the participants, value lifetime of LEDs (Q8.7) with very high importance, 28% with high importance, 25% with moderate importance, and 7% with low importance. No participant claimed that lifetime is of very low importance, whereas 5% of the sample did not reply to the question. Note that the results are rounded to the correct value.

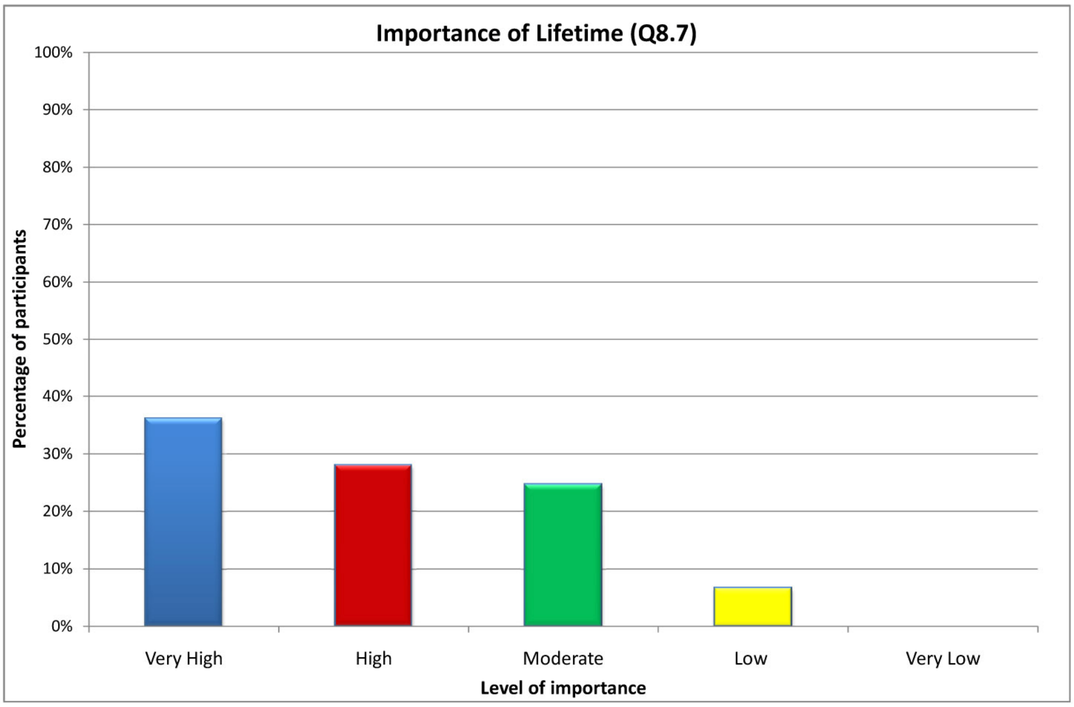


Figure 5.13: Importance of Lifetime of LEDs (8.7)

Figure 5.14 shows that 13% of the participants value RGB colour mixing (Q8.8) with very high importance and 23% with high importance. Nevertheless, the majority of the participants expressed by 43% claimed that RGB colour mixing is of moderate importance. At the same time, 13% of the participants said that RGB colour mixing is of low and 2% said it is of very low importance. Finally, 7% of the sample did not reply to this question. Note that the results are rounded to the correct value.

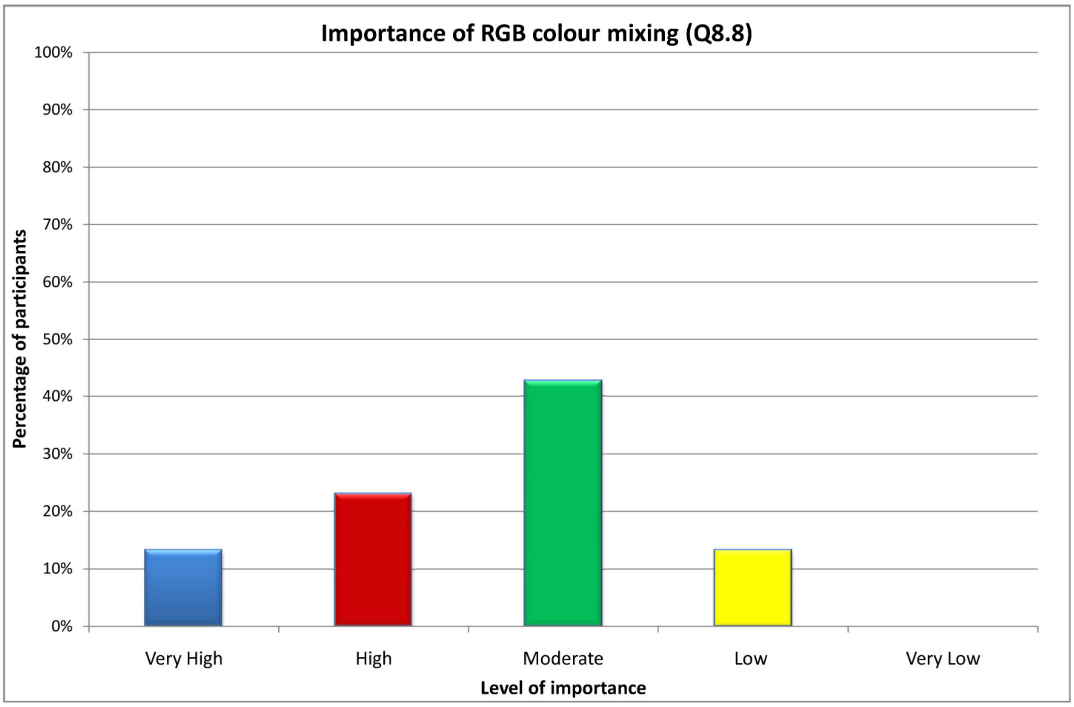


Figure 5.14: Importance of RGB colour mixing (Q8.8)

Figure 5.15 suggests that the majority of participants, 67%, value white colour availability (Q8.9) with very high importance. In addition, 21% of the participants value white colour availability with high importance, 2% with moderate importance, and 5% with low importance. No participant claimed that white colour availability is of very low importance, while 5% of the participants did not reply to the question.

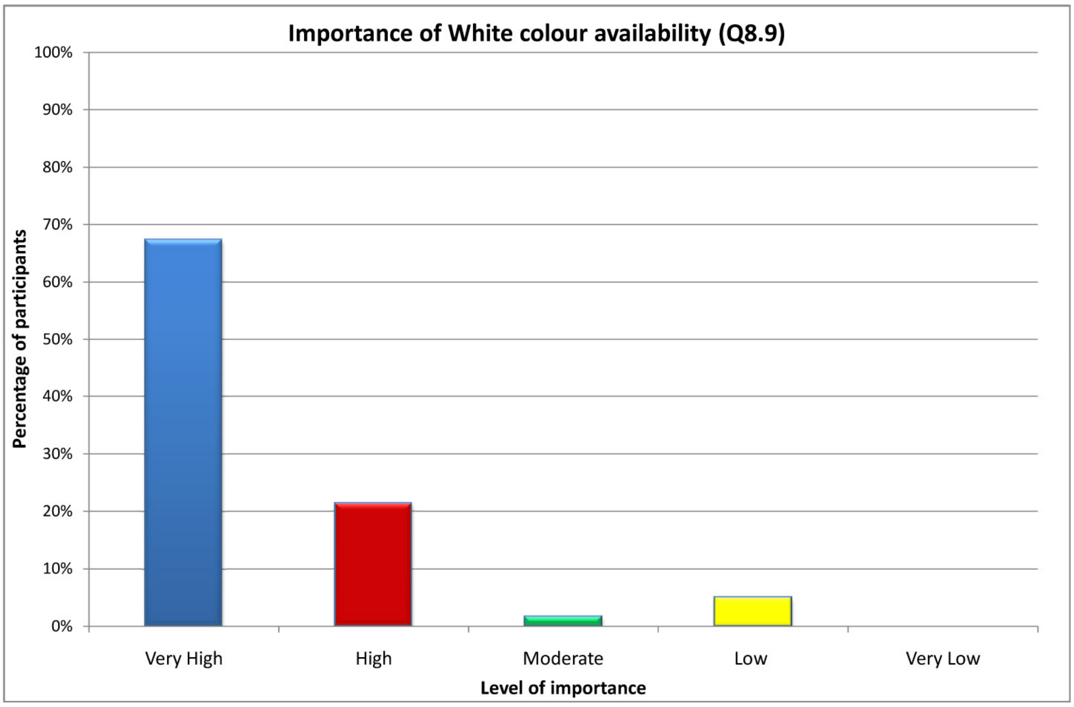


Figure 5.15: Importance of White colour availability (Q8.9)

Figure 5.16 illustrates that the majority of the participants, 61%, value Correlated Colour Temperature (Q8.10) with very high importance, 23% with high importance, 8% with moderate importance, and 3% with low importance. No participant said that CCT is of very low importance, while 5% of the participants did not reply to the question.

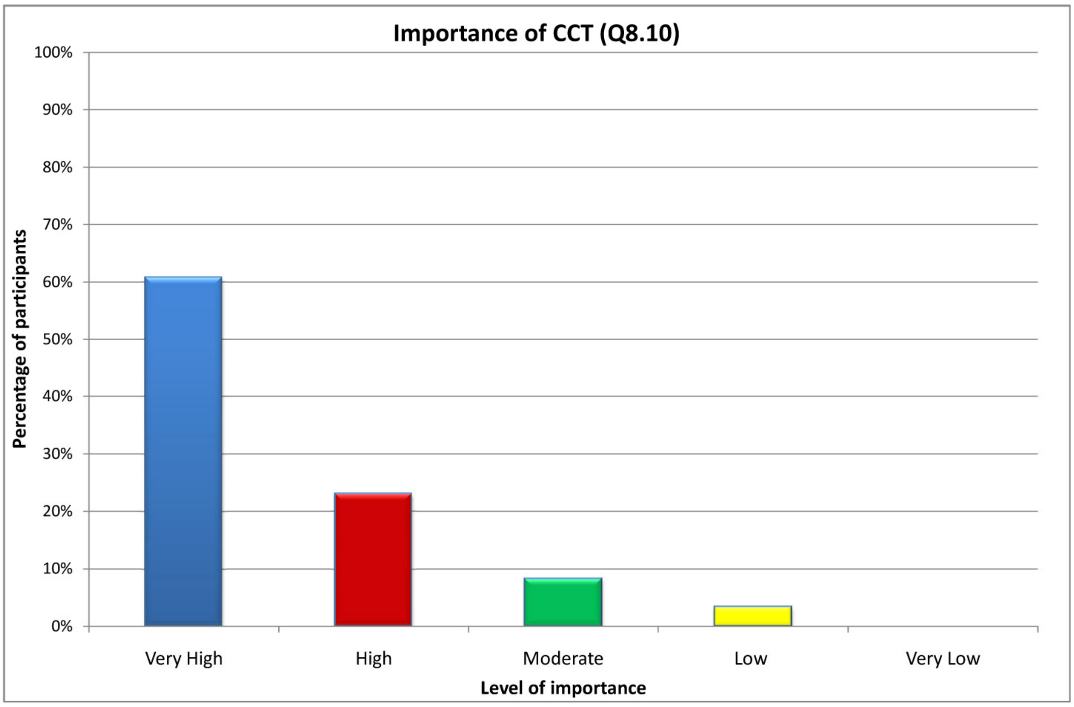


Figure 5.16: Importance of Correlated Colour Temperature (Q8.10)

Figure 5.17 indicates that 52% of the participants value Colour Rendering Index (Q8.11) with very high importance, 23% with high importance, 15% with moderate importance, and 3% with low importance. No participant claimed that CRI is of very low importance, while 7% did not reply to the question.

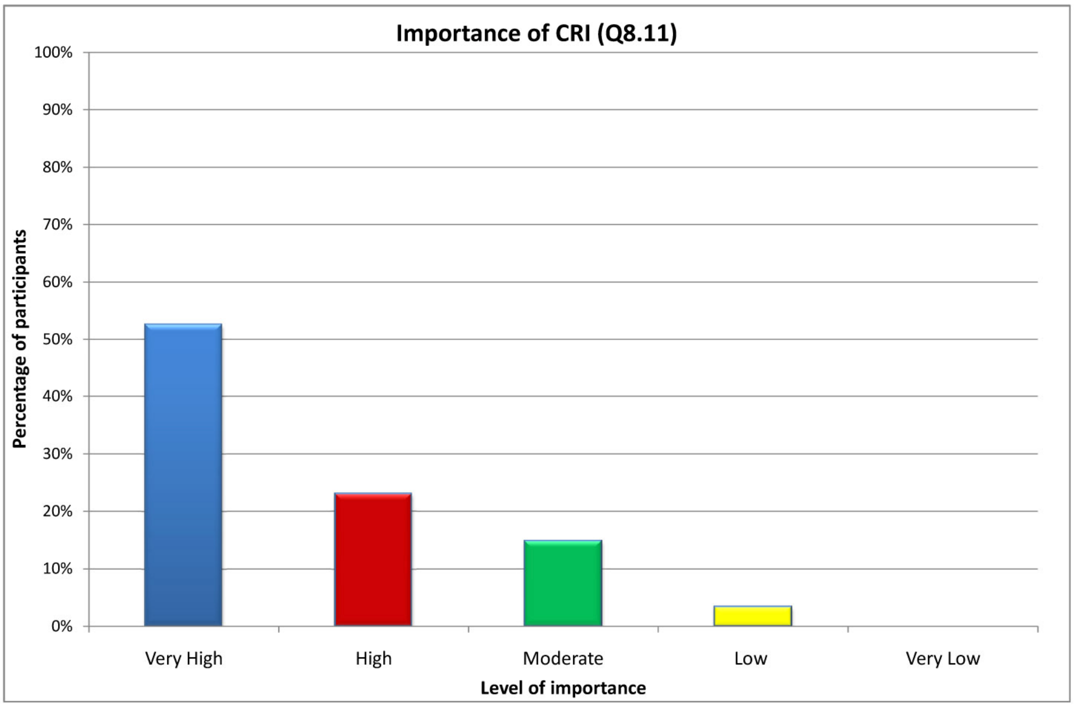


Figure 5.17: Importance of Colour Rendering Index (Q8.11)

Figure 5.18 shows that 49% of the participants value LED luminaire design (Q8.12) with very high importance, 31% with high importance, 11% with moderate importance, and 2% with low importance. No participant said that LED luminaire design is of very low importance, whereas 7% did not reply to the question.

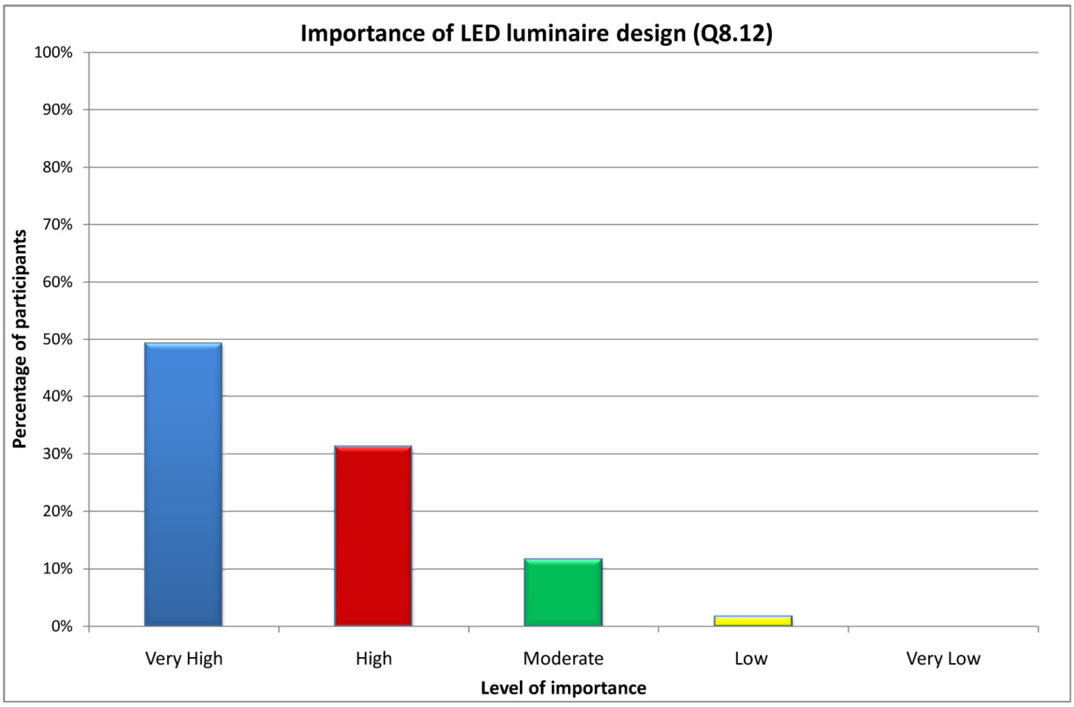


Figure 5.18: Importance of LED luminaire design (Q8.12)

Figure 5.19 suggests that 36% of the participants value cost (Q8.13) with very high importance, 31% with high importance, 18% with moderate importance, and 8% with low importance. No participant said that cost is of very low importance, while 7% did not reply to the question.

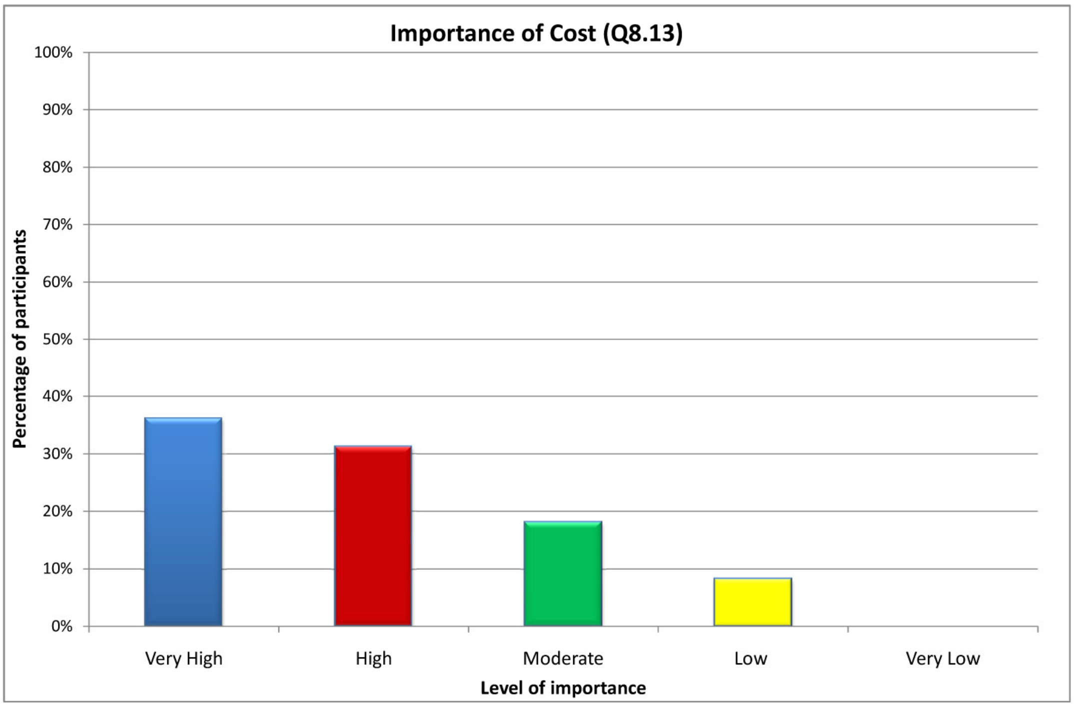


Figure 5.19: Importance of Cost (Q8.13)

Figure 5.20 indicates that 38% of the participants value the power of LEDs (Q8.14) with very high importance, 31% with high importance, 18% with moderate importance, and 7% with low importance. No participant said that LED power is of very low importance, while 7% did not reply to the question. Note that the results are rounded to the correct value.

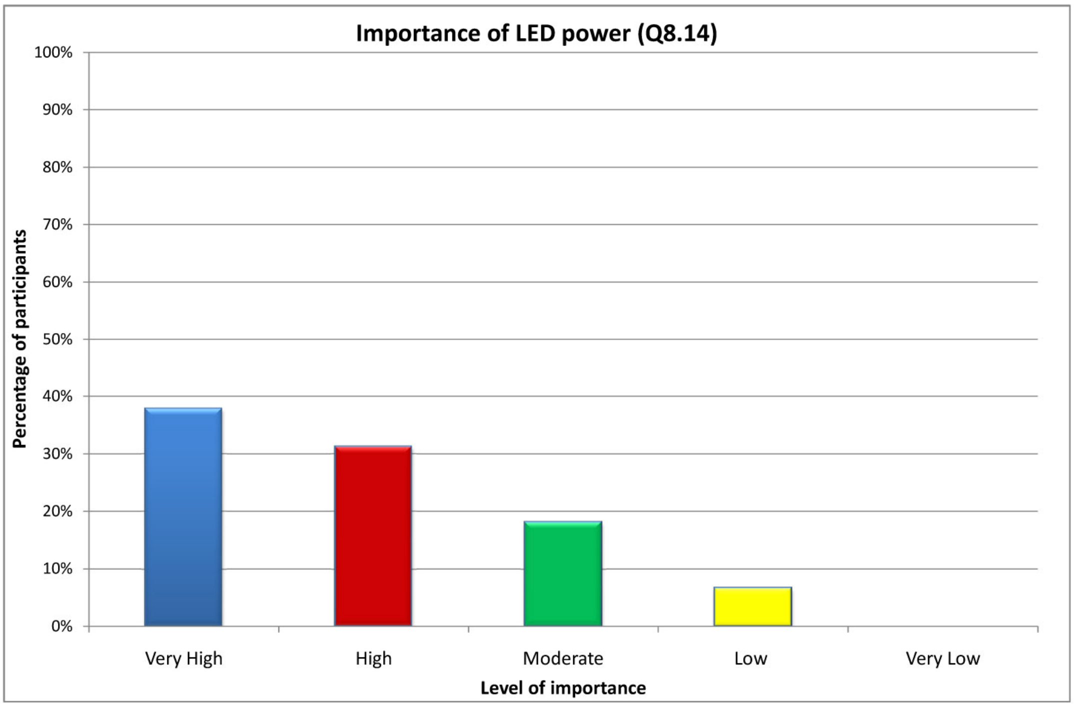


Figure 5.20: Importance of Power of LEDs (Q8.14)

The findings of Figures 5.7-5.20 show that participants require a variety of information from manufacturers, which they value as more or less important.

Figure 5.21summarizes the information of very high importance that participants require from manufacturers. The statistical data derived by capturing the percentages of participants that valued with ‘very high’ importance the various lighting parameters (refer to the blue columns in Figures 5.7-5.20).

In particular, Figure 5.21 shows that colour consistency is the most important information (69%) that participants require from LED manufacturers. Moreover, participants value with very high importance information on white colour availability (67%), CCT (61%), lumen output (59%), colour range availability (54%), and CRI (52%). Stability (49%) and luminaire design (49%) have the same but less importance for participants. In turn, lumen maintenance (43%), control capabilities (39%), and power (38%) are even less important. Consecutively, lifetime of LEDs (36%) and cost (36%) have the same but low importance to participants, while RGB colour mixing is the least important (13%) information that participants require from LED manufacturers.

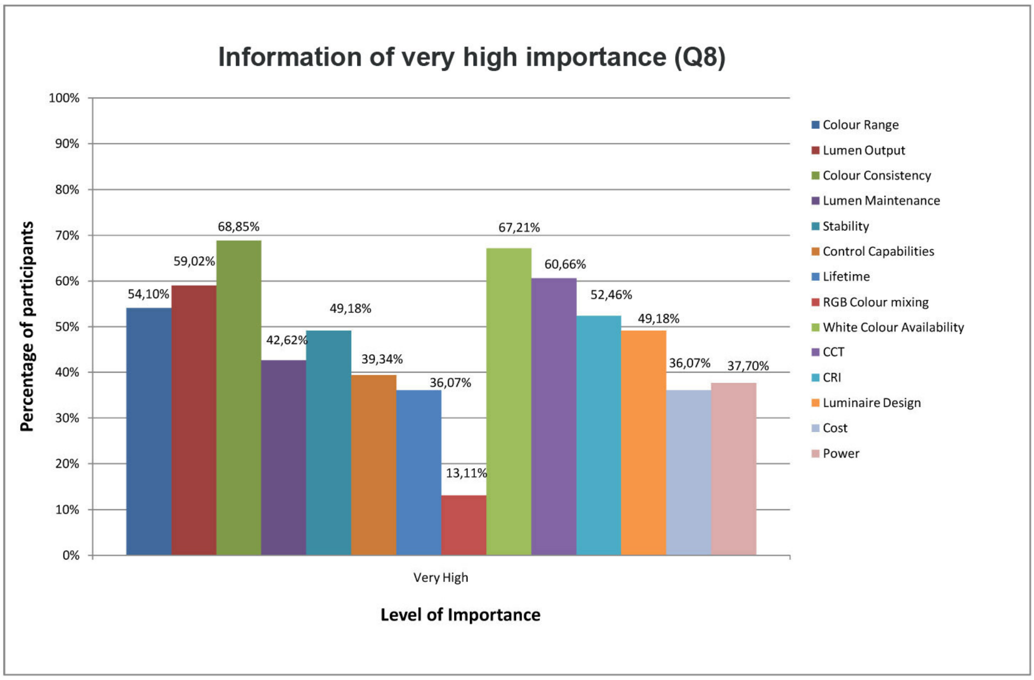


Figure 5.21: Information of very high importance expected from manufacturers

Similarly, Figure 5.22 summarizes the information that is of very high and high importance. In this case, the statistical data derived by adding the percentages of participants that claimed 'very high' and 'high' importance to the various parameters (refer to the blue and red columns in Figures 5.7-5.20).

In particular, Figure 5.22showsthatcolour consistency (90%) is indeed the most important data that participants expect from manufacturers. Similarly, participants value with very high and high importance the following parameters: lumen output (89%), white colour availability (89%), stability (85%), CCT (84%), lumen maintenance (80%), control capabilities (82%), luminaire design (80%), colour range (79%), CRI (75%), lifetime (64%), RGB colour mixing (36%), cost (67%), power (67%).

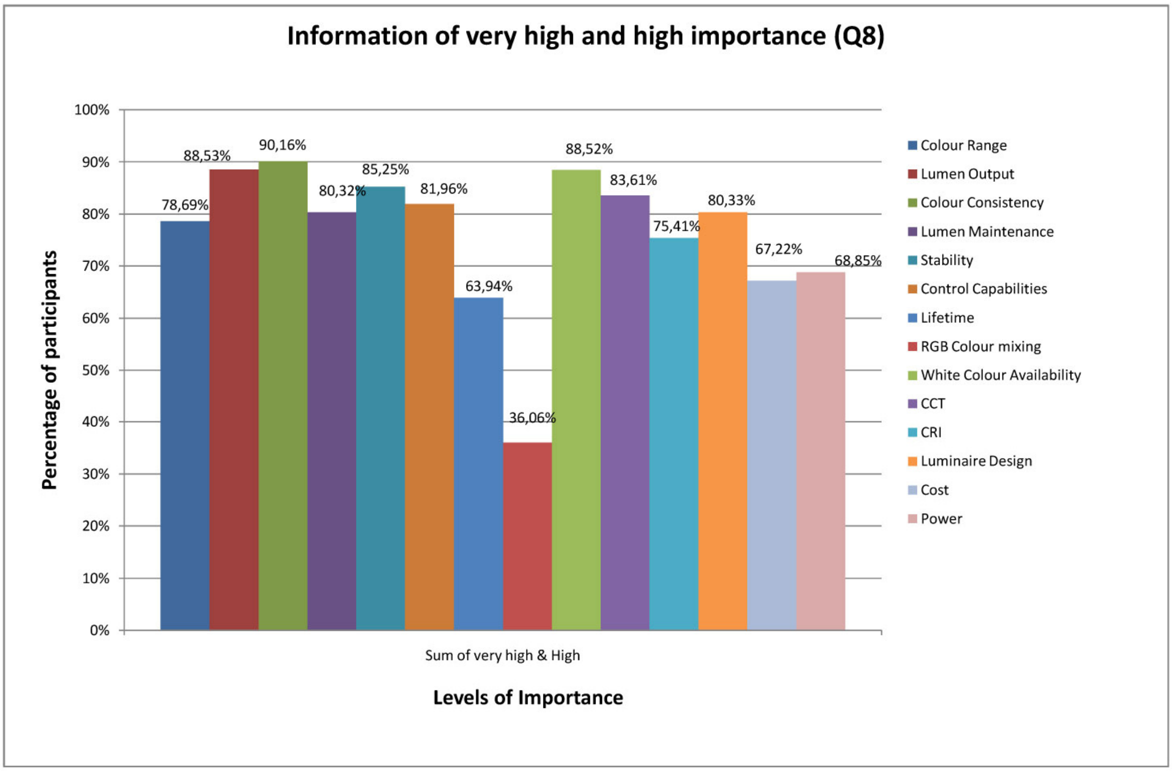


Figure 5.22: Information of very high and high importance expected from manufacturers

Figure 5.21 and Figure 5.22 indicate that there is a pattern as to what information is most important or least important to participants. In particular, colour consistency is the number one priority, whereas RGB colour mixing or cost is the least important information.

5.1.2. Second Part of the Questionnaire

The second part of the Questionnaire referred to Lighting Design in the Leisure Industry.

Question 9: If the leisure industry is defined as hotels, bars and restaurants, what are the objectives of lighting in the leisure industry?

From amongst the 61 participants, 57 replied to the question. This means that the sample size that responded to Question 9 is 93%.

Question 9 revealed that lighting in the leisure industry should aim at creating an environment that is consistent with the customer's brief and the vision of the design team. Nevertheless, the major lighting objective should be to illuminate for the tasks in the space. In other worlds, lighting should be such so as to enable the end user to easily and safely perform the corresponding task.

After light for tasks, comes light for aesthetics. Thus, depending on the project the lighting objective could be to establish the appropriate ambience, to make the desired environment, to add sparkle, to create contrast. For example, the lighting objective could be to create a welcoming profitable experience that is perceived as an escape from day-to-day worries; to generate exciting and comfortable spaces that form memorable experiences; to make an attractive and relaxing venue to encourage visitors to repeat their visit. Alternatively, the lighting objective could be to create the desired mood; to generate an inviting atmosphere that merges with the architecture; to create a luminous ambience coherent with the interior design, the identity of the place and the activities; to create visual comfort, functionality and safety; to generate variety and interest; to be flexible so as to change depending on the different activities and times of the day.

According to most of the participants, the installation should generate quality light that makes the user experience in the space unique. This is why lighting designers usually aim at creating an aesthetically pleasing, relaxed, friendly, and calm environment in the leisure industry. Often, they add spikes of excitement and drama to generate interesting and stimulating spaces. This can be achieved by establishing a colourful environment, by adding lighting effects, by creating dynamic lighting, or by allowing dimming and control of lighting scenes.

In all cases, it is very important to consider a variety of factors when setting the lighting objectives in the leisure industry, including maintenance, energy efficiency and energy costs, sustainability, cost of the entire installation, appearance of lighting fixtures, dimming and control capabilities, as well as ease of use.

Question 10: What important issues should be considered when generating lighting design schemes in the leisure industry?

From amongst the 61 participants, 54 replied to the question. This means that the sample size that responded to Question 10 is 89%.

Question 10 revealed it is important to have in mind the vision of the customer and the design team, and then to think of the end users and their needs. In fact, most of the participants think that the focus should primarily be on people, their needs and their emotions, and then on the technology. In other words, it is important to consider what people expect and what will make them feel good.

In addition, it is important to consider the aesthetics and ambience in relation to the general architecture and interior design, finishes, and forms of the space. Consequently, it is important to create psychological and physiological comfort and interest within the space, to generate a warm and friendly atmosphere, to establish a safe and practically easy to use environment, to add drama, to make spatial and visual compositions, and to create a memorable experience.

Many participants also explained that it is important to balance the aesthetics and the quality desires against the realities of budget, maintenance, and energy consumption. Cost of fixtures, ease of maintenance of the installation, and energy costs are all important issues to consider. In turn, it is important to consider the appropriate and not excessive use of light, dimming and control capabilities, colour mixing and colour stability, dynamic effects, glare control, contrast between horizontal and vertical planes. Other issues to consider include functionality, safety, flexibility, integration of lighting scenes, interaction of light with space, sustainability, practicality, equipment integration and consistency of system operation, uniformity in the appearance of fixtures, safety, and security.

Question 11: What are the End User requirements and expectations in the leisure industry in terms of lighting and lighting design?

From amongst the 61 participants, 53 replied to the question. This means that the sample size that responded to Question 11 is 87%.

Most of the participants believe that end users, customers, and visitors, expect that installations in the leisure industry will look and feel like the ones they already love. Thus, it is important that lighting contributes to the creation of a relaxing and pleasant environment and to the establishment of a welcoming atmosphere. Moreover, lighting should create the appropriate mood and ambience, accentuate the architecture and design, and embellish the sense of space. Additionally, lighting should create visual comfort, drama, diversity, flexibility, and interest within the space so as to make a memorable experience.

Many responses show that end users expect that lighting will generate adequate levels of illumination so as to enhance the activities taking place within the space. Also, end users expect good, glare free, lighting. At the same time, end users request simplicity of operation and ease of control. In other words, end users want to be able to operate and control lighting according to their own needs. Thus, they expect a user friendly interface for the lighting control and relevant guidelines on how to play with light.

In the meantime, owners of hotels, bars or restaurants, request fabulous lighting design in relation to the available budget. They expect the maximum value (best lighting result) with the minimum possible cost. Owners also expect that the lighting installation will be easily maintained, while it will be cost effective and low energy consuming. In addition, owners want to ensure the longevity and safety of the installation, so that end users do not notice problems. Thus, owners are interested in the lifetime of lamps, the warranty provided by lighting manufacturers, the colour consistency between products, the availability of spare parts and so on.

Question 12: According to your personal view, please refer to some good lighting design schemes in the leisure industry?

From amongst the 61 participants, 38 replied to the question. This means that the sample size that responded to Question 12 is 62%.

Most of the participants suggested that there are many examples of good lighting design schemes in the leisure industry. If one only takes a look at lighting magazines or refer to the IALD awards of any year, (s)he could find many good lighting schemes. In any case, most of the participants explain that a good lighting design scheme should create an attractive ambience and a welcoming environment by offering a variety of scenes during the day. At the same time, the scheme should be energy efficient and within the owner's budget and objectives.

In regard to hotels, participants gave the examples of Semiramis hotel Athens, St. Martins Lane hotel, Killarney Bulgari hotel Bali, Molton Brown Spa, Sake No Hana Haymarket hotel, The Starwood hotels, Puerto America hotel Barcelona, Cumberland hotel London, Park Hyatt Tokyo, and Park Hyatt Philadelphia.

In regard to bars, other participants gave the examples of Killarney The Ice Bar, Home House (bar & club), and Sketch bar London.

In regard to restaurants, participants gave the examples of GuiesspireArnaldo and Sons restaurant Melbourne, Saka No Hana restaurant, Rock Sugar restaurant Los Angeles, Pompidou restaurant Paris, Hakkasan restaurant London, Yauatcha restaurant London, St. Albans restaurant London, Morimoto restaurant New York, Lever House restaurant New York, and Farralon restaurant in San Francisco.

5.1.3. Third Part of the Questionnaire

The third part of the Questionnaire referred to LED Technology in the Leisure Industry.

Question 13: Do you use LEDs in lighting designs in the leisure industry? No, Frequently, Yes?

The question aimed at understanding whether participants use or not, and how often, LEDs in lighting designs in the leisure industry. For this reason, participants could select amongst the following answers: No, Frequently, Yes.

From amongst the 61 participants, 59 replied to the question. This means that the sample size that responded to Question 13 is 97%. In particular, 67% of the participants said that they do use LEDs (Yes), 20% said that they use LEDs frequently, 10% said that they do not use LEDs at all, while 3% did not reply to the question.

Question 13.1: If No, what kind of lamps do you usually use in different applications?

From amongst the four participants who claimed that they do not use LEDs, the first participant explained that (s)he uses low voltage tungsten halogen and compact fluorescent lamps for functional light, while LEDs are only used for decorative elements. The second participant said that (s)he uses mainly halogen and incandescent lamps for decorative, accent, and downlighting. The third participant also explained that (s)he uses incandescent lamps for warm, gentle, and relaxed illumination. Finally, the fourth participant clarified that (s)he is not involved in the leisure industry, but only in residences.

Question 13.2: If No, what are the limitations that make you not use LEDs?

From amongst the four participants who claimed that they do not use LEDs, the first participant said that the main limitations for not using LEDs are colour inconsistency and low lumen output. The second participant explained that the major limitations are cost, lumen output, complications of drivers, programming and installation difficulties, lack of information and training on control systems. The third and fourth participants explained that they are mainly involved in residential lighting designs where they find the use of LEDs not so appropriate.

Q13.3 Do you use LEDs in lighting designs in the leisure industry? If yes or frequently in which kinds of applications do you use LEDs?

From amongst the 61 participants, 52 replied to the question. This means that the sample size that responded to Question 13.3 is 85%.

Most of the participants use LEDs in a variety of different applications. To begin with, LEDs are used in both interior and exterior lighting. LEDs are used in linear, concealed and cove lighting. Moreover, LEDs are used for backlighting, decorative lighting, accent lighting, and indication lighting. Alternatively, LEDs are used for up-lighting, wall glazing, and flood lighting. Furthermore, LEDs are used for signal, emergency, step or path lighting.

In other cases, LEDs are used because of their colours, and their ability of colour changing and creating special effects. LEDs can also be used in special constructions such as furniture and display cases, as well as for under-counter lighting and fountain lighting. Additionally, LEDs are used in installations where it is hard to reach the light source. What's more, LEDs are used to enhance the architecture, to highlight features, and to reinforce the ornamental details of a venue. Finally, LEDs are used in order to create the desired atmosphere within the space, whether a hotel, bar or restaurant.

Q13.4 Do you use LEDs in lighting designs in the leisure industry? If yes or frequently: do you use RGB LEDs, in what kind of applications and for what reasons?

From amongst the 61 participants, 50 replied to the question. This means that the sample size that responded to Question 13.4 is 82%.

A few participants claimed that they do not use RGB LEDs, while others explained that they infrequently use RGB LEDs in the leisure industry. Nevertheless, the majority of the participants explained that they do use RGB LEDs mainly for decoration lighting, backlighting, wall washing, concealed and cove lighting, signal lighting, accent lighting, underwater and fountain lighting.

The main reason for using RGB LEDs is the ability to change colours and the capability of controlling the colour changes and creating special effects. In addition, RGB LEDs are used to enhance the architecture, while they add a potential dynamic to heighten visual impact for decorative elements. Moreover, RGB LEDs can highlight features, enhance the aesthetics, create a dynamic colour atmosphere or set the appropriate mood within a space. In general, RGB LEDs can make a space more attractive and can add different perceptions to a static structure.

Additionally, although some participants think that RGB is overdone, RGB LEDs are used due to their small size, their efficiency and efficacy, in special constructions and in places where it is hard to reach the light source. Thus, RGB LEDs are found not only in the leisure industry – hotels, bars, restaurants – but also in the retail, residential and hospitality industries.

Q13.5 Do you use LEDs in lighting designs in the leisure industry? If yes or frequently: do you use white LEDs, in which kind of applications and for what reasons?

From amongst the 61 participants, 49 replied to the question. This means that the sample size that responded to Question 13.5 is 80%.

Despite of the fact that a few participants do not use or use rarely white LEDs, the majority of the participants explained that they use white LEDs in a variety of applications, including concealed and cove lighting, highlighting architectural features, wall washing, pathway lighting, display downlighting, indirect lighting, backlighting, under-counter lighting, accent lighting, millwork lighting, exterior and façade lighting, landscape lighting, fountain lighting, task lighting, ambient lighting, as well as additive lighting to general illumination. Alternatively, white LEDs can be used to highlight receptions and entrances, to decorate a bar, and to emphasize an ornamental element.

White LEDs are preferred to other light sources due to their low power consumption and long lifetime. They are also preferred due to their small size, durability, low maintenance, and energy efficiency. Moreover, white LEDs do not emit thermal radiation, thus they are used to illuminate artwork. Some participants also think that the use of colour is getting overplayed, thus they use more white LEDs. Participants prefer to use the warm white, instead of the cool white, version of LEDs, i.e. warm white MR16 LED lamps that replace halogen lamps. White LEDs are ideal in spaces with minimal decoration and in cases where the design requires interplay of cool and warm white effects.

Q13.6 Do you use LEDs in lighting designs in the leisure industry? If yes or frequently: do you use single coloured LEDs, in which kind of applications and for what reasons?

From amongst the 61 participants, 45 replied to the question. This means that the sample size that responded to Question 13.6 is 74%.

More than a third of the participants who replied to the question, claimed that they do not use or that they rarely use monochromatic LEDs other than white. The main explanation to that was that participants prefer to use RGB LEDs instead of monochromatic LEDs. As one participant said *'when you know you can get an RGB version, why settle for only one colour?'*

On the other hand, the majority of participants claimed that they use monochromatic LEDs in lower budget designs, because they are low cost compared to RGB LEDs. In addition, monochrome colours emitted by LEDs can be more intense, visually consistent and easier to control than RGB LEDs. Additionally, in some cases the possibility of controlling RGB LED is not possible or there is no need at all for colour changes.

Monochromatic LEDs are used for decoration lighting, wall washing, concealed and cove lighting, decorative lighting, accent lighting, ambient lighting, interior and exterior lighting, swimming pool lighting, indication lighting, highlighting, floodlighting, and landscape lighting. They are also used in special constructions and signal lighting, for instance to illuminate a corporate sign with the colours of the company. Monochromatic LEDs are also used to reinforce the architecture, enhance the colours of a surface, strengthen the design vision, create effects, and generate a relaxing atmosphere. All participants claimed that monochromatic LEDs are used because they are long lasting, efficient, small in size, more economic than RGB LEDs, and easy to control. They are also ideal in installations that are hard to reach.

Question 14: What kind of LED products do you use? (Select with an x all that apply)

In this question participants were asked to note (with an x) the LED products that they use. Participants could give more than one answer to the question. Five participants did not reply to the question at all, thus the sample size that replied to this question was 92%. The results are analytically presented in Figures 5.23-5.35.

Figure 5.23shows that 51% of the participants use and 49% do not use LED wall washers (Q14.1).

Figure 5.24reveals that 41% of the participants use and 59% do not use LED spotlights (Q14.2).

Figure 5.25indicates that 28% of the participants use and 72% do not use LED lamps (Q14.3).

Figure 5.26reports that 64%of the participants use and 36% do not use flexible LEDs (Q14.4).

Figure 5.27shows that 67%of the participants use and 33% do not use high power LEDs (Q14.5).

Figure 5.28illustrates that 18% of the participants use and 82% do not use low power LEDs (Q14.6).

Figure 5.29reveals that 49% of the participants use and51% do not use decorative LEDs (Q14.7).

Figure 5.30indicates that 28% of the participants use and 72% do not use downlights with LEDs (Q14.8).

Figure 5.31suggests that the vast majority of 97% do not use LED parcans and moving heads (Q14.9).

Figure 5.32shows that 84% of the participants use and 16% do not use linear LEDs (Q14.10).

Figure 5.33illustrates that 38% of the participants use and 62% do not use LED displays (Q14.11).

Figure 5.34reveals that 62% of the participants use and 38% do not use IP protected LEDs (Q14.12).

Figure 5.35indicates that 66% of the participants use and 34% do not use control systems for LEDs (Q14.13).

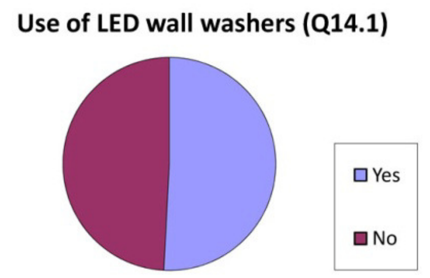
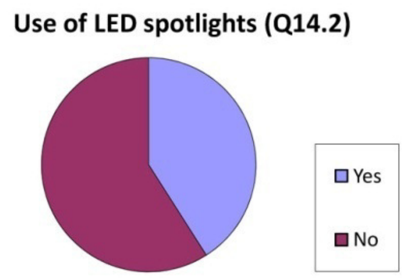


Figure 5.23



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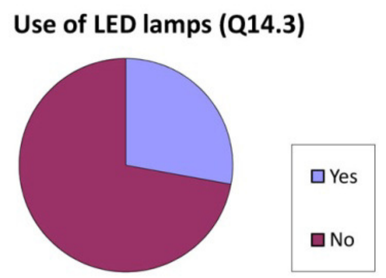

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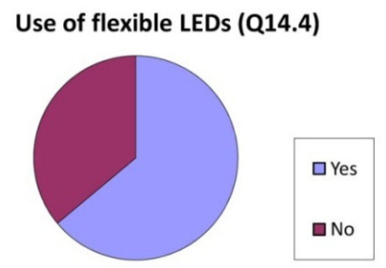

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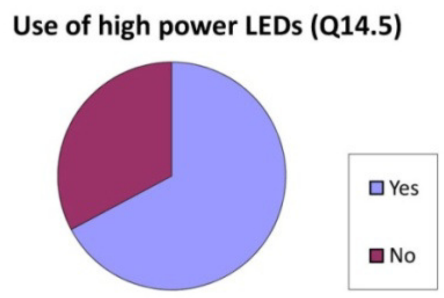

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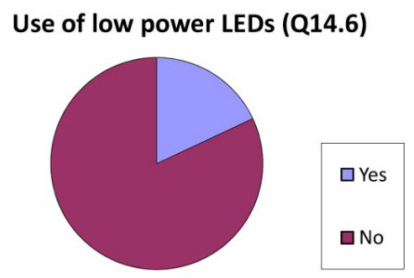

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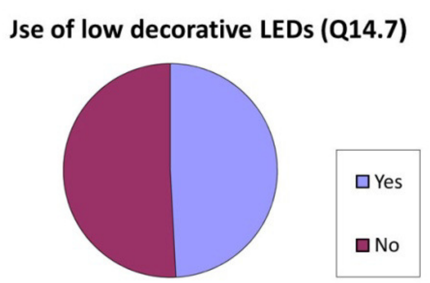

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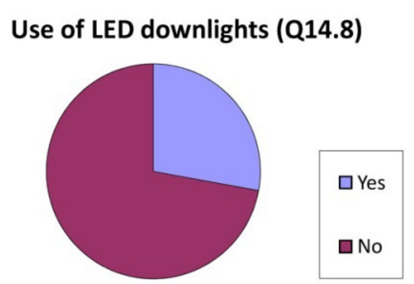

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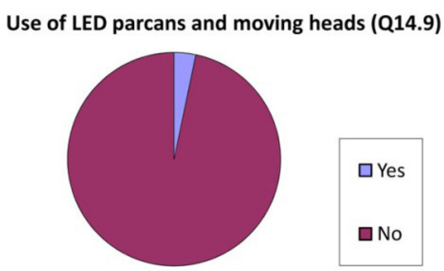

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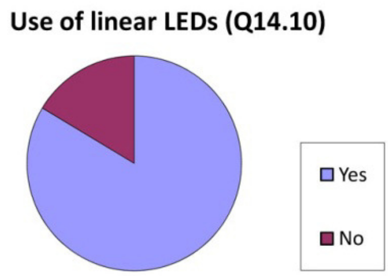

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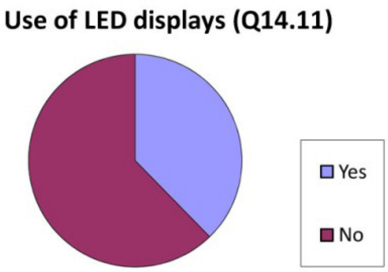

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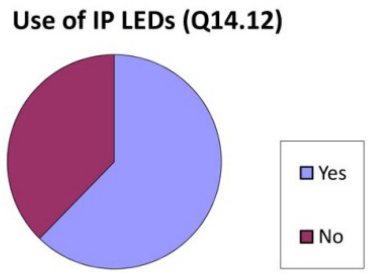

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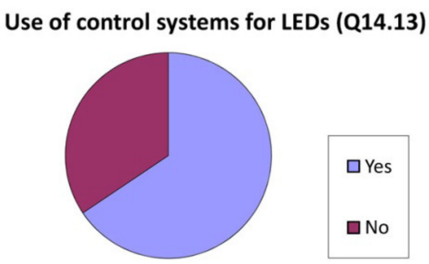


Figure 5.35

Question 15: In which applications do you use LEDs (select with an x all that apply)

In this question participants were asked to note (with an x) in which applications they use LED products. Participants could give more than one answer to the question. The sample size that replied to this question was 88.52%. The results are analytically presented in Figures 36-48.

Figure 5.36reveals that 85% of the participants use, whereas15% do not use LEDs for exterior lighting (Q15.1).

Figure 5.37reports that 44% of the participants use, whereas 56% do not use LEDs for interior lighting (Q15.2).

Figure 5.38indicates that 21% of the participants use, whereas 79% do not use LEDs for general illumination (Q 15.3).

Figure 5.39illustrates that 39% of the participants use LEDs, whereas 61% do not use LEDs for accent lighting (Q15.4).

Figure 5.40suggests that 77% of the participants use LEDs, whereas 23% do not use LEDs for concealed lighting (Q15.5).

Figure 5.41indicates that 59% of the participants use LEDs, whereas 41% do not use LEDs for decoration lighting (Q15.6).

Figure 5.42reports that 56% of the participants use LEDs, whereas 44% do not use LEDs for illuminating special constructions (Q15.7).

Figure 5.43reveals that 43% of the participants use LEDs, whereas 57% do not use LEDs for highlighting (Q15.8).

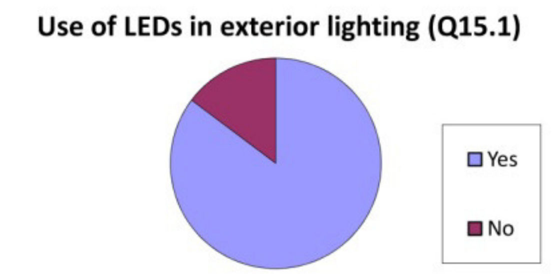
Figure 5.44illustrates that 69% of the participants use LEDs, whereas 31% do not use LEDs for backlighting (Q15.9).

Figure 5.45suggests that 57% of the participants use LEDs, whereas 43% do not use LEDs for indication lighting (Q15.10).

Figure 5.46reports that 8% of the participants use LEDs, whereas 92% do not use LEDs for illuminating epigrams (Q15.11).

Figure 5.47reveals that 62% of the participants use LEDs, whereas 38% do not use LEDs for creating special effects (Q15.12).

Figure 5.48illustrates that 33% of the participants use LEDs, whereas 67% do not use LEDs for emergency lighting (Q15.13).



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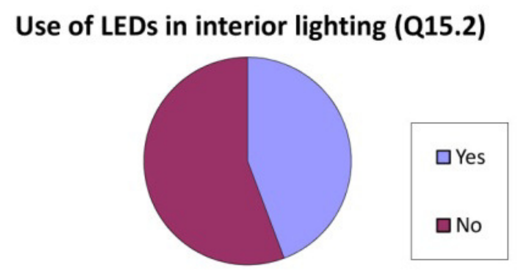

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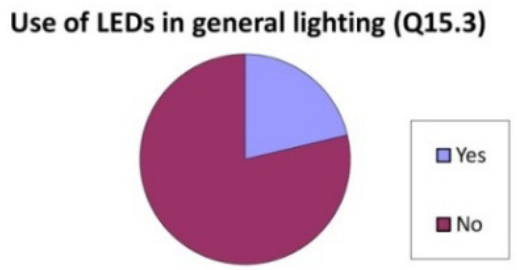

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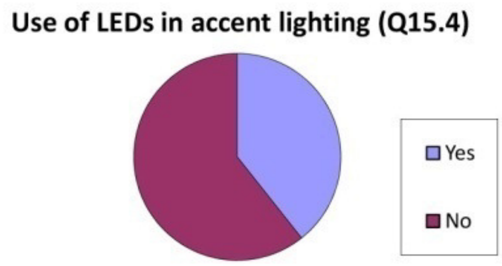

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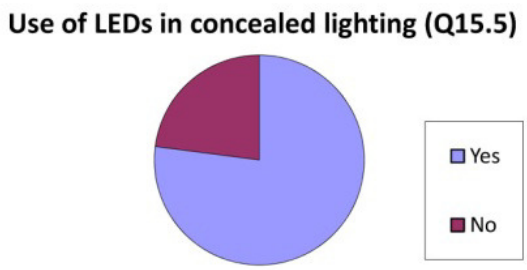

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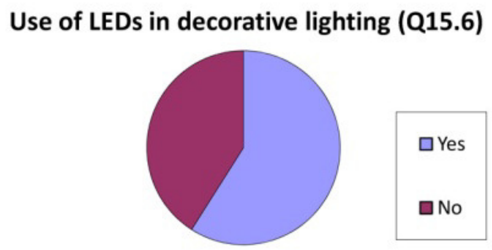

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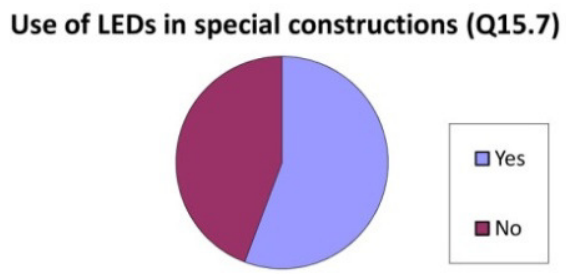

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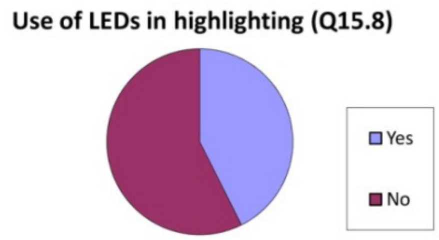

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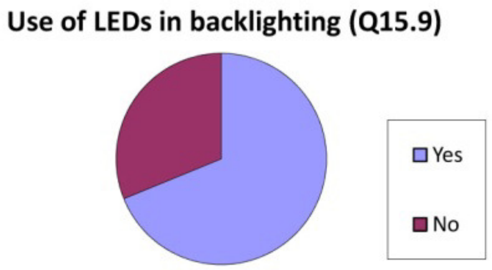

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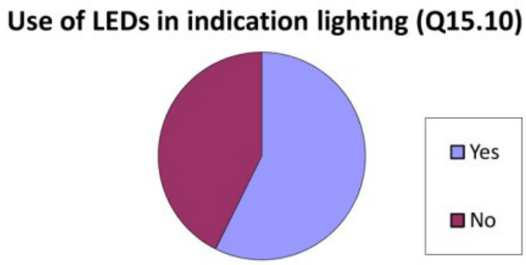

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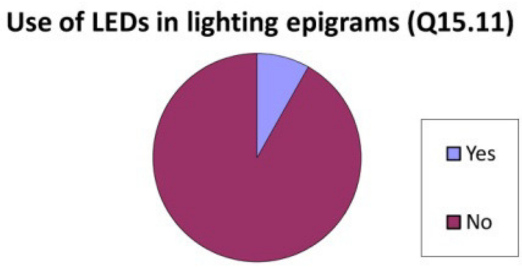

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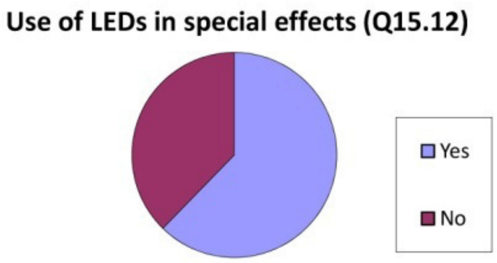

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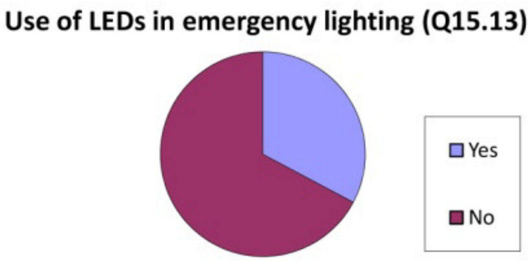

Figure 5.48

Question 16: What capabilities are offered by LEDs?

The sample size that responded to Question 16 is 80%.

All of the participants claim that one of the main advantages of LEDs is that they have long life. Therefore, they are ideal for lighting placed in areas with no accessibility or very little accessibility, allowing low maintenance costs. In addition, LEDs are small in size and flexible, thus they can fit easily into the conceptual mechanism and design. The beam angle of the emitted light of LEDs is usually very narrow, which is ideal for directing the light to the place where it is required.

In addition, LEDs offer low energy and power consumption, generating energy efficient and environmental friendly installations. LEDs operate usually at low operating voltage, with low connected loads, and daisy chain connections, which make them safer to use. LEDs have less forward heat than other light sources, which makes them appropriate in a number of applications. Furthermore, LEDs have low operating temperature, they are vibration resistant, and they emit no UV or IR radiation.

LEDs are controlled in terms of their intensity with the suitable control systems or remote drivers. The appropriate illumination levels can, therefore, be achieved from 0-100%, depending on the lighting design scheme. For example, a high light output is needed for enhancing decorative details; a low light output is needed for decorative illumination.

LEDs are available in various static colours: cool white, warm white, blue, green, red and amber. RGB (Red, Green, Blue) LEDs are totally controlled in terms of colour and offer a wide range of saturated colours. With the appropriate control systems, RGB LEDs generate dynamic colour changes, colours that change with different speeds and fade times. RGB LEDs in combination with the appropriate control systems can also generate images and videos.

To conclude, all participants claim that LEDs offer endless capabilities, such as a good range of additive and saturated colours, flexibility of controls and visual images, colour mixing and dynamic colour changes, all of which can affect the feelings and emotions in a space. Given that, LEDs are brilliant tools as long as they are used in the right way in the right installation.

Question 17: What are the limitations of LEDs today?

From amongst the 61 participants, 55 replied to the question. This means that the sample size that responded to Question 17 is 90%.

According to the majority of the participants, one of the most important limitations of LED technology is the lack of colour consistency and colour stability amongst LEDs, not only between different manufacturers, but also from different production batches of the same manufacturer. For example, white and especially warm white LEDs present colour shifts mainly due to the way that phosphors are used during the manufacturing process. In turn, the Correlated Colour Temperature (CCT) is not consistent. In addition, LEDs do not always have a high Colour Rendering Index (CRI).

LEDs are usually low in power and light output, which makes them inappropriate for general or task lighting. Furthermore, LEDs have a high purchase cost and remain expensive compared to other light sources. Participants explained that because LEDs do not produce enough lumens, additional lamps are added in installations, increasing the power consumption (wattage) and, therefore, the operational costs.

Additional limitations to LED technology are related to heat dissipation in which LED fixtures can become very hot and present thermal problems. Other limitations are related to drivers which fail before the LEDs. Participants also explained that LED technology changes so fast that in the future there will be no product available in the market to match already existing LED installations, because of the rapid development of the technology. In addition, participants feel that there are a lot of poor quality products available in the market. In fact, one participant claimed that '*most of them are junk'*, meaning that LEDs are not efficient or reliable.

In addition, many participants explain that there are no standards against which performance of LEDs can be evaluated and compared, and there are no guidelines to test colour and lumen stability. Also, manufacturers usually provide no technical information and no photometric/ colorimetric measurements for their products. Moreover, manufacturers do not always say the truth about the specifications of their products. For instance, originally manufacturers claimed a lifetime of 100,000 hours which proved to be false. The lack of reliable data and standards often makes lighting designers ask for samples in order to ensure themselves about the performance characteristics of the products.

Finally, many participants explained that although the capabilities of LEDs are endless, manufacturers are usually limited to investigating the integration of LEDs into already existing fixtures. LEDs, however, cannot always replace traditional light sources in terms of colour and lumen output.

Question 18: What are the barriers for the further adoption of LEDs?

From amongst the 61 participants, 52 replied to the question. This means that the sample size that responded to Question 18 is 85%.

The findings are in consistent with the replies given to Question 17 and verify that one of the major barriers for the further adoption of LED technology is the lack of colour consistency and colour stability amongst white LEDs. LEDs differ in terms of colour between manufacturers. LEDs may also differ from one production batch to another, although they come from the same manufacturer. In addition, different manufacturers define and use different binning systems. As a result, there are differences in the definitions of colours and CCTs, and in the actual colour of emitted light. What's more, CRI is often very poor.

Other barriers are poor lumen output and lumen instability. Moreover, manufacturers use different definitions in relation to lumen maintenance. For example, only a few manufacturers claim 70% of lumen output after 50.000 hours of operation.

As discussed in Question 7 other barriers for the further adoption of LEDs include the high initial purchase cost, the limited availability of luminaire designs, and the rapid change of the technology that does not ensure spare part availability in the future. Other barriers are heat management, optic management because LEDs are mainly point sources, driver availability that will last as long as the LEDs.

Many participants explain that no adequate research has been performed in relation to LEDs. In fact, no standards or guidelines have been established, against which to evaluate and compare data by different manufacturers. And manufacturers usually do not offer photometric and colorimetric data or adequate technical information on their products. Given that, many participants reported the need for establishing LED standards against which all LEDs will be evaluated and compared. Only then, will accurate specifications and reliable information become available. And only then will LED technology be further adopted.

Question 19: How do you take decisions on which LEDs to use?

From amongst the 61 participants, 52 replied to the question. This means that the sample size that responded to Question 19 is 85%.

Many participants explained that the decision on which LED to use depends on the application and the design requirements. To begin with, participants test if LEDs fit in the installation better than conventional lighting. In case that LEDs do fit better the installation requirements and the project demands, participants focus on the effect they want to create before they decide what kind of LEDs they need to use.

Most of the participants check the design, quality, material, and appearance of the LED luminaire, so as to make sure it fits with the project requirements. Many participants also check the reflector design to ensure that the beam angle is according to the installation needs. Furthermore, all participants check the size of the fixtures which is important especially in applications where there is not much space. They also usually compare cost of the products in relation to the budget of the project.

To make decisions, most of the participants check the availability of well documented information on LEDs. When available, participants study photometric, colorimetric and technical data of LED fixtures, including CCT, colour stability, CRI, lumen output, power consumption, control capabilities, overall performance. When not available, many participants request samples from manufacturers to do in-house mock-ups and test the specifications of the products. These participants value not only the availability of product information, but also the ease of getting samples from manufacturers.

Most of the participants select products based on the reputation of both the LED manufacturer and the reputation of the fixture manufacturer. As one participant explained, it needs to be a *“reputable LED manufacturer in a reputable lighting* *manufacturer's fixture"*. Most of the participants prefer to use products from manufacturers that demonstrate expertise and knowledge on LEDs; that offer a wide range of products; that provide a long warrantee period; and that provide support and after-sales service.

Question 20: How confident do you feel about using LED technology in your designs and why?

From amongst the 61 participants, 54 replied to the question. This means that the sample size that responded to Question 20 is 89%.

Some participants feel very confident when using LEDs. High confidence derives from the fact that participants test samples before recommending the products. It also derives from the fact that participants work with reputable manufacturers who offer reliable information on their products. Additionally, some participants spend a lot of effort in gaining knowledge and expertise on LED technology so as to be able to evaluate products. These participants then feel certain about what to use depending on the application. In addition, these participants explain that they feel confident to use LEDs that have already been used in other installations.

Other participants said that they are moderately confident when using LEDs. These participants explain that they feel as confident as one can be when using any product that has no empirical, but only proposed data.

Other participants do not feel confident when using LEDs, because the technology is very new and unstable. The available products are not always good in terms of quality, and there are not many proven results. These participants have often experienced a number of problems with products from different manufacturers. Problems relate to uncertain life time, colour instability, low lumen outputs, differences in colour, and high initial cost. This makes those participants very cautious using LEDs.

Finally, other participants claimed that they only use LED technology because they are forced to when nothing else fits, when they have to meet energy efficiency codes, or when coloured effects are needed. LEDs are used for clients who are willing to risk the potential problems and troubleshooting inherent with the new technology. These participants explained the significance of understanding the capabilities and limitations of LEDs, the importance of getting trained on LEDs, i.e. on future programming or maintenance of LEDs, and the need to undertake research in relation to LEDs.

Question 21: What important considerations should be taken into account when using LEDs in the leisure industry in the following applications? White colour (21.1), RGB colour (21.2), and Single colour (21.3).

From amongst the 61 participants, 53 replied to Question 21.1. Thus, the sample size that responded to this question is 87%. The findings were that one of the most important considerations when using white LEDs is colour consistency and colour stability. The Correlated Colour Temperature (CCT) of white LEDs should be consistent between different batches of LEDs from the same manufacturer and between different manufacturers. In addition, the Colour Rendering Index (CRI) of white LEDs should be high (Ra= 80+) so that LEDs attribute the actual colours of materials and surfaces.

Another important consideration when using white LEDs is the light output. For instance, white LEDs do not always have the adequate lumen output to replace halogen lamps for general downlighting. On the other hand, they can be ideal tools for concealed and cove lighting. In relation to that, it is important to consider the lifetime and lumen depreciation of LEDs over time.

Other important considerations in applications where white light is applied are the optics and lenses that are used to generate the desired beam angle; price which should be in consistence with the budget of the project; variability of white colour; consistency of 2700K or 3000K warm white LEDs which is what end users usually like; reliability of the product; thermal management so as to ensure proper operation of the luminaire; availability of LEDs for future replacement. Actually, some lighting designers often recommend customers to buy a percentage more than what is originally needed so as to maintain a similar look in case of any unforeseen damage.

From amongst the 61 participants, 49 replied to Question 21.2. Thus, the sample size that responded to this question is 80%. The findings revealed that the most important consideration when using RGB LEDs is the controllability of LEDs. Most of the participants want to know if the RGB LEDs are controlled and how the control is realized. They also want to know how the LEDs will be powered and driven and how easily the control and programming will be performed.

Another important consideration is the colour mixing capability of RGB LEDs in order to have a wide colour gamut. Many participants prefer RGB LEDs that are in one chip, rather than LEDs that have separate red, green, and blue LEDs in a series. RGB in one chip LEDs offer better saturated colours and facilitate lighting designers create the effects that they desire. At the same time, all of the participants do not expect RGB LEDs to give good white colour. Therefore, when it comes to white it is less sensible to use RGB LEDs.

RGB LEDs must offer smooth controlling, smooth colour mixing, and smooth colour changing. In fact, many participants think that when colour changes happen quickly, then it usually ruins the sophistication and design of the project. Thus, there should always be careful consideration of the RGB lighting design, so that a balance and the concept are kept.

Other important considerations when using RGB LEDs are the optics that are used to generate the desired beam angle; the source configuration in the luminaire; the price of the RGB LEDs and the related power supplies, drivers, and control gear; the reliability of the product and the system; the availability of spare parts for future replacement; the flexibility of the system; the light output; the lifetime; and the maintenance of lumen output and colours over time.

From amongst the 61 participants, 45 replied to Question 21.3. Thus, the sample size that responded to this question is 74%. Most of the participants claim that when using monochromatic colour (other than white) it is important to consider the appropriateness of the colour in regard to the lighting design scheme. It is also important to consider the appearance and saturation of colours, and to check the stability of colours between LEDs to ensure consistency. For example, many participants claimed that monochromatic colours can be very ‘heavy’ or intense, thus they might need to be mixed with other colours such as white. In any case, there should be careful lighting design so that the colours are in consistent with the lighting concept and appropriate for the application needs.

Other important considerations when using monochromatic colourful LEDs include the light output which varies depending on the colour, the intensity controls, the optics and lenses that emit the desired beam angle, the reliability and uniformity of the product, the availability of the product for future replacement; the flexibility and efficiency of the LEDs; the price of the product; and the lifetime.

Question 22: What lighting goals should be achieved when using LEDs in the following applications? White colour (22.1), RGB colour (22.2), and Single colour (22.3).

From amongst the 61 participants, 42 replied to Question 22.1. Thus, the sample size that responded to Question 22.1 is 69%. The findings reported that lighting goals depend on the application and the lighting design, and are independent of the light source. Therefore, lighting goals with LEDs in white applications are the same with any other light source, and should provide an outcome that matches a quality lighting design. The use of white LEDs should fit the overall scene and should create the appropriate mood and atmosphere. For example, interplay of cool white and warm white light within the space could reinforce the desired feelings and emotions.

According to the majority of the participants, to achieve lighting goals in white applications it is important to consider colour stability between white LEDs and colour consistency over time, so as to accomplish a uniform and homogeneous outcome. In addition, Colour Rendering Index (CRI of 80+) is important, so as to represent the actual colours of surfaces and/ or materials. Important is also to consider the lumen output so as to achieve the appropriate illumination on the horizontal plane. Other issues that become important in white applications are the selection of fittings that integrate well with the architecture of the space, as well as the use of the proper optics and reflectors to achieve the appropriate emission of light. In an effort to get the right effect and the appropriate blending with other lighting within the space, other issues to consider are lumen efficacy and efficiency, energy consumption, thermal management, control of the installation.

From amongst the 61 participants, 35 replied to Question 22.2. Thus, the sample size that responded to this question is 57%.As in the case of white applications many participants claimed that lighting goals do not change depending on the light source. Other participants said that lighting goals in RGB applications depend on the actual application. Whatever the case may be, the lighting goal should always aim at realizing a quality lighting design, with the appropriate use of RGB LEDs, without overdoing it. For example, colour changing RGB LEDs can be used to change the mood in a space or to create dynamic colour effects. Also, RGB LEDs can be used to highlight features or to reinforce the general decoration of the space. Alternatively, RGB LEDs can be used to create video displays and effects.

To achieve the above, several issues become important, including good colour mixing (especially from RGB in one chip LEDs), coherent colour changing, colour stability over time, saturation of colours, smoothness in dimming, flexibility in controls, management capabilities, and ease of colour mixing and control.

From amongst the 61 participants, 32 replied to Question 22.3. Thus, the sample size that responded to the question is 52%. As in the case of white and RGB applications, most of the participants claimed that lighting goals do not change with the source. Other participants suggested that lighting goals change with the project. In any case, the lighting goal should always aim to achieve a quality lighting design scheme, with the appropriate use of colours. Colours must match the design and add meaning to a space. Colours can be used in contrast to play with mood or with shadows to create mystery. Additionally, colours can be used for accent lighting, for decorative lighting, or even for orientation. Depending on the application, several issues become important, including colour stability between LEDs, colour consistency over time, colour saturation, colour distribution, brightness, efficiency, and maintenance.

Question 23: According to your personal view, please refer to some good LED lighting design schemes in the leisure industry.

From amongst the 61 participants, 23 replied to the question. This means that the sample size that responded to Question 23 is 38%.

Some participants like projects, where LEDs are used for wall washing, cove lighting, indication lighting in hallways, backlighting bars. Other participants could not easily think of any LED lighting design schemes in the leisure industry. And other participants claimed that there are too many to name. Some participants also explained that by referring to the IALD awards or lighting magazines, one can find a variety of good LED lighting design schemes in the leisure industry. Examples of good LED lighting design schemes include the Semiramis hotel Athens, the Target Interactive Breezeway in the Rockefeller Center New York, and the Anemix Installations.

5.1.4. Fourth Part of the Questionnaire

The fourth part of the Questionnaire included some general questions about the background of participants.

Question 24: What kind of projects do you handle?

From amongst the 61 participants, 56 replied to the question. This means that the sample size that responded to Question 24 is 92 %.

About one fifth of the participants explained that they handle all kind of projects in regard to architectural lighting. At the same time, many participants said that they handle projects in the leisure industry (hotels, bars and restaurants), and especially in the hospitality industry. Other participants explained that they handle a variety of projects including, leisure, hospitality, commercial, retail, municipal, public buildings, museums, galleries, landscape, urban, residential, offices, education, live events (corporate, concerts, theatres), show, theme parks, spa, hospitals, Houses of Worship, educational institutions, street lighting, and master plans. Only a couple participants explained that they handle only residences or only offices.

Question 25: In which countries or areas have you worked?

From amongst the 61 participants, 55 replied to the question. This means that the sample size that responded to Question 25 is 90%.

Most of the participants explained that they have worked in many different countries around the world. In particular, many participants have worked in Europe, in countries such as the UK, Greece, Portugal, France, Germany, Ireland, Russia, Italy, Poland, Romania and Switzerland. In addition, other participants have worked in Canada, the USA, Mexico, Argentina, Brazil, as well as in the Middle East, UAE, Saudi Arabia, Oman, Kuwait, Bahrain, and Lebanon. Finally, other participants have worked in Australia, Mauritius, Ecuador, and the Maldives, as well as in Japan, Korea, China, Singapore, Thailand, Taiwan, and India.

Question 26: Please select your gender?

From amongst the 61 participants, 56 replied to the question. This means that the sample size that responded to Question 26 is 92%. From those who replied, 48% are male and 44% are female. This suggests that there was a good diversity in terms of gender in the sample.

Question 27: Please select your age group: 18-30, 31-45, 46 or above?

From amongst the 61 participants, 56 replied to the question. This means that the sample size that responded to Question 27 is 92%. In turn, 28% of the participants claimed that they are in the age group 18-30, 41% of the participants claimed that they are in the age group of 31-45, 23% claimed that they are 46 and above. This indicates a quite diverse sample of participants in regard to age.

Question 28: Please write in your background.

From amongst the 61 participants, 50 replied to the question. This means that the sample size that responded to Question 28 is 82%. The majority of the participants have studied architecture or architectural engineering. Other participants have studied lighting design in an educational institution or have worked as lighting designers for several years. Others have been involved with interior design or electrical and electronic engineering. Finally, there are some participants who have originally worked as theatrical or stage lighting designers before getting involved in architectural lighting.

Question 29: Please indicate your job title: Independent lighting designer, Lighting designer in a lighting manufacturer, Architect, Decorator, Electrical Engineer, Student, Employee in lighting company, Other

From amongst the 61 participants, 56 replied to the question. This means that the sample size that responded to Question 26 is 92%. Participants could allocate themselves more than one job title. For example, participants may be employed in a lighting company but at the same time they also work independently as lighting designers.

The vast majority of participants expressed by 70% said they work as independent lighting designers. 15% work as employees in lighting companies, 10% work as architects, 2% work as decorators, 2% work as electrical engineers, 2% work as lighting designers in a lighting manufacturer. None participant is a student. 7% claimed other job title.

Question 30: Please write in your name if you like (but not necessarily).

The specific question was asked so that the researcher could come in contact with the participant in case there was a need for clarifications or explanations. Otherwise, it was handled in confidence, thus the names of the participants are not presented in this paragraph.

Question 31: Please write in the name of your office/ company (but not necessarily).

The specific question was asked so that the researcher could come in contact with the participant in case there was a need for clarifications or explanations. Otherwise, it was handled in confidence, thus the names of the offices or companies where the participants work are not presented in this paragraph.

5.2 Results of the Survey

This section analyses the results of the Survey.

5.2.1 Comparing Results

This section of the thesis examines the importance that lighting designers give to various lighting parameters (Q8.1), depending on the level of knowledge that they have on LEDs (Q4.1). To achieve this, sub-samples deriving from Figure 5.1 (a lot of knowledge, moderate knowledge, little knowledge) and Figures 5.7-5.20 (very high, high, moderate, low, very low importance), are used together to investigate the importance of lighting parameters based on thelevel of knowledge of the participants. The sub samples were defined as indicated in Table 5.1.

Level of Knowledge	**Value number attributed**	**Level of importance of lighting factor**	**Value number attributed**
Little	1	**Very High**	5
Moderate	2	**High**	4
A lot	3	**Moderate**	3
		Low	2
		Very Low	1

Table 5.1: Value numbers attributed to the levels of knowledge (Q4.1) and level of importance of lighting parameters (Q8)

The sub samples were calculated for each of the questions asked so that the influence of designer knowledge on the weighing given to each of the questions could be assessed.

As an example, take Colour range availability (Q8.1). The results of the sub samples are given in Table 5.2. These data are also plotted in Figure 5.49. This data shows the way the responses to colour range availability (Q8.1)varied for designers with different levels of knowledge (little, moderate, or a lot).

Level of Knowledge of lighting designers	**Level of Importance of colour range availability (Q8.1)**	**Percentages %**
Little (1)	Very high (5)	0
Little (1)	High (4)	50%
Little(1)	Moderate (3)	50%
Little(1)	Low (2)	0
Little(1)	Very low (1)	0
Moderate(2)	Very high (5)	56%
Moderate(2)	High (4)	22%
Moderate(2)	Moderate (3)	22%
Moderate(2)	Low (2)	0
Moderate(2)	Very low (1)	0
A lot(3)	Very high (5)	59%
A lot(3)	High (4)	27%
A lot(3)	Moderate (3)	11%
A lot(3)	Low (2)	3%
A lot(3)	Very low (1)	0

Table 5.2: Level of importance of colour range availability (Q8.1) depending on the level of knowledge of participants

Figure 5.49 illustrates graphically the findings of Table 5.2, and indicates that participants with little knowledge on LEDs value colour range availability with either high (50%) or moderate (50%) importance. The majority of participants with moderate knowledge on LEDs value colour range availability with very high importance (56%), with high importance (22%) or with moderate importance (22%). Similarly, the majority of participants with a lot of knowledge on LEDs value colour range availability with very high importance (59%), as compared to high (27%) or moderate (11%) or low (3%) importance.

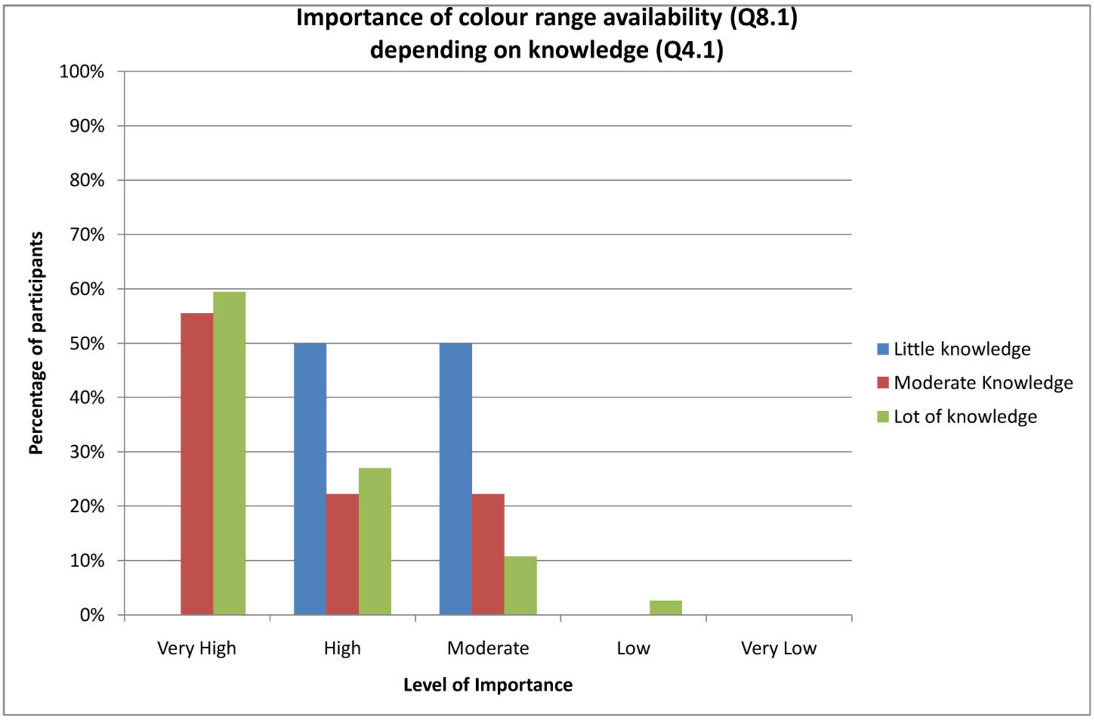

Figure 5.49: Importance of colour range availability for lighting designers, depending on their level of knowledge on LEDs (Q8.1- Q4.1)

The same procedure was realized in order to examine the importance of the rest of lighting parameters, depending on the level of knowledge of lighting designers on LEDs, and the findings are illustrated in Figures 5.50- 5.62.

Figure 5.50 reveals that lumen output was very important to all lighting designers with little knowledge on LEDs (100%), as well as to the majority of lighting designers with moderate knowledge (61%) and high knowledge (59%) on LEDs.

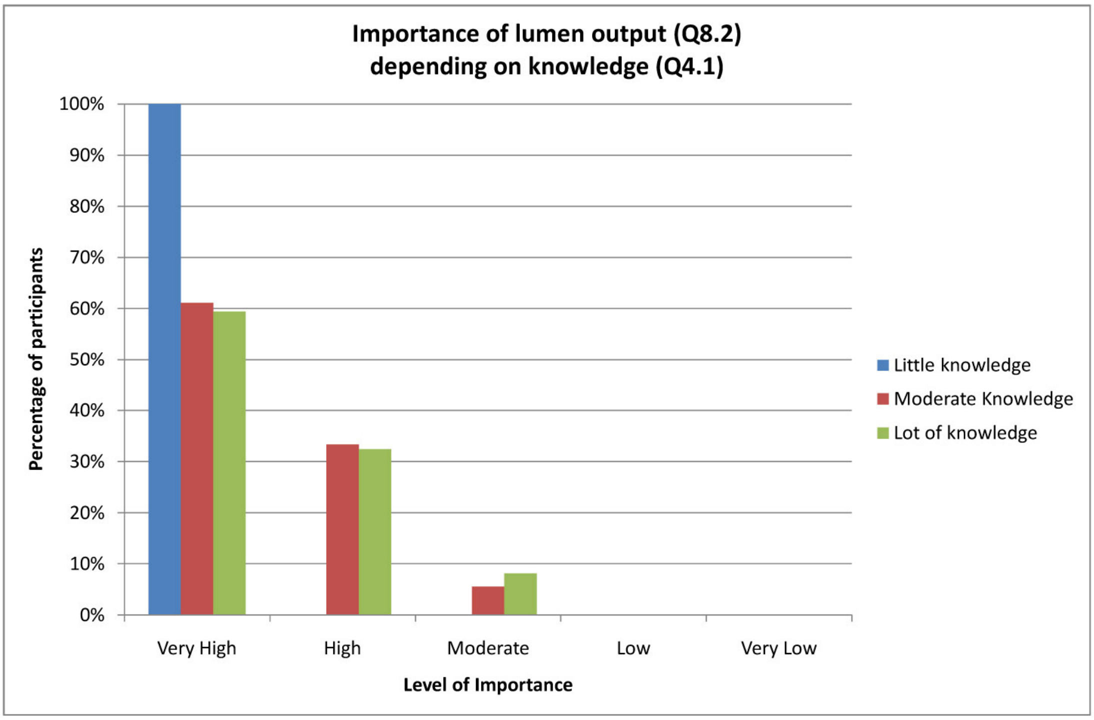

Figure 5.50: Importance of lumen output for lighting designers, depending on their level of knowledge on LEDs (Q8.2- Q4.1)

Figure 5.51points out that colour range consistency is of very high importance to both lighting designers with a lot of knowledge (73%) and moderate knowledge (72%) on LEDs. Colour range consistency was equally of very high (50%) or high (50%) importance to lighting designers with little knowledge on LEDs.

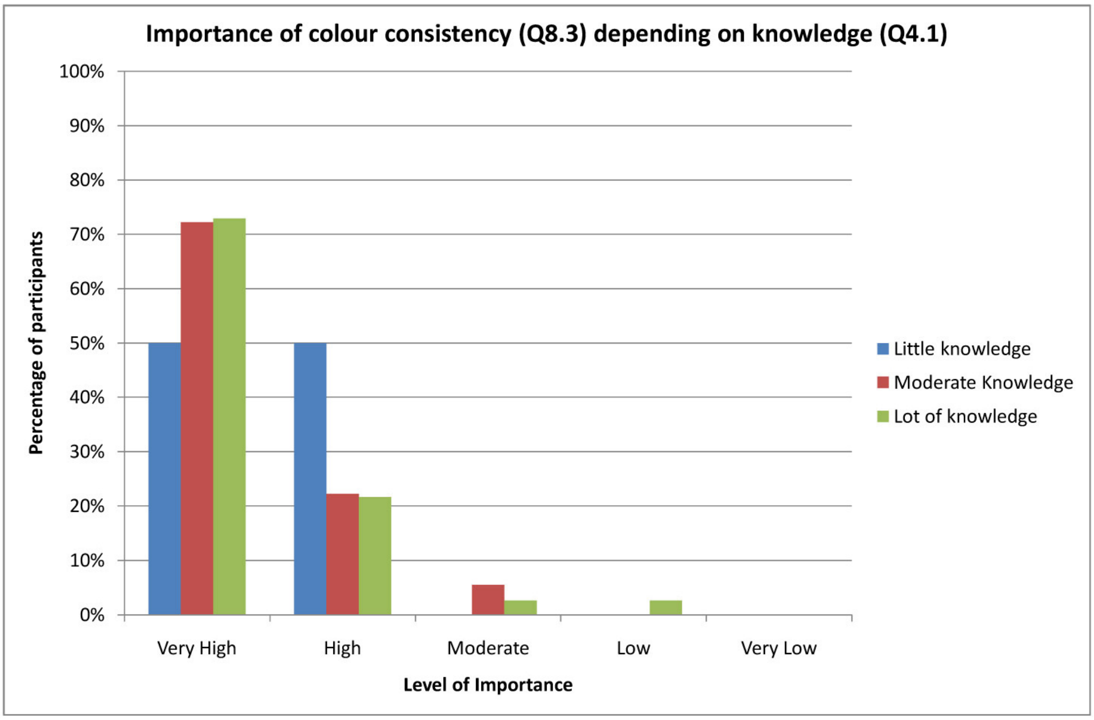

Figure 5.51: Importance of Colour range consistency for lighting designers, based on their level of knowledge on LEDs (Q8.3- Q4.1)

Figure 5.52 illustrates that lumen maintenance was of very high importance to the majority of lighting designers with moderate knowledge on LEDs (61%). Lumen maintenance was equally of very high importance (50%) or of moderate importance (50%) to lighting designers with little knowledge on LEDs. However, lumen maintenance seemed less important to lighting designers with a lot of knowledge on LEDs (49% claimed high importance, 35% claimed very high importance).

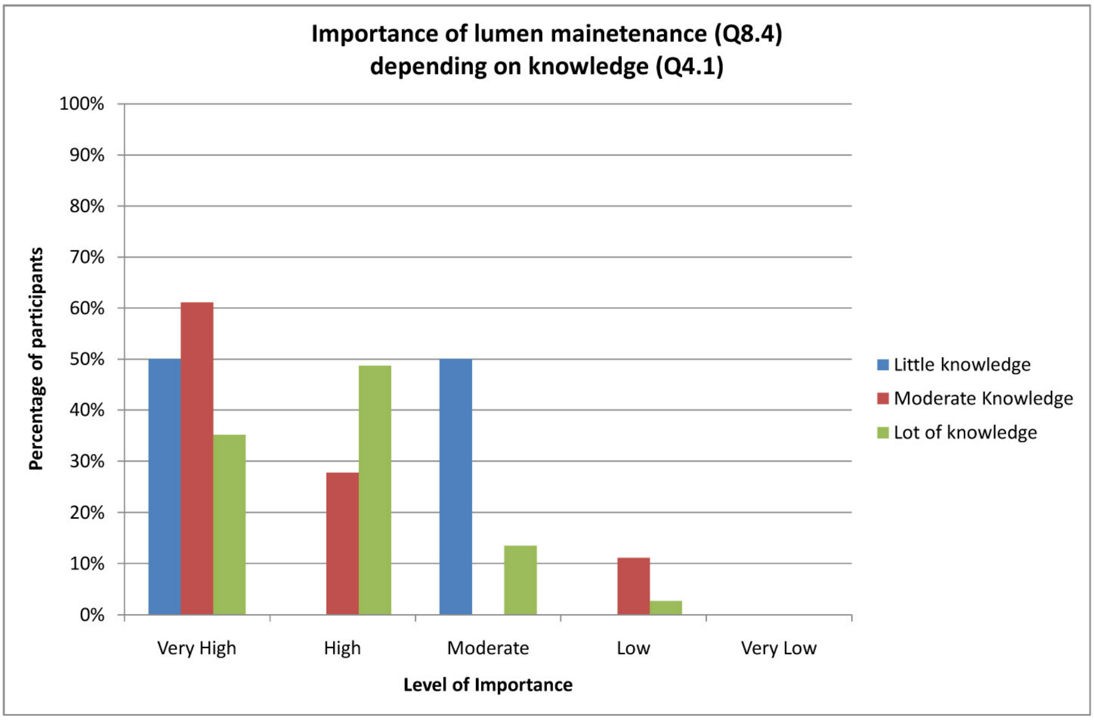

Figure 5.52: Importance of lumen maintenance for lighting designers, depending on their level of knowledge on LEDs (Q8.4- Q4.1)

Figure 5.53 shows that stability of LEDs is very important to the majority of lighting designers with moderate knowledge on LEDs (61%). Stability was either of very high (50%) or high (50%) importance to lighting designers with little knowledge on LEDs. On the contrary, stability seemed to be less important to lighting designers with a lot of knowledge on LEDs (46% claimed very high importance, and 49% claimed high importance).

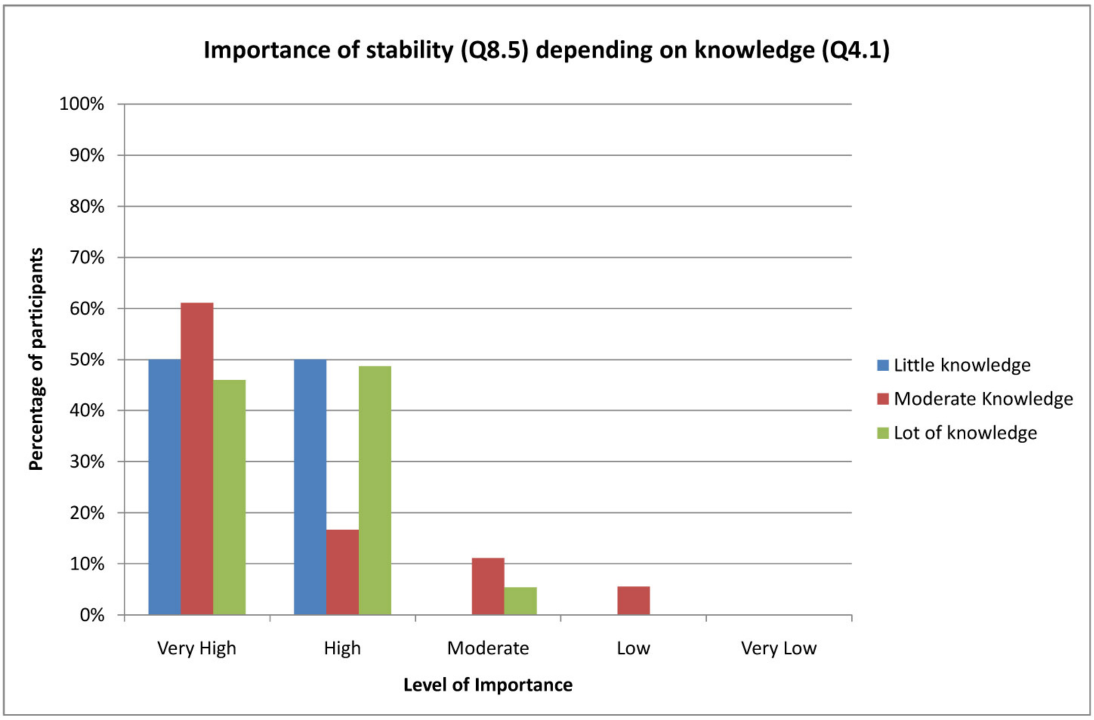

Figure 5.53: Importance of stability for lighting designers, depending on their level of knowledge on LEDs (Q8.5- Q4.1)

Figure 5.54 indicates that control capabilities were mainly of very high (50%) or high (50%) importance to lighting designers with little knowledge on LEDs. On the contrary, control capabilities seemed to be less of a priority to lighting designers with a lot or moderate knowledge on LEDs.

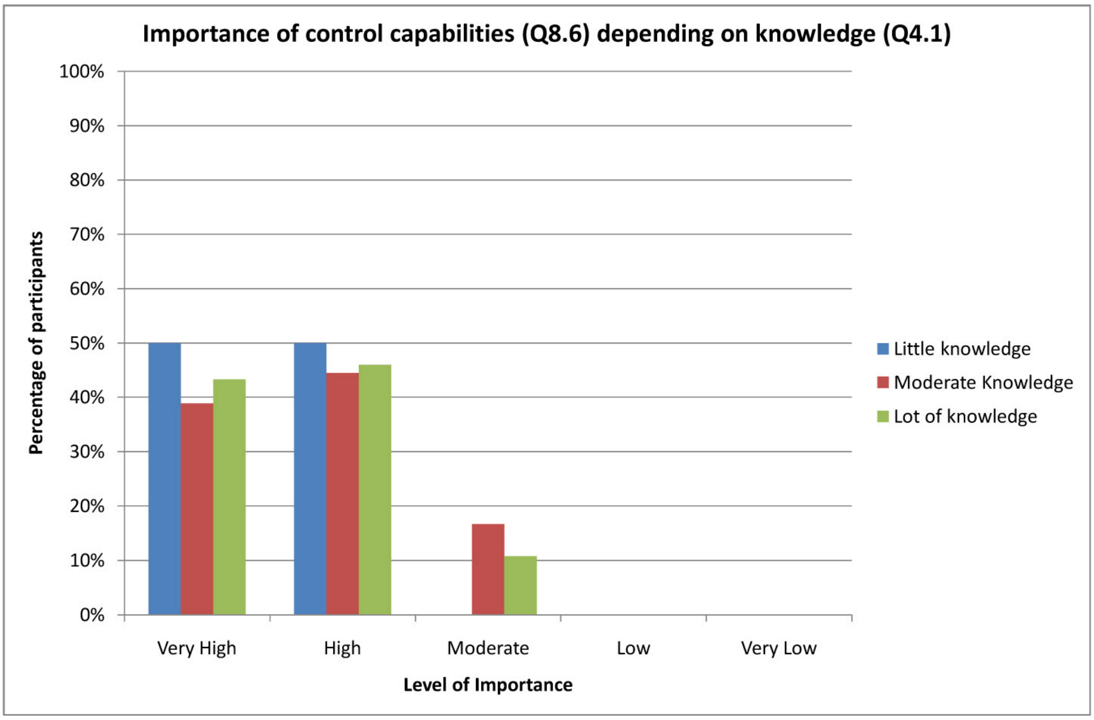

Figure 5.54: Importance of control capabilities for lighting designers, depending on their level of knowledge on LEDs (Q8.6- Q4.1)

Figure 5.55 illustrates that lifetime was of very high importance to all lighting designers (100%) with little knowledge on LEDs. On the contrary, lifetime was of no particular interest to lighting designers with moderate or a lot of knowledge on LEDs.

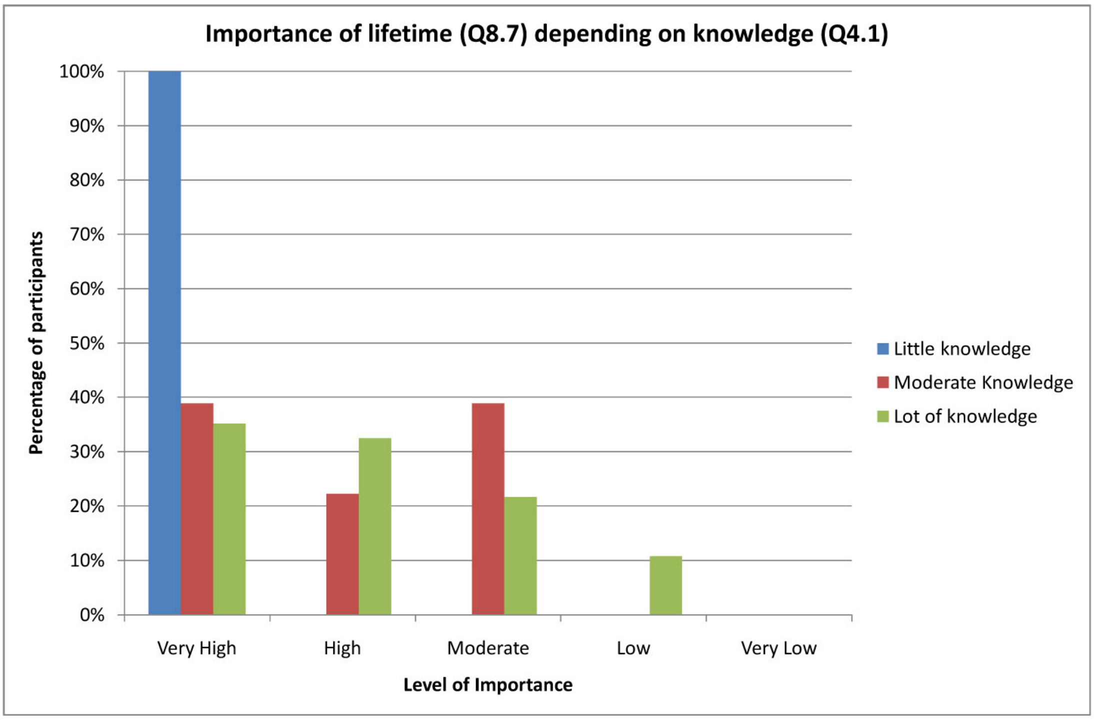

Figure 5.55: Importance of lifetime for lighting designers, depending on their level of knowledge on LEDs (Q8.7- Q4.1)

Figure 5.56 reveals that RGB colour mixing was equally of high importance (50%) or of moderate importance (50%) to lighting designers with little knowledge on LEDs. RGB colour mixing was of moderate importance to less than half of the lighting designers with moderate (44%) or a lot of knowledge on LEDs (46%).

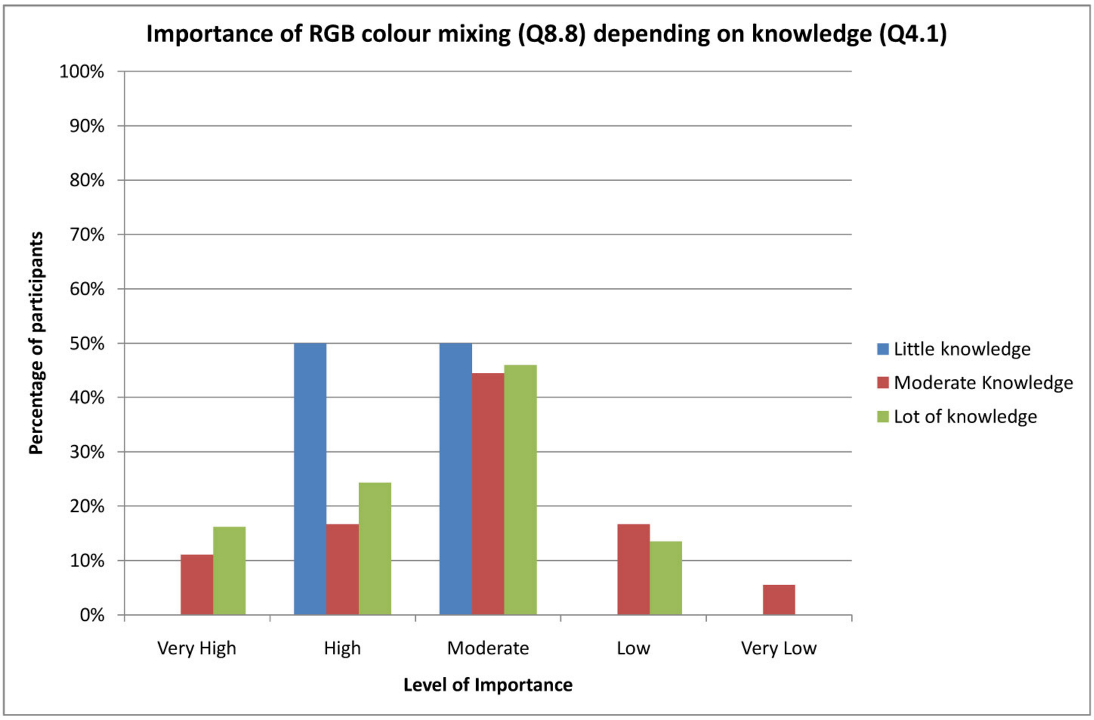

Figure 5.56: Importance of white colour availability for lighting designers, depending on their level of knowledge on LEDs (Q8.8- Q4.1)

Figure 5.57 shows that white colour availability was of very high importance to all lighting designers with little knowledge on LEDs (100%), as well as to the majority of lighting designers with moderate (72%) or a lot of knowledge (68%) on LEDs.

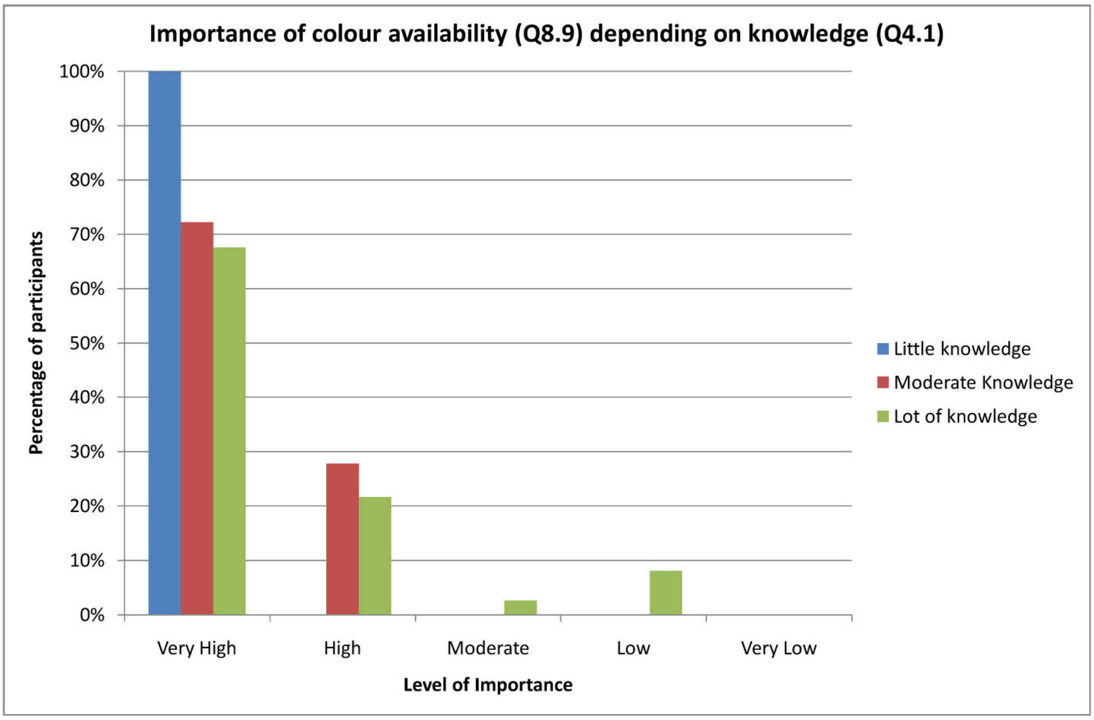

Figure 5.57: Importance of white colour availability for lighting designers, depending on their level of knowledge on LEDs (Q8.9- Q4.1)

Figure 5.58 reports that Correlated Colour Temperature (CCT) was of very high importance to the majority of lighting designers with a lot of knowledge on LEDs (70%). CCT was of very high importance to half of the lighting designers with moderate knowledge on LEDs (50%). Finally, half of the lighting designers with little knowledge on LEDs claimed that CCT is of very high (50%) or high (50%) importance.

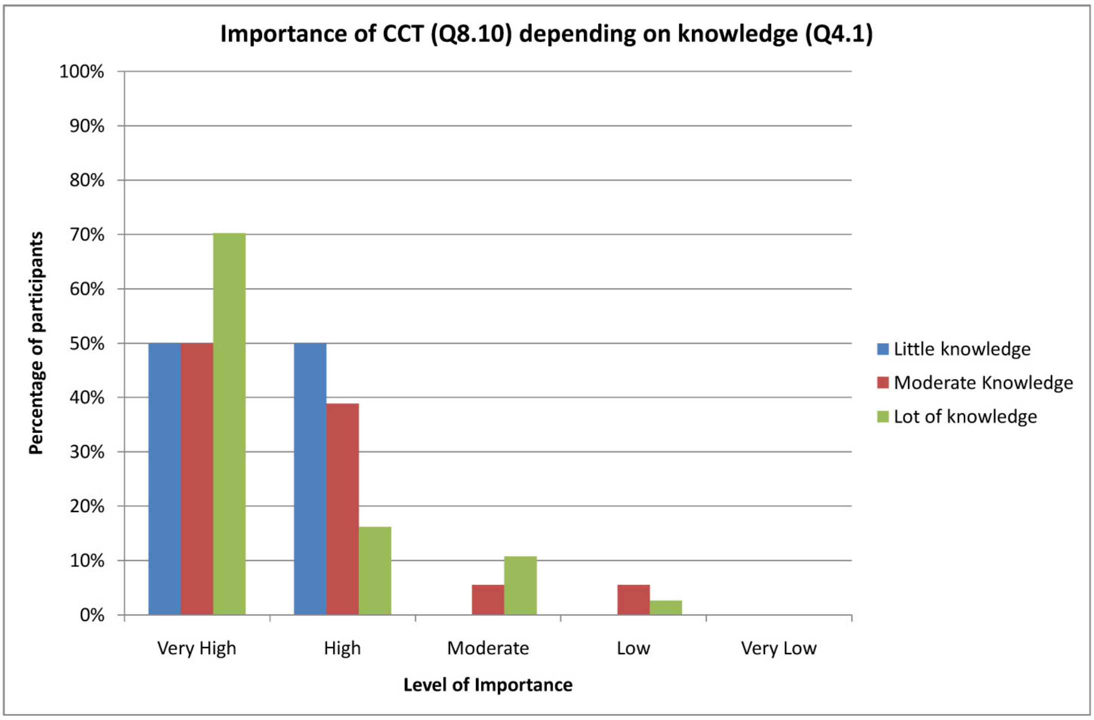

Figure 5.58: Importance of CCT for lighting designers, depending on their level of knowledge on LEDs (Q8.10- Q4.1)

Figure 5.59 suggests that CRI was of very high importance to the majority of lighting designers with a lot of knowledge on LEDs (62%). CRI was either of very high (50%) or high (50%) importance to lighting designers with little knowledge on LEDs. Surprisingly, lighting designers with moderate knowledge on LEDs were less interested on CRI (44% claimed very high importance, 28% moderate importance, and 22% high importance).

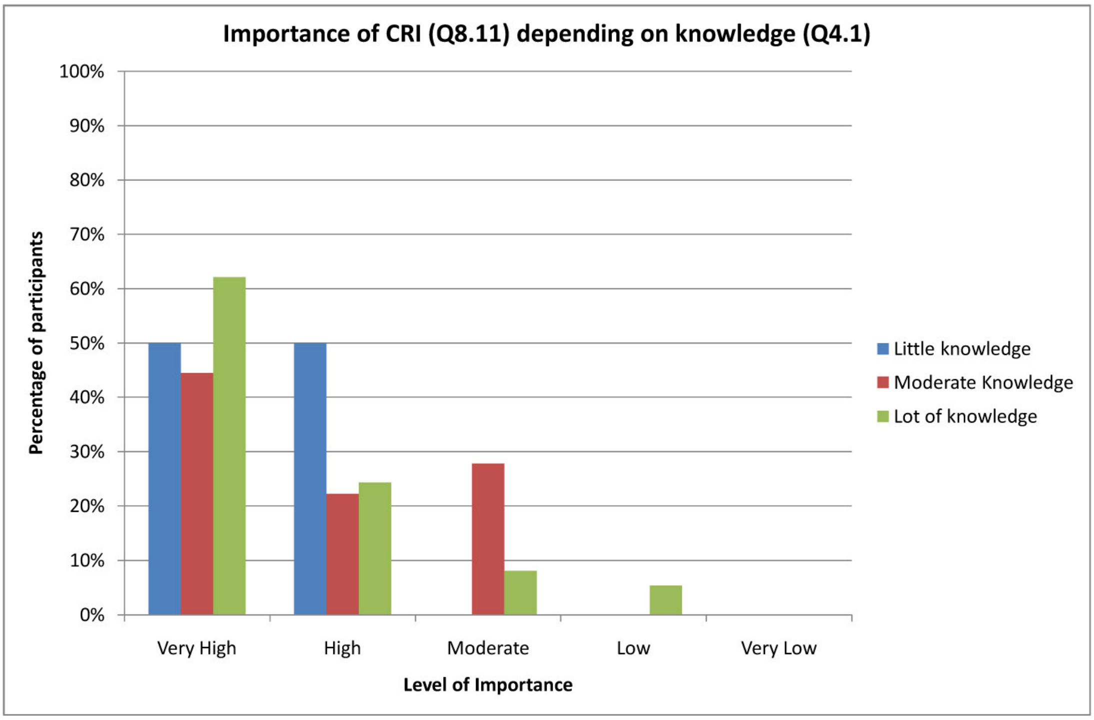

Figure 5.59: Importance of CRI for lighting designers, depending on their level of knowledge on LEDs (Q8.11- Q4.1)

Figure 5.60 concludes that LED luminaire design is of very high importance to all lighting designers with little knowledge on LEDs (100%). On the contrary, only half of the lighting designers with moderate (50%) or high knowledge (51%) on LEDs were very interested in the luminaire design.

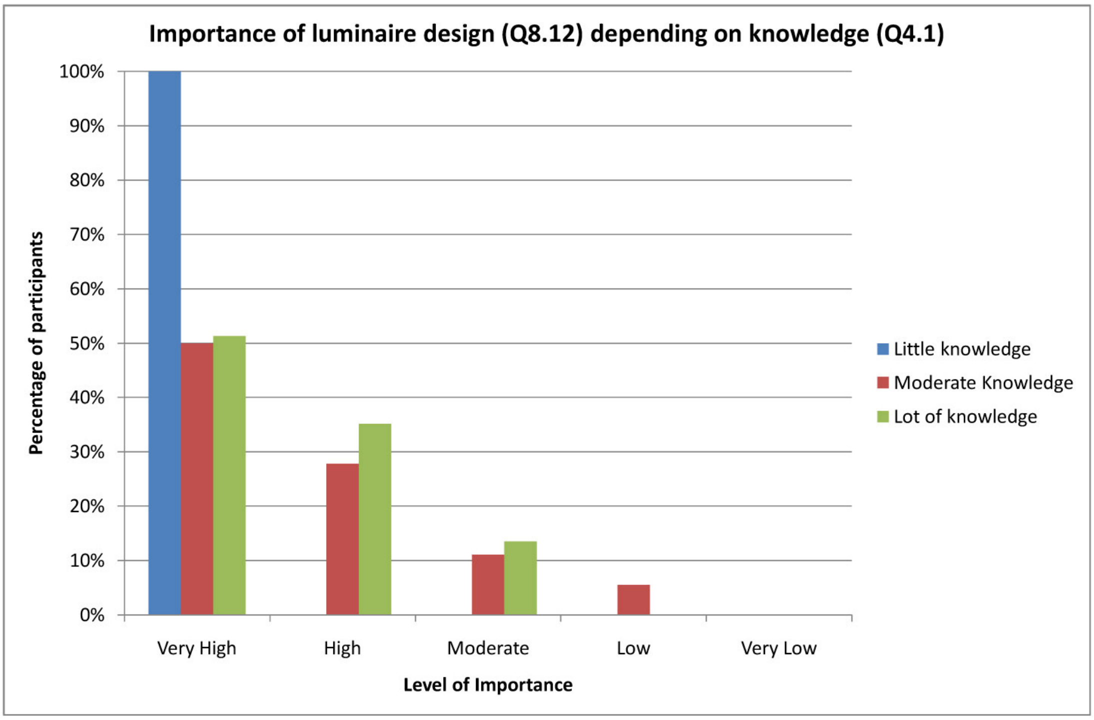

Figure 5.60: Importance of LED luminaire design for lighting designers, depending on their level of knowledge on LEDs (Q8.12- Q4.1)

Figure 5.61 shows that cost is of very high importance to all lighting designers with little knowledge on LEDs (100%). On the contrary, this was not really interesting for lighting designers with moderate or a lot of knowledge on LEDs.

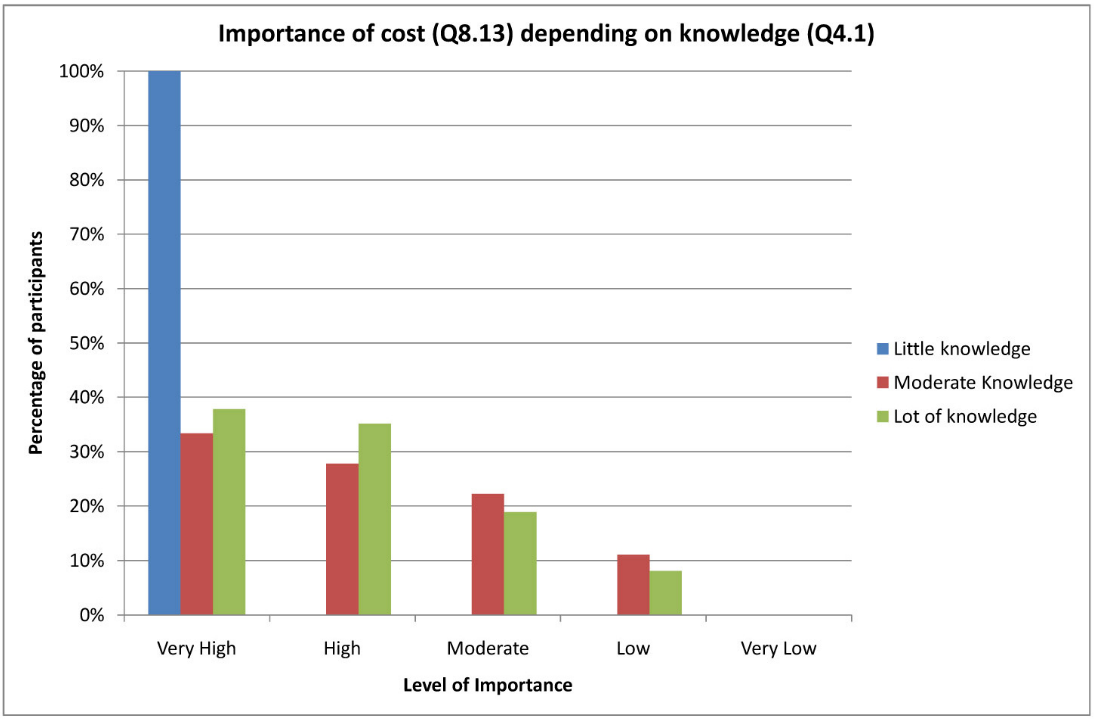

Figure 5.61: Importance of cost for lighting designers, depending on the level of their knowledge on LEDs (Q8.13- Q4.1)

Figure 5.62 explains that power consumption of LEDs is either of very high (50%) or moderate (50%) importance to lighting designers with little knowledge on LEDs. Power consumption was not so interesting for lighting designers with moderate or a lot of knowledge on LEDs.

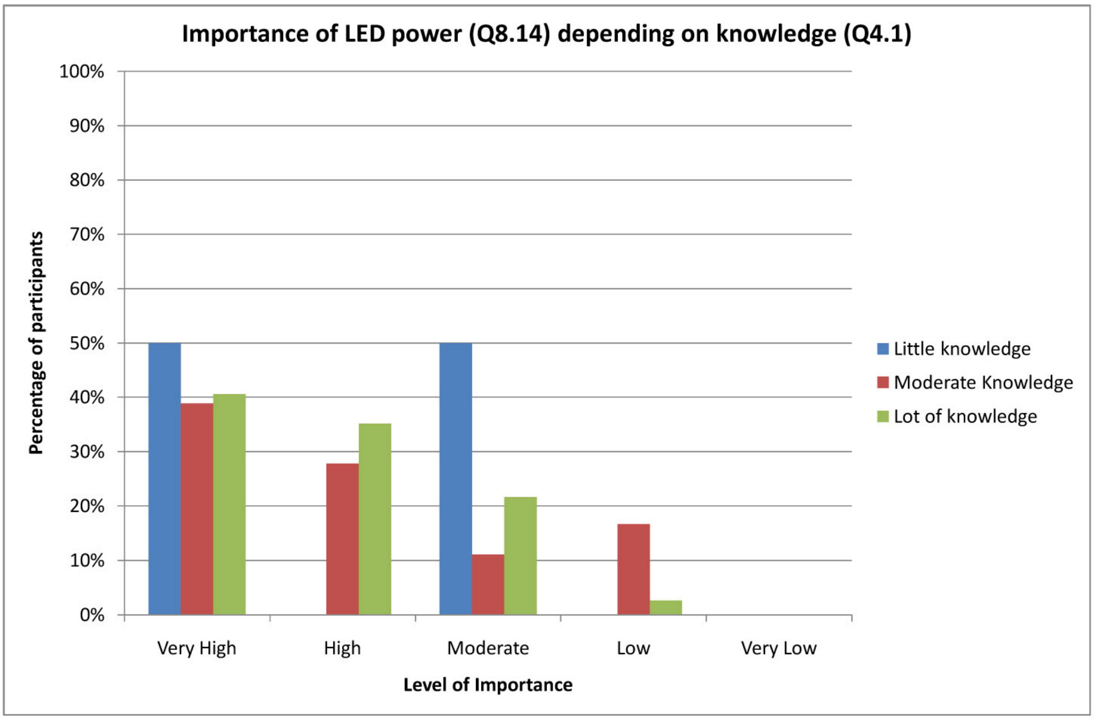

Figure 5.62: Importance of power for lighting designers, depending on their level of knowledge on LEDs (Q8.14- Q4.1)

5.2.2 Regression Analysis &Scatter Diagrams

This section presents Statistical Data and Correlations of Results of the Survey, using Linear Regression Analysis.

Regression analysis[1] is the statistical process for estimating the relationships among variables. It helps understand how the typical value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed. Linear regression was the first type of regression analysis to be used extensively in practical applications. Linear regression[2] focuses on the conditional probability distribution of y given X.

In this thesis, a regression function was developed in Excel file, by using the "value numbers" to the replies of Question 8 in regard to the importance of various lighting parameters, as defined in Table 5.1.

[1] http://en.wikipedia.org/wiki/Regression_analysis 15/4/15
[2] http://en.wikipedia.org/wiki/Linear_regression 15/4/15

Table 5.3 shows, as an example, the "value numbers" that correspond to the replies of 60 participants to Questions Q8.2 and Q8.3.

Participant	Lumen output Q8.02	Colour Consistency Q8.3	Participant	Lumen output Q8.02	Colour Consistency Q8.3
1	4	5	**31**	4	3
2	5	4	**32**	4	4
3	4	4	**33**	5	5
4	4	5	**34**	5	5
5	4	5	**35**	5	5
6	5	5	**36**	5	5
7	4	5	**37**	5	4
8	5	5	**38**	5	4
9	3	2	**39**	4	5
10	5	5	**40**	5	5
11	3	4	**41**	4	5
12	5	5	**42**	5	5
13	5	5	**43**	5	5
14	4	4	**44**	5	4
15	3	3	**45**	4	5
16	5	5	**46**	5	4
17	5	5	**47**	5	5
18	5	5	**48**	5	5
19	0	0	**49**	3	4
20	0	0	**50**	4	5
21	0	0	**51**	4	4
22	5	5	**52**	5	5
23	5	5	**53**	4	5
24	5	5	**54**	5	5
25	5	5	**55**	4	5
26	5	4	**56**	5	5
27	4	5	**57**	5	5
28	4	5	**58**	5	4
29	5	5	**59**	5	5
30	4	5	**60**	5	5

Table 5.3: "Value Numbers" allocated to the replies of participants to Q8.2 and Q8.3, where very high importance =5, high importance= 4, moderate importance= 3, low importance= 2, very low importance= 1

In turn, Scatter Diagrams were developed. The Scatter Diagram[3] is a type of mathematical diagram using Cartesian coordinates to display values for two variables for a set of data. The data is displayed as a collection of dots, each having the value of one variable determining the position on the horizontal axis and the value of the other variable determining the position on the vertical axis.

In the thesis, Scatter Diagrams were developed to display the correlation between two different lighting parameters. One lighting parameter was displayed in the horizontal axis, and another one in the vertical axis.It should be noted that a small random perturbation to each “value number” data point was conducted, by developing a formula in excel file, so that the answers do not overlap the one on top of the other, and the size of the clusters can be more easily seen. These data points are shown from the red dots on the Scatter Diagrams.

In the Scatter Diagrams, if the pattern of dots is along a diagonal line then this suggests that there is a correlation between the variables under consideration. A line of best fit is drawn in order to study the correlation between the variables, and the coefficient of determination[4] (R^2) is usually calculated. The coefficient of determination R^2 is a number that indicates how well data fit a statistical model. The coefficient of determination ranges from 0 to 1. Significant correlations are noted when $R^2>0.5$. The thesis explored all the interrelationships and calculated the R^2 values.

[3] http://en.wikipedia.org/wiki/Scatter_plot 15/4/15
[4] http://en.wikipedia.org/wiki/Coefficient_of_determination 15/4/15

In the thesis, a Scatter Diagram was developed to examine the interrelationship between colour consistency (Q8.3) plotted on the horizontal axis, and lumen output (Q8.2) plotted on the vertical axis. Figure 5.63suggests a high correlation between responses to the questions about lumen output (Q8.2) and colour consistency (Q8.3), as indicated from the concentrated plots on the scatter diagram. In fact, this is the most significant interrelationship identified in the thesis, with an R^2 value of 0.737. This means that lighting designers that place high importance on lumen output tend to also place high importance on colour consistency.

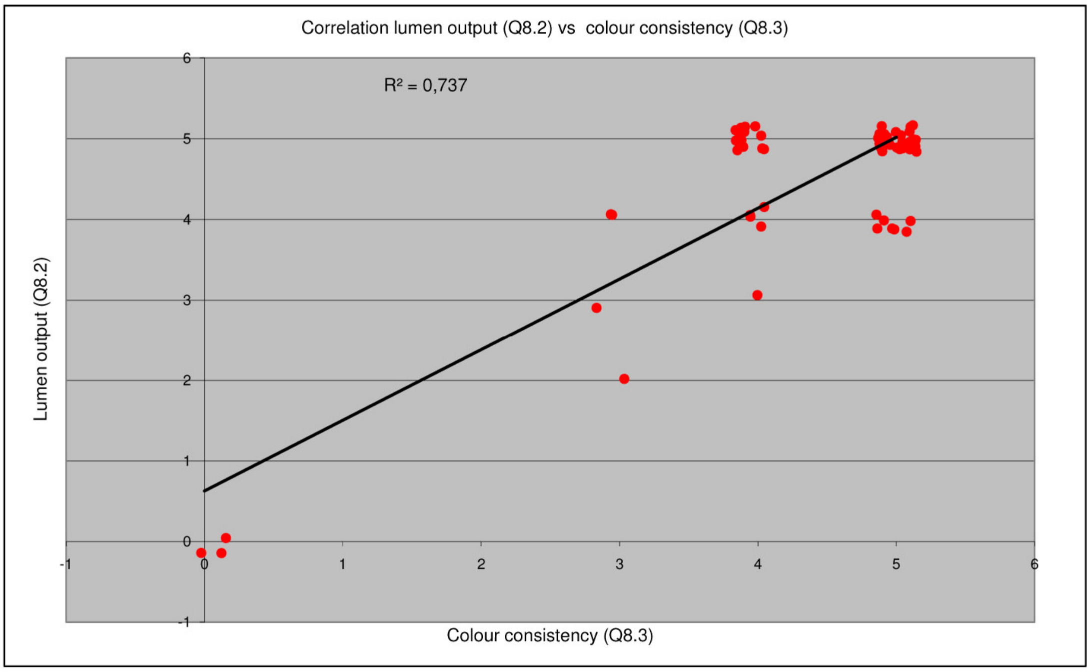

Figure 5.63: Highest correlation between lumen output and colour consistency

A second Scatter Diagram was developed plotting CRI (Q8.11) on the horizontal axis and RGB colour mixing (Q8.8) on the vertical axis. The answers plotted in Figure 5.64show that there is a low correlation between RGB (Q8.8) and CRI (Q8.11), illustrated by the widespread plots on the scatter diagram. Also, the R^2 value of 0,151 verifies the low correlation between these two parameters. In fact this is the lowest R^2 value identified in the thesis, and suggests that lighting designers do not relate RGB colour mixing with CRI.

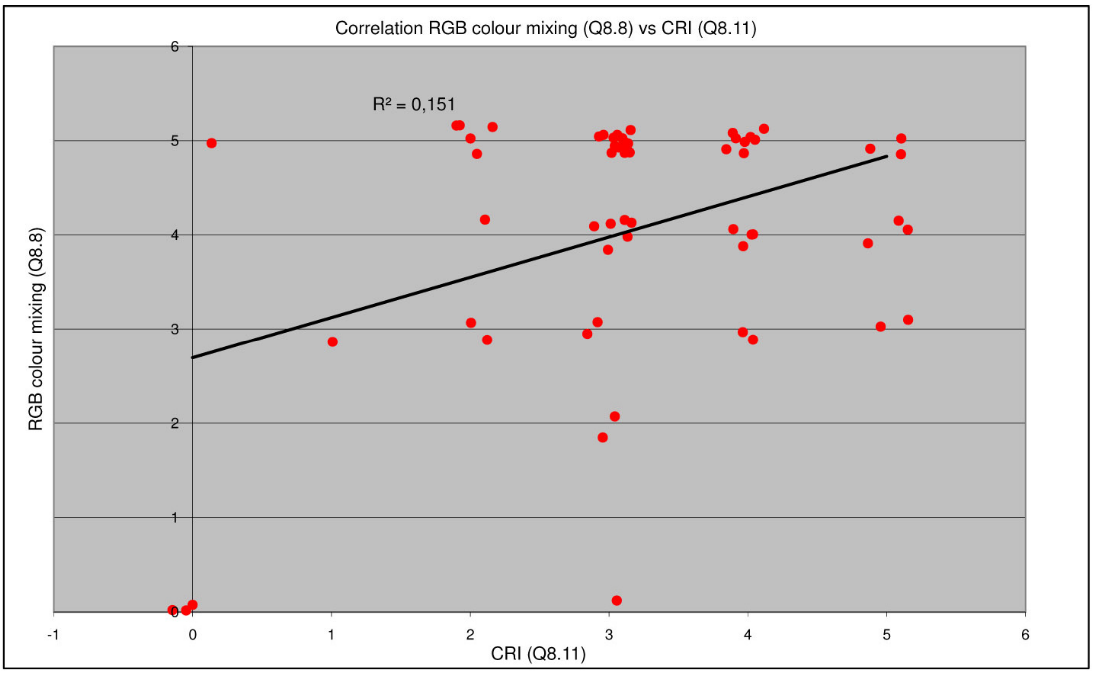

Figure 5.64: Lowest correlation between RGB colour mixing and CRI

The results of the Regression Analysis are summarized in Table 5.4. The table presents the correlations between all the lighting parameters, deriving from the R^2 values calculated based on the answers given in Question 8 (Figures 5.7-5.20) and as defined in Table 5.1. The most important values with $R^2>0.5$ that show high interrelationships are highlighted; whereas the least significant values with $R^2<0.5$ that show poor interrelationships are grayed.

In particular, lumen output (Q8.2) and colour consistency (Q8.3) have the highest correlation. High correlation is also identified between colour range availability (Q8.1) and colour consistency(Q8.3), colour consistency (Q8.3) and lumen maintenance (Q8.4), cost (Q8.13) and power (Q8.14), lumen output (Q8.2) and lumen maintenance (Q8.4), colour consistency (Q8.3) and white colour availability (Q8.9), CCT(Q8.10) and CRI(Q8.11), colour range availability (Q8.1) and lumen maintenance (Q8.4), colour consistency (Q8.3) and CCT (Q8.10), control capabilities (Q8.6) and white colour availability (Q8.9), colour range availability (Q8.1) and lumen output (Q8.2), white colour availability (Q8.9) and CCT (Q8.10), luminaire design (Q8.12) and power (Q8.14).

The fact that some parameters are very highly correlated together means that people with interest in one area are also likely to be interested in another area. More particularly, lighting designers that are interested in colour consistency are also very much interested in Lumen output and colour range availability. Similarly, lighting designers who have an interest in Lumen maintenance are also interested to know about colour consistency, lumen output and colour range availability of LEDs. Likewise, lighting designers who are interested in white colour availability are also interested in control capabilities and colour consistency.

Table 5.4 also shows that there is low correlation between lumen output (Q8.2) and CCT (Q8.10), stability (Q8.5) and power (Q8.14) of LEDs, colour availability (Q8.1) and CRI (Q8.11), white colour availability (Q8.9) and CRI (Q8.11), lifetime (Q8.7) and power (Q8.14) of LEDs. Finally, there is very low correlation between control capabilities (Q8.6) and RGB colour mixing (Q8.8), CRI (Q8.11) and cost (8.13), RGB colour mixing (Q8.8) and colour consistency (Q8.3).

The low correlation between parameters suggests that people are less likely to be interested in these two areas. For example, lighting designers who use RGB colour mixing are unlikely to expect a high CRI of LEDs. Similarly, lighting designers do not seem to care about the cost of LEDs when it comes to CCT and CRI.

Correlations	**Q8.2**	**Q8.3**	**Q8.4**	**Q8.5**	**Q8.6**	**Q8.7**	**Q8.8**	**Q8.9**	**Q8.10**	**Q8.11**	**Q8.12**	**Q8.13**	**Q8.14**
Q8.1	**0,644**	**0,711**	**0,654**	0,418	0,550	0,367	0,279	0,584	0,475	0,408	0,436	0,321	0,355
Q8.2		**0,737**	**0,678**	0,533	0,590	0,530	0,312	0,580	0,496	0,429	0,530	0,482	0,504
Q8.3			**0,684**	0,596	0,539	0,394	0,277	**0,677**	**0,652**	0,565	0,532	0,351	0,418
Q8.4				0,582	0,462	0,513	0,227	0,521	0,406	0,480	0,503	0,393	0,386
Q8.5					0,521	0,500	0,208	0,530	0,469	0,434	0,478	0,375	0,463
Q8.6						0,563	0,343	**0,648**	0,421	0,349	0,538	0,418	0,493
Q8.7							0,276	0,539	0,405	0,326	0,446	0,431	0,396
Q8.8								0,289	0,203	0,151	0,145	0,251	0,261
Q8.9									**0,606**	0,406	0,498	0,339	0,403
Q8.10										**0,668**	0,436	0,221	0,414
Q8.11											0,495	0,283	0,402
Q8.12												0,567	**0,600**
Q8.13													**0,680**

Table 5.4: Correlations between lighting parameters

Chapter Six

Completed in July 2012

Market Analysis

Chapter Six presents the findings of the market analysis which took place in the period January- July 2012 through a thorough internet research. The market research focused on the three major categories of LED products available in the market: LED Chips, LED Modules and LED Luminaires. The research aimed at discovering the information that different groups of manufacturers offer to the LED Supply Chain. To achieve this, a few products were analyzed per company. In turn, tables and graphs were developed in order to summarize the most important information available from various manufacturers.

6.1. LED Chips

This section presents the findings of the market research in regard to LED Chips. The LED Chips manufacturers studied are PhilipsLumileds, Cree, Osram, Edison, and Samsung.

6.1.1 Philips Lumileds

Philips Lumileds Lighting Company[1] was founded in 1999. Nowadays, it is one of the world's leading manufacturers of LED dies, packaged LEDs, and high brightness LEDs designed for integration into general lighting products. The company also makes white, red, amber, blue and green LED light sources. In general, Philips Lumileds is a pioneer in the use of solid-state lighting solutions.

For the purposes of this research, four products were analyzed from Philips Lumileds: Luxeon Rebel White DS63 and DS64[2], Luxeon Rebel White ES DS61[3], and Luxeon Rebel and Rebel ES Color DS68[4].The products are from the Luxeon Rebel series[5] which is an award winning LED series. According to the company, Luxeon Rebel is the most widely used power LED available that delivers optimized combinations of light quality and light output needed in lighting applications. The results are summarized in Table 6.1, where the 'x' denotes availability of data and the '–' the lack of data:

PRODUCT INFORMATION[6]	DS63 Luxeon Rebel white	DS64 Luxeon Rebel white	DS61 Luxeon Rebel white ES	DS68 LuxeonRebel&LuxeonRebel ES colour portfolio
General Product Information	X	X	X	X
ProductNomenclature	X	X	X	X
Average Lumen Maintenance Characteristics	X	X	X	X
Environmental Compliance	X	X	X	X
Luminous Flux Characteristics	X	X	X	X
Flux Performance, Binning, and Supportability	X	X	X	X
Product specifications (Product selection)	X	X	X	X
Thermal pad temperature	X	X	X	X
CCT range	X	X	X	X

[1]http://www.philipslumileds.com/about-us 4/4/12
[2]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-white 4/4/12
[3]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-white 4/4/12
[4]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-color#blue 4/4/12
[5]http://www.philipslumileds.com/products/luxeon-rebel 4/4/12
[6]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-white 26/4/12

Min CRI	X	X	X	X
Typical R9	X	X	X	X
Min Luminous Flux	X	X	X	X
Typical Flux at 350mA	X	X	X	X
Typical Efficacy lm/w at 350mA	X	X	X	X
Typical Luminous Flux	X	X	X	X
Optical characteristics	X	X	X	X
Nominal CCT	X	X	X	X
CCT Min	X	X	X	X
CCT Typ	X	X	X	X
CCT Max	X	X	X	X
Typical Viewing Angle (degrees) 2θ ½	X	X	X	X
Electrical Characteristics	X	X	X	X
Forward Voltage Vf Min	X	X	X	X
Forward Voltage VfTyp	X	X	X	X
Forward Voltage Vf Max	X	X	X	X
Typical Temperature coefficient of forward voltage (mV/°C)	X	X	X	X
Typical Thermal Resistance Junction to thermal pad (°C/W)	X	X	X	X
Typical Forward voltage Vf	X	X	X	X
Absolute Maximum Ratings	X	X	X	X
JEDEC Moisture Sensitivity	X	X	X	X
Reflow Soldering Characteristics	X	X	X	X
Mechanical Dimensions	X	X	X	X
Pad Configuration	X	X	X	X
Solder Pad Design	X	X	X	X
Wavelength Characteristics	X	X	X	X
Relative Spectral Distribution vs. Wavelength Characteristics	X	X	X	X
Typical Light Output Characteristics over Temperature	X	X	X	X
Typical Forward Current Characteristics	X	X	X	X
Typical Relative Luminous Flux	X	X	X	X
Current Derating Curves	X	X	X	X
Typical Radiation Patterns	X	X	X	X
Emitter Pocket Tape Packaging	X	X	X	X
Emitter Reel Packaging	X	X	X	X
Product Binning and Labeling	X	X	X	X

Luminous Flux Bins	X	X	X	X
Bin structures	X	X	X	X
Bin coordinates	X	X	X	X
Forward Voltage Bins	X	X	X	X

Table 6.1: LED Chip information by Philips Lumileds

6.1.2. Cree

Cree[7] is a market-leading innovator of LEDs, LED lighting and semiconductor solutions for wireless and power applications. Actually, Cree first brought the blue LED to the market in 1989, and today the CreeXLamp® LEDs have continually exceeded industry standards for brightness and efficiency, as the company claims. Cree's high brightness LEDs are also introducing new performance levels for decorative lighting.

For the purposes of this research, seven products were selected from the Cree selection. All products are part of the EZBright LED series[8], which offers the brightest LED chips, ideal for applications where high brightness and low power consumption are required, such as decorative lighting, task lighting and outdoor illumination. The EZBright LEDs combine highly efficient InGaN materials with Cree's proprietary optical design and wafer-level submount technology to deliver superior value for high-intensity LEDs. The LED Chips studied in this current research are: EZ290, EZ400[9], EZ500, EZ600, EZ700, EZ900, EZ1000.The results are summarized in Table 6.2, where 'x' denotes availability of data and '– ' the lack of data.

[7]http://www.cree.com/about/overview.asp 5/4/12
[8]http://www.cree.com/products/ezbright.asp 5/4/12
[9]http://www.cree.com/products/pdf/CPR3EJ.pdf 5/4/12

PRODUCT INFORMATION[10]	EZ290	EZ400	EZ500	EZ600	EZ700	EZ900	EZ1000
Features	X	X	X	X	X	X	X
Applications	X	X	X	X	X	X	X
Chip diagram	X	X	X	X	X	X	X
Maximum Ratings at TA = 25°C	X	X	X	X	X	X	X
Thermal pad temperature	X	X	X	X	X	X	X
DC Forward Current	X	X	X	X	X	X	X
Peak Forward Current	X	X	X	X	X	X	X
LED Junction Temperature	X	X	X	X	X	X	X
Reverse Voltage	X	X	X	X	X	X	X
Operating Temperature Range	X	X	X	X	X	X	X
Storage Temperature Range	X	X	X	X	X	X	X
Electrostatic Discharge Threshold (HBM)	X	-	-	-	-	-	-
Electrostatic Discharge Classification (MIL-STD-883E)	X	-	-	-	-	-	-
Typical Electrical/Optical Characteristics at TA = 25°C, If = 20 mA	X	X	X	X	X	X	X
Forward Voltage (Vf, V)	X	X	X	X	X	X	X
Reverse Current [I(Vr=5V), µA]	X	X	X	X	X	X	X
Full Width Half Max (λD, nm)	X	X	X	X	X	X	X
Mechanical Specifications	X	X	X	X	X	X	X
P-N Junction Area (µm)	X	X	X	X	X	X	X
Chip Area (µm)	-	X	X	X	X	X	X
Top Area (µm)	X	-	-	-	-	-	-
Bottom Area (µm)	X	-	-	-	-	-	-
Chip Thickness (µm)	X	X	X	X	X	X	X
Au Bond Pad Diameter (µm)	X	X	X	X	X	X	X
Au Bond Pad Thickness (µm)	X	X	X	X	X	X	X
Back Contact Metal Area (µm)	X	X	X	X	X	X	X
Back Contact Metal Thickness (µm)	X	X	X	X	X	X	X
Standard Bins	X	X	X	X	X	X	X
Radiant flux and dominant wavelength bins	X	X	X	X	X	X	X
Forward Current vs. Forward Voltage curve	X	X	X	X	X	X	X
Wavelength Shift vs. Forward Current curve	X	X	X	X	X	X	X
Relative Intensity vs. Forward Current curve	X	X	X	X	X	X	X

[10] http://www.cree.com/products/ezbright.asp 26/4/12

Relative Intensity vs Peak Wavelength curve	X	-	-	-	-	-	-
Radiation pattern	-	X	X	X	X	X	X
Relative Light Intensity vs Junction Temperature curve	-	X	X	X	X	X	X
Voltage Shift vs Junction Temperature curve	-	X	X	X	X	X	X
Dominant Wavelength Shift vs Junction Temperature curve	-	X	X	X	X	X	X
Max Forward current vs Ambient Temperature	-	-	-	-	-	X	X

Table 6.2: LED Chip Information by CREE

6.1.3 OsramOpto Semiconductors

OsramOpto Semiconductors [11] is the pioneer of Thinfilm technology for InGaAlPIndium Gallium Aluminium Phosphide), InGaN (Indium Gallium Nitride) and GaAs (Gallium Arsenide) and for high-performance LEDs in the visible and infrared spectrum. It is also a leader in manufacturing technology, backend volume production and has a wide portfolio of package (LED-casing) types. The company claims that the OSTAR range of products has made them a leader in compact, high-performance light sources for visible and invisible light.

OsramOpto Semiconductorsmost popular products include the Diamond Dragon which is, according to the company, the brightest single chip LED with excellent thermal resistance and long lifetime, that is reflow solderable and lead free[12]. Another popular product is the Golden Dragon Plus which is a high power LED with silicone dome, excellent thermal management, maximum current of 1A, long lifetime[13]. And the Platinum Dragon which is a high power, lead free light source[14].Given the above, the following LED Chips were studied in this current

[11] http://www.osram-os.com/osram_os/EN/About_Us/We_shape_the_future_of_light/Awards/index.html 6/4/12

[12] http://catalog.osram-os.com/catalogue/catalogue.do;jsessionid=A8814C8D83CA46CD28D2C53FECC25B47?act=showBookmark&favOid=000000010001feb602880023 9/4/12

[13] http://catalog.osram-os.com/catalogue/catalogue.do?act=showBookmark&favOid=000000030000ad4f037c0023 9/4/12

[14] http://catalog.osram-os.com/catalogue/catalogue.do?act=showBookmark&favOid=000000010003dc3901850023 9/4/12

research: Diamond Dragon LUW W5AP[15], Golden Dragon Plus LH W5AM[16], and Platinum Dragon LV W5SN[17].The results are summarized in Table 6.3, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	DIAMOND DRAGON[18]	DIAMOND DRAGON LUW W5AP[19]	GOLDEN DRAGON PLUS LH W5AM[20]	PLATINUM DRAGON LV W5SN[21]
Applications	X	X	X	X
Colour/ Wavelength	X	X	-	-
Features	X	X	X	X
Construction	X	-	X	-
Radiation characteristics	X	-	x	-
Handling	X	-	x	-
Processing	X	-	x	-
Reflow solder profile for lead-free soldering	X	-	x	-
Thermal considerations	X	-	x	-
Influence of Junction Temperature	X	-	x	-
Reliability	X	-	x	-
Lifetime	X	-	x	-
Construction and aging mechanisms	X	-	-	-
Degradation characteristics	X	-	-	-
L70/ B50	X	-	-	-
Product Family	X	-	X	-
Universal Solder Pad Design	X	-	-	-

[15] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000400011c6402e30023&act=showBookmark 9/4/12
[16] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000300018fab056f0023&act=showBookmark 9/4/12
[17] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000500019b6000a50023&act=showBookmark 9/4/12
[18] http://catalog.osram-os.com/catalogue/catalogue.do?act=showBookmark&favOid=000000000000028b00010023 26/4/12
[19] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000400011c6402e30023&act=showBookmark 26/4/12
[20] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000300018fab056f0023&act=showBookmark 26/4/12
[21] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000500019b6000a50023&act=showBookmark 26/4/12

PCB material	X	-	-	-
Related product types	-	X	-	-
Parameter List	-	X	X	X
Ordering No.	-	X	X	X
Lead (Pb) Free Product - RoHS Compliant	-	X	X	X
Colour of Emission	-	X	X	X
Package Colour	-	X	X	X
Wavelength	-	X	X	X
Technology	-	X	X	X
Optical efficiency	-	X	X	X
Luminous Flux	-	X	X	X
Luminous Intensity	-	X	X	X
Viewing angle at 50 % I_V (horizontal)	-	X	X	X
Package	-	X	X	X
Datasheet	-	X	X	X
CCT	-	X	X	X
Maximum Ratings	-	X	X	X
Operating temperature range	-	X	X	X
Storage temperature range	-	X	X	X
Junction temperature for short term application	-	X	X	X
Junction temperature	-	X	X	X
Forward current(TS=25°C)	-	X	X	X
Surge current at t=...ms, D = , TS=25°C	-	X	X	X
Reverse voltage (TS=25°C)	-	X	X	X
Characteristics (TS = 25 °C)	-	X	X	-
Viewing angle at 50 % IV	-	X	X	X
Forward voltage	-	X	X	X
Reverse current	-	X	X	X
Thermal resistance	-	X	X	X
Junction/soldering point	-	X	X	X
Wavelength at peak emission	-	-	X	X
Dominant wavelength	-	-	X	X
Centroid wavelength	-	-	X	-
Spectral bandwidth at 50 % Φrel max	-	-	X	X
Temperature coefficient of λcentroid	-	-	X	-

Chromaticity coordinate groups	-	X	-	X
Colour Bins	-	X	-	X
Brightness Groups	-	X	X	X
Luminous Flux	-	X	-	X
Luminous Intensity	-	X	-	X
Radiant power	-	-	X	-
Graphs	-	X	X	-
Relative Spectral Emission	-	X	X	X
Radiation Characteristic	-	X	x	X
Forward Current	-	X	x	X
Relative Luminous Flux	-	X	-	X
Relative Radiant Power	-	-	X	-
Chromaticity Coordinate Shift	-	X	-	-
Relative Forward Voltage	-	X	-	X
Relative Voltage	-	-	X	-
Relativer Luminous Flux	-	X	-	-
Chromaticity Coordinate Shift2	-	X	-	X
Max. Permissible Forward Current	-	X	X	X
Permissible Pulse Handling Capability	-	X	X	X
Package Outlines, Drawings & Dimensions	-	X	X	X
Method of Taping / Polarity and Orientation	-	X	X	X
Recommended Solder Pad	X	X	X	X
Soldering Conditions	-	X	X	X
Reflow Soldering Profile for lead free soldering	-	X	X	X
Profile Feature	-	X	X	X
Barcode-Product-Label (BPL)	-	X	X	X
Tape and Reel	-	X	x	X
Driving	-	-	X	-

Table 6.3: LED Chip Information by Osram

6.1.4 Edison Opto Corporation

Edison[22] is a leading high power LED manufacturer. The company offers a comprehensive line of products ranging from 1Watt to 120Watts, single-chip to multi-chip, with high flux and high CRI. The company aims to challenge the limitations in order to create the ideal LED products for the emerging solid-state lighting field. Their goal is to transform the LED experience so as to enrich people's life style but also to promote a better living environment.

The company offers a variety of LED chips. The Federal 3535[23] is a surface mount, compact high brightness LED that is built for various application needs, including general illumination. Edipower II[24] is available in different colours and operating powers. It serves as optical engine and it offers high CRI, thus it can be used in general lighting applications. Edixeon Series[25] creates exceptional colour mixing with vivid colours and vibrant effects, but also reduces total LED system cost by reducing the number of components. The results are summarized in Table 6.4, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	FEDERAL 3535	FEDERAL 3535 7	Edipower II	Edipower II	Edixeon RGB 3W
Wavelength λd (nm)	X	-	X	X	X
Forward voltage VfTyp	X	-	X	X	X
Forward current IF mA	X	X	X	X	X
Radiation patterns	X	-	X	X	X
CRI	X	-	X	X	-
Features	X	X	X	X	X
Applications	X	X	X	X	-
Environmental compliance	X	-	X	X	X
Nomenclature/ Bin groups/ CCT ranks	X	X	X	X	X
Photometric luminous flux ranks lm (min, max) per colour	X	-	X	-	-
CCT ranks- Edison Optostandardard ranks	X	-	X	-	-
Drawings/ Dimensions	X	X	X	X	X
Polarity	-	-	-	-	X
Emitter circuit layout	-	-	X	X	-
Specifications	X	-	X	-	-
Test current mA	X	-	-	-	-
Flux (lm) group	X	-	X	-	-
Tj=25□C Flux lm	X	-	-	-	-
Rth (□C/W)	X	-	-	-	-

[22]http://www.edison-opto.com.tw/00_page.asp?sn=1 9/4/12
[23]http://www.edison-opto.com.tw/01_products_detail.asp?sn=136 9/4/12
[24]http://www.edison-opto.com.tw/01_products_detail.asp?sn=99 9/4/12
[25]http://www.edison-opto.com.tw/01_products_detail.asp?sn=46 9/4/12

2θ1/2	X	-	-	-	-
Colour spectrum and radiation pattern	X	-	X	-	-
Colour spectrum at Tj=25□C	X	-	X	-	-
Radiation pattern	X	-	X	-	-
Colour temperature or dominant wavelength Tj=25□C	-	-	-	x	-
Electric curves at Tj=25□C	X	-	-	-	-
Relative luminous flux vs forward current	X	-	-	-	-
Wavelength vs forward current	X	-	-	-	X
Forward voltage vs forward current	X	-	-	-	-
Tj influence curve	X	-	-	-	-
Relative luminous flux vs thermal pad temperature	X	-	-	-	-
Typical CCT vs Tj	X	-	X	X	-
Max operating current vs ambient temperature	X	-	-	-	-
Reliability test items at Tj=25□C	X	-	-	-	-
Package, transportation, storage	X	-	X	X	-
Moisture sensitivity levels	X	-	-	-	-
Handling	X	-	X	-	-
Installation instructions	X	-	-	-	-
Selection of solder	X	-	-	-	-
Optical support	X	-	X	-	-
Driving method	X	-	X	-	-
Thermal management	X	-	X	-	-
Absolute max ratings	-	X	X	X	X
Peak pulsed current	-	X	X	-	X
Transient surge voltage	-	X	X	-	-
Reverse voltage	-	X	X	X	X
LED junction temperature	-	X	X	X	X
Operating temperature	-	X	X	X	X
Storage temperature	-	X	X	X	X
ESD sensitivity	-	X	X	X	X
Allowable reflow cycles	-	X	-	-	-
Soldering temperature	-	X	-	-	X
Thermal measurement point	-	-	X	X	-
Isolation voltage	-	-	X	X	-
Luminous flux characteristics If=350mA, Thermal pad 25□C	-	X	-	-	-
Luminous flux characteristics Thermal pad 25□C	-	X	X	X	-
Typical luminous flux lm at Tj=60□ or 25□	-	-	X	X	-
Typical Light Output Characteristics over Thermal Pad Temperature	-	-	-	X	-
Typical Power Output Characteristics vs. Thermal Measuring Point Temperature	-	-	-	X	-
Luminous flux Min	-	X	-	-	X
Luminous flux Typ	X	X	X	X	X
Luminous flux Max	-	-	-	-	X
Forward voltage Min	X	-	-	-	X
Forward voltage Max	X	-	-	-	X

Optical characteristics at Tj=25°C, 350mA and 700mA	-	X	-	-	-
Power consumption	-	X	-	-	-
CCT (K) Min, Typ, Max	-	X	-	-	-
Viewing angle (degrees)	-	X	-	-	-
Electrical characteristics at Tj=25°C	-	X	-	-	-
Thermal resistance (°C/W)	-	X	X	X	-
JEDEC Moisture sensitivity	-	X	-	-	X
Curves	-	X	-	-	-
Spectrum curve	-	X	-	X	X
Radiation diagram	-	X	-	X	X
Luminous flux vs Junction temperature	-	X	-	-	-
CCT and junction temperature	-	X	-	-	-
Forward voltage and forward current	-	X	-	-	-
Luminous flux and forward curent	-	X	-	-	-
CCT and forward current	-	X	-	-	-
Reliability items and failure measure	-	-	X	X	X
Typical light output over thermal pad temperature	-	-	X	-	-
Typical power output vs thermal measuring point temperature	-	-	X	-	-
Soldering and assembly	-	-	X	X	X
Temperature coefficient of forward voltage and thermal resistance junction	-	-	-	-	X
Operating current vs ambient temperature	-	-	-	-	X
Forward current vs relative luminous	-	-	-	-	X
Wavelegth characteristics per colour	-	-	-	-	X
Photometric Luminous Flux Bins per colour	-	X	-	X	X
Colour and x,y groups	X	X	X	X	X
Product bin group code	-	X	-	X	X
Radiometric power ranks mW per colour	X	-	-	-	X
Wavelength ranks	X	-	-	-	X
Dominant wavelength and CIE coordinate	X	-	-	-	X
Reflow profile	-	-	-	-	X
Product thermal application information	-	-	-	-	X
Thermal resistance calculation	-	-	-	-	X

Table 6.4: LED Chip Information by Edison

6.1.5 Samsung

Samsung Electronics[26] claims to be a globally specialized company offering semiconductors and LEDs, two integral parts of device soloutions. Indeed, the design and manufacture of semiconductors for storage of digital information is the main task for the memory business of Samsung. In turn, the company provides optical semiconductors to suit needs in the market where highly-integrated products are required. At the same time, Samsung is leading with innovations in the next generation of new light sources of environmentally friendly LEDs. Samsung produces high performance LED chips and packages and offers lighting solutions ranging from display modules to lighting engines with integrated optical, thermal and power technologies.

For the purposes of this research, the Middle Power Chips were studied. These are lower- power consumption LED chips with long lifetime and high reliability, characterized by quick response speed and excellent colour reproduction. The results are summarized in Table 6.5, where ‘x’ denotes availability of data and ‘-‘ the lack of data.

PRODUCT INFORMATION	SPMWHT5206N 2BAA0S0	SPMWHT221MD5 WAW0S0	SPMWHT521M D5WAW0S0
DATASHEETS	X	X	X
Model No	X	X	X
Colour	X	X	X
Dimensions	X	X	X
Luminous intensity (typ)	X	X	X
Absolute Maximum Rating	X	X	X
Electrical/ Optical Characteristics	X	X	X
Chromaticity Coordinates	X	X	X
Luminous Intensity	X	X	X
Chromaticity Diagram	X	X	X
Typical Characteristics Graph	X	X	X
Relative luminous intensity vs forward current	X	X	X
Forward current vs forward voltage	X	X	X
Forward current derating curve	X	X	X
Spectrum distribution	X	X	X
Radiation diagram	X	X	X
Forward current vs colour	-	X	X
Forward voltage vs temperature	-	X	X
Relative luminous flux vs temperature	-	X	X
LED Package Outline Dimensions	X	X	X
Reliability Test Items and Conditions	X	X	X
Solder Conditions	X	X	X
Label Structure	X	X	X

[26] http://www.samsungled.com/eng/intro/about.asp 9/7/12

Precaution for Use	X	X	X
Hazard Substance Analysis	X	X	X

Table 6.5: LED Chip information by Samsung

6.1.6 Other companies

Tekcore[27] is a leading LED wafer and chip production companies in Taiwan that specializes in high brightness LED technology of the entire visible spectrum as well as infrared and ultraviolet wavelengths. The company offers[28] Power chips (UV, blue), HB ITO chip (UV, blue, green) and AlGaInP WP (Red, Yellow), as well as a New chip (blue). Nevertheless, the product information was very limited on the website and no datasheets were available at the time that this research took place.

Finally, one very popular LED manufacturer is Epistar[29], a premier global supplier that pursues cutting-edge production and engineering innovation in epitaxy. The company offers[30] the High Voltage series which is an evolutionary and innovative product, the InGan series which actualizes the LED potential, and the AlGaInP series which is the world's number one chip in performance and high brightness capacity, according to the company. Nevertheless, the research on Epistar products could not be realized through the internet search, as the company website was not working at the time that this research was carried out.

6.1.7 Information on LED Chips available in the market

Table 6.6 shows that all LED chip manufacturers give information about the features and applications of their products, as well as ordering guidelines. All of them also provide data such as the colour of the chips, electrical characteristics, forward voltage, forward current, LED junction temperature, and maximum ratings. In addition, they all provide mechanical dimensions and various drawings, graphs and curves.

[27] http://www.tekcore.com.tw/index.php?option=com_content&task=view&id=12&Itemid=84 9/4/12
[28] http://www.tekcore.com.tw/index.php?option=com_content&task=view&id=28&Itemid=97 9/4/12
[29] http://www.epistar.com.tw/_english/06_about/01_about.php?AID=1 9/4/12
[30] http://www.epistar.com.tw/_english/01_product/01_overview.php 9/4/12

Most LED chip manufacturers give information on the design resources, on the viewing angle of their chips, as well as on the photometry, luminous flux, luminous flux binning, and luminous intensity. Similarly, most LED chip manufacturers offer data on colorimetry and optical characteristics, together with CCT, colour binning, chromaticity coordinates and wavelength characteristics. Moreover, most manufacturers also provide information on the pad configuration including the thermal pad temperature, on reverse voltage, soldering characteristics, radiation patterns, operating temperature, and thermal characteristics, as well as on the reliability and environmental compliance of their products.

However, only few LED chip manufacturers present information on the lifetime, lumen maintenance, luminous efficacy, radiant power, and CRI of their products. Also, very few offer information on the polarity and driving method of the chips, on reverse current, Jedec moisture sensitivity, as well as on the installation instructions.

	LED CHIP MANUFACTURERS				
LED CHIP PRODUCT INFORMATION	**PHILIPS**	**CREE**	**OSRAM**	**EDISON**	**SAMSUNG**
Features	YES	YES	YES	YES	YES
Ordering guide	YES	YES	YES	YES	YES
Viewing angle	YES	NO	YES	YES	YES
Lifetime	SOMETIMES	NO	YES	NO	NO
Photometry	YES	NO	YES	YES	NO
Lumen maintenance	YES	NO	YES	NO	NO
Luminous flux lm	YES	NO	YES	YES	YES
Luminous flux binning	YES	NO	SOMETIMES	YES	YES
Luminous efficacy	YES	NO	NO	NO	NO
Luminous intensity	YES	YES	YES	NO	YES
Radiant power	NO	NO	YES	SOMETIMES	NO
Colourimetry/ Optical characteristics	YES	NO	YES	YES	YES
CCT	YES	NO	YES	YES	YES
CRI	YES	NO	NO	YES	NO
Wavelength characteristics	YES	YES	YES	YES	NO
Colour binning	YES	NO	YES	YES	YES
Radiation characteristics/ patterns	YES	YES	YES	YES	NO
x, y coordinates	YES	NO	YES	YES	YES
Colour	YES	YES	YES	YES	YES
Electrical characteristics	YES	YES	YES	YES	YES
Forward voltage Vf	YES	YES	YES	YES	YES

Thermal resistance/ thermal characteristics	YES	NO	YES	YES	NO
Forward current If Ma	YES	YES	YES	YES	YES
Polarity	NO	NO	NO	YES	NO
JEDEC Moisture Sensitivity	YES	NO	NO	YES	NO
Driving method	NO	NO	YES	YES	NO
Maximum ratings	YES	YES	YES	YES	YES
Thermal pad temperature	YES	YES	YES	YES	NO
LED Junction Temperature Tj	YES	YES	YES	YES	YES
Reverse voltage Vr	NO	YES	YES	YES	YES
Reverse current Ir	NO	NO	YES	NO	NO
Design resources	YES	YES	YES	YES	NO
Pad configuration	YES	YES	YES	YES	NO
Soldering characteristics	YES	NO	YES	YES	YES
Mechanical dimensions/ drawings	YES	YES	YES	YES	YES
Operating temperature Top	NO	YES	YES	YES	YES
Applications	YES	YES	YES	YES	YES
Environmental compliance	YES	YES	NO	YES	YES
Graphs/ Curves	YES	YES	YES	YES	YES
Reliability	NO	NO	YES	YES	YES
Installation instructions	SOMETIMES	SOMETIMES	YES	YES	NO

Table 6.6: Product information on LED Chips available in the market

6.2. LED Modules

This section presents the findings of the Market research. The LED Module manufacturers that are studied include Xicato, Philips, Bridgelux, Seoul Semiconductors, Vexica, Sharp, GE and Samsung.

6.2.1 Xicato

Xicato[31]is a recognized leader in creating LED modules that provide superior aesthetics, economics and durability. The company aspires to be the trusted partner of the global lighting design community and luminaire manufacturers.

Xicato has developed a Spot Module[32] that has consistent colour appearance. Each module is targeted exactly on the Black Body Locus for perfectly natural white light, with very tight colour point conformity. The module also has faithful

[31]http://www.xicato.com/index.php 13/4/12
[32]http://www.xicato.com/technology.php 13/4/12

colour rendering and perfect uniformity. In particular, the Artist Series carefully controls both the LED and the phosphor specification, thus a CRI of Ra over 95 is achieved, as compared to a CRI of Ra over 80 of their standard range. In addition, the module offers perfect uniformity as it has a uniform (Lambertian) emitting disk as source, emitting perfectly uniform beam with no multiple shadows or colour variations over angle. To sum up, the company claims that its module offers light quality for life, since the module is simple and rugged with a full aluminium shell and inset glass (IP66). The Xicato has patented the Corrected Cold Phosphor Technology™ which ensures long term maintenance of the phosphor properties, contrary to phosphor on chip solutions.

For the purposes of this current research, the following series[33] were studied: XSM series, XLM series, and XSM Artist. The results are summarized inTable 6.7, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	XSM 80 SERIES	XLM 80 SERIES	XSM Artist
Specification Features	X	X	X
Physical Characteristics	X	X	X
Module Source Type	X	X	X
Maximum Case Temperature	X	X	X
Phosphor Proximity	X	X	X
Module Weight	X	X	X
Interfaces	X	X	X
Module Housing	X	X	X
Storage Temperature	X	X	X
Photometric Characteristics	X	X	X
Colour Consistency	X	X	X
Colour Rendering Index	X	X	X
Colour Rendering Index Consistency	X	X	X
Module Life	X	X	X
Other	X	X	X
Regulatory	X	X	X
Mercury Content	X	X	X
UV or IR Content	X	X	X
Ordering Guide	X	X	X
Technical Data Lighting	X	X	X
Luminous Flux (lm)	X	X	X
CCT	X	X	X
CRI (Ra)	X	X	X
Colour Consistency SDCM	X	X	X
Colour Consistency CCT	X	X	X
Colour Consistency Duv	X	X	X
Lumen Maintenance (hrs)	X	X	X
Technical Data Electrical	X	X	X

[33] http://www.xicato.com/products.php 13/4/12

Drive Current (mA)	X	X	X
Forward Voltage Min	X	X	X
Forward Voltage Typ	X	X	X
Forward Voltage Max	X	X	X
Power Consumption	X	X	X
Lumen output (typical)	X	X	X
Efficacy (typical)	X	X	X
Thermal class	X	X	X
Wattage	X	X	X
Life (hrs)	X	X	X

Table 6.7: LED Module information by Xicato

6.2.2 Philips Lumileds Lighting Company

As already mentioned, Philips Lumileds is a leading manufacturer of high-power LEDs and a pioneer in the use of solid-state lighting solutions for everyday purposes. Philips has developed the Fortimo LED system[34] which offers the required quality and sheer flexibility on all lighting parameters, becoming the trusted LED light source in hundreds of luminaire designs. The company claims that its Fortimo LEDs offer high Colour Rendering Index (90 to 100) to allow the ideal display of colours. Also, the Fortimo LED modules are specified with a specific colour temperature (CCT) with colour consistency of 3 MacAdam Ellipses (SDCM), ensuring high quality and even spread of white light. The Fortimo LED modules also ensure best-in-class beam uniformity by a variety of techniques, one is remote phosphor in combination with a mixing chamber.

For the purposes of this current research, the following Fortimo models were studied[35]: Fortimo Twistable module[36] which is an easy to install, flexible and future-proof LED system ideal for the retail and hospitality industry. Fortimo DLM Gen3[37] which offers high energy efficiency and new lower consumption. Fortimo SLM[38]which offers improved quality of light due to its high CRI, perfect colour consistency and excellent lumen maintenance. The Fortimo LED disk[39] which is an easy to design in module, thanks to integrated driver and optics, compact

[34]http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo/philips-fortimo-led-systems.wpd 19/4/12
[35]http://www.lighting.philips.co.uk/subsites/oem/product_pages/product_portfolio.wpd 19/4/12
[36]http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo_led_twistable.wpd 19/4/12
[37]http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo_led_dlm_system.wpd 19/4/12
[38]http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo_led_slm.wpd 19/4/12
[39]http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo_led_disk.wpd 19/4/12

and cost-effective.Lexel LED systems[40] which is designed for general lighting applications, enabling the creation of various atmospheres with changing tones of white light and different colours from a single light source.The results are summarized in Table 6.8, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	TWIST TDLM	DLM	SLM	LED disk	Lexel DLM
Features	X	-	X	X	-
Dimensional drawing	X	-	X	X	-
General Characteristics	X	-	-	X	-
Average Lifetime	X	X	-	-	-
Housing Colour	X	-	-	-	-
Light Technical Characteristics	X	-	-	-	-
Colour Code	X	-	-	-	-
Luminous Flux	X	X	-	-	-
Electrical Characteristics	X	-	-	-	-
Wattage	X	-	-	X	-
Voltage	X	-	-	-	-
Line Frequency	X	-	-	-	-
Dimmable	X	-	-	-	X
Beam angle	-	-	-	X	-
Temperature Characteristics	X	-	-	-	-
T-case maximum	X	-	-	-	-
Recommended module / driver combinations or at 230V	X	X	-	-	
Light Output lm	-	X	X	X	X
Lumen output at 230V	X	-	-	-	-
Module Power W	-	X	X	-	X
Module Efficacy lm/W	-	X	X	-	X
Efficacy module+ driver	X	-	-	X	-
System Power W	-	X	-	-	X
System Efficiency lm/W	-	X	X	-	X
Input Voltage V	X	X	-	X	-
CCT	X	X	X	X	X
CRI	X	X	X	X	X
Colour ConsistencySDCM	X	X	X	-	-
Colour consistency initial & @10 k hrs	-	-	-	-	X
Lm Maintenance 50k hours	-	X	X	-	X
Power Factor	X	X	-	X	-
Tc life LED module	-	X	X	X	X
Tc life LED driver	-	X	-	-	-
Total harmonic distortion	X	-	-	X	-
Frequency Hz	X	-	-	-	-
Dimming Range	X	-	-	-	-
B50L70 @max Tc life (hrs)	-	-	X	-	-
Driver and cable combination	-	X	X	-	-
Fortimo ordering data	X	X	X	X	-

[40] http://www.lighting.philips.co.uk/subsites/oem/product_pages/lexel_led_systems.wpd 19/4/12

Control interface	-	-	-	-	X

Table 6.8: LED Module information by Philips Lumileds

6.2.3 Bridgelux

Bridgelux[41] is a US based LED manufacturer that aims in bringing innovation to light by providing high power, energy efficient and cost-effective LED solutions. The Bridgelux LED Arrays specifically address the quantity of light, energy efficiency, Colour Rendering, colour consistency, beam uniformity, and cost. These features make high performance, environmentally friendly products ideal for the hospitality industry.

For the purposes of this current research, the following Bridgelux models were studied[42]: LS Array series which is a new set of miniaturized LED arrays that enable both diffuse and directional light sources. ES Array series which enables manufacturers to cost effectively meet global regulatory standards for general lighting. RS Array series which delivers high light output (3100 to 8500 lumens) for various applications, replacing common lamps. The results are summarized inTable 6.9, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	LS ARRAYS	DS14 LS Array	ES ARRAYS	DS 17 ES Arrays	RS ARRAYS	RS ARRAYS	DS 16 RS ARRAY
FEATURES	X	x	X	X	X	X	X
Luminous Flux (Tj25°)	X	-	X	-	-	X	-
Luminous Flux (Tj60°)	X	-	X	-	-	X	-
Voltage V	X	-	X	-	-	X	-
Vf (Typical V)	-	-	X	-	X	-	-
Typical Pulsed Flux (Tj25°C) lm	-	-	-	-	X	-	-
Typical DC Flux Tcase 70°C lm	-	-	-	-	X	-	-
Product Nomenclature	-	X	-	X	-	-	X
Average Lumen Maintenance Characteristics	-	X	-	X	-	-	X
Environmental Compliance	-	X	-	X	-	-	X
UL Recognition	-	X	-	X	-	-	X
Minor Product Change Policy	-	X	-	X	-	-	X
Cautionary Statements	-	X	-	X	-	-	X
Case Temperature Measurement Point	-	X	-	X	-	-	X

[41] http://bridgelux.com/about/ 19/4/12
[42] http://bridgelux.com/products/ledarray_productselectionguide.html 19/4/12

Flux Characteristics	-	X	-	X	-	-	X
Typical luminous flux φv lm (Tcase=60°C)	-	X	-	X	-	-	X
Minimum luminous flux φv lm (Tj=25°C)	-	X	-	X	-	-	X
Typical luminous flux φv lm (Tj=25°C)	-	X	-	X	-	-	X
Test current mA	X	X	X-	X	X	X	X
Optical Characteristics	-	X	-	X	-	-	X
CCT Min	-	X	-	-	-	-	X
CCT Typ	X	X	X	X	-	X	X
CCT Max	-	X	-	-	-	-	X
Typical CRI	X	X	X	X	-	X	-
Typical viewing angle (degrees)	-	X	-	-	-	-	X
Typical center beam candle power cd	-	X	-	-	-	-	X
Min CRI	-	-	-	-	-	-	X
Electrical Characteristics	-	X	-	X	-	-	X
Forward voltage Vf Min	-	X	-	X	-	-	X
Forward voltage VfTyp	-	X	-	X	-	-	X
Forward voltage Vf Max	-	X	-	X	-	-	X
Typical temperature coefficient of forward voltage (mV/°C)	-	X	-	X	-	-	X
Typical thermal resistance junction to case (°C/W)	-	X	-	X	-	-	X
Absolute Minimum and Maximum Ratings	-	X	-	X	-	-	X
Max DC Forward current mA	-	X	-	X	-	-	X
Min DC Forward current mA	-	X	-	X	-	-	X
Max Peak pulsed current mA	-	X	-	X	-	-	X
Max reverse voltage Vr	-	X	-	X	-	-	X
LED Junction temperature	-	X	-	X	-	-	X
Storage temperature	-	X	-	X	-	-	X
Operating case temperature	-	X	-	X	-	-	X
Soldering temperature	-	X	-	X	-	-	X
Typical Performance at Alternative Drive Currents	-	X	-	X	-	-	X
Typical Luminous flux φv lm Tcase=60°C	-	X	-	X	-	-	X
Typical Luminous flux φv lm Tcase=25°C	-	X	-	X	-	-	X
Typical forward voltage Vf	-	X	-	X	-	-	X
Forward current mA	-	X	-	X	-	-	X
Mechanical Dimensions	-	X	-	X	-	-	X

Typical Radiation Pattern	-	X	-	X	-	-	X
Typical Spatial Radiation Pattern	-	X	-	X	-	-	X
Typical Polar Radiation Pattern	-	X	-	X	-	-	X
Wavelength Characteristics at Rated Test Current, Tj=25°C	-	X	-	X	-	-	X
Typical Relative Luminous Flux vs. Current, Tj=25° C	-	X	-	X	-	-	X
Typical Light Output Characteristics vs. Temperature	-	X	-	X	-	-	X
Typical Chromaticity Characteristics vs. Temperature	-	X	-	X	-	-	X
Typical Forward Current Characteristics at Tj = 25°C	-	X	-	X	-	-	X
Current Derating Curves	-	X	-	X	-	-	X
Product Binning	-	X	-	X	-	-	X
Luminous Flux Binning Information	-	X	-	-	-	-	-
Colour Binning Information	-	X	-	X	-	-	X
xy Bin Coordinates and Associated Typical CCT	-	X	-	-	-	-	X
Mechanical Assembly and Handling	-	X	-	X	-	-	X
Product Packaging and Labeling	-	X	-	X	-	-	X
Packaging Tube Design	-	X	-	X	-	-	X
Design Resources	-	X	-	X	-	-	X
Application Notes	-	X	-	X	-	-	X
Optical Source Models	-	X	-	X	-	-	X
3D CAD Models	-	X	-	X	-	-	X

-

Table 6.9: LED Module Information by Bridgelux

6.2.4 Seoul Semiconductors

Seoul semiconductors is a leading company of optoelectronic semiconductor applied products. Over the years the company has launched many products that offer energy saving design and longer durability, easy design application and lower maintenance costs.

For the purposes of this current research, the following models were studied: Acrich[43] which is the first semiconductor light source that operates directly on AC power without a converter. This makes Acrich ideal for several applications as it minimizes component requirements. Acrich 2[44] which is also directly connected to AC power using an Acrish IC but with increased power efficiency of more than 90%. Acrish 2 also features amongst other characteristics, high power factor, making it an ideal source for replacement of common lamps. Z power is a series of high luminous flux and large output LED for general lighting, characterized by low power consumption, and low maintenance costs. The results are summarized in Table 6.10, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	ACRICH 2	ACRICH	Z POWER LED N42180	Z6 SERIES SZF06F0A
Features	X	X	X	-
Lifetime	X	X	-	-
Efficiency	X	-	-	-
Power Factor	X	-	-	-
THD : ≤ 25%	X	-	-	-
Directly connect to AC power via 2 wires	X	X	-	-
Common lamp replacement	X	-	-	-
Dimming	X	-	-	-
Applications	X	X	X	X
Standards compliance	X	-	-	-
Driver Configuration	X	-	-	-
IC has a direct-driving	X	X	-	-
Acrich IC PKG Pin Configurations	X	-	-	-
AC input range	X	-	-	-
Rated power	X	-	-	-
Power efficiency	X	-	-	-
Total harmonic distortion	X	-	-	-
Drawings	X	X	X	X
Acrich IC Module Circuit Configurations	X	-	-	-
Circuit Configurations	X	-	-	-
Functional Description of Acrich IC Module	X	-	-	-

[43] http://www.acriche.com/en/product/prd/acriche.asp 19/4/12
[44] http://www.acriche.com/en/product/prd/acrich2.asp 19/4/12

Surge Protection Circuit	X	-	-	-
EMI Reduction Circuit	X	-	-	-
Dimming Performance	X	-	-	-
Electrical protection point	X	-	-	-
Wire solder pad protection	X	-	-	-
Wire hole in MCPCB protection	X	-	-	-
Electro-optical characteristics	X	X	X	X
Luminous Flux	X	X	X	X
Luminous Flux Min	-	-	X	-
Luminous Flux Typ	-	-	X	X
Luminous Flux Max	-	-	X	-
Illuminance	-	X	-	-
Colour	X	X	-	-
V_F[V]	X	-	X	X
CCT	X	X	X	X
CRI	X	X	X	X
Operating power	-	X	-	-
Operating Voltage	X	X	-	-
Operating Current	-	X	-	X
Operating Frequency	X	X	-	-
View Angle 2θ½[˚]	X	X	X	X
Thermal resistance	-	-	X	X
λd[nm]	-	-	-	X
Absolute Maximum Ratings	X	X	-	X
Power Dissipation	X	X	X	X
Operating Temperature	X	X	X	X
Junction temperature	X	X	X	X
Storage Temperature	X	X	X	X
ESD Sensitivity	X	X	X	X
Forward current	-	-	X	X
Outline dimensions	X	-	-	-
Characteristics	X	-	-	-
Colour spectrum	X	X	-	X
Relative spectral power distribution Ta=25°	X	X	X	-
Power characteristics	X	-	-	-
Relative power distribution vs voltage Ta=25°	X	-	-	-
Relative Luminous flux vs Forward voltage Ta=25°	X	-	-	-
Junction temperature characteristics	X	-	X	X
Relative luminous flux vs junction temperature 220V	X	-	X	X
Relative CCT vs junction temperature	X	-	-	-
Relative light output vs Junction temperature	-	-	X	-
Forward Voltage Shift vs. Junction Temperature	-	-	-	X
Wavelength Shift vs Junction Temperature	-	-	-	X
Radiation pattern	X	-	-	X
Binning structure	X	X	-	X

Tray packing	X	-	-	-
Precautions for use	X	X	-	-
Handling of silicone resin for LEDs	X	X	-	-
PCB type	-	X	-	X
Lens type	-	X	-	X
Current – Voltage characteristics, Ta=25oC	-	X	-	-
Voltage – Relative flux characteristics, Ta=25oC	-	X	-	-
Relative Flux – Junction temperature characteristics	-	X	-	-
Typical dome type radiation pattern, Ta=25oC	-	X	X	-
Acriche Binning structure graphical representation	-	X	-	-
Operating and biasing instructions	-	X	X	-
Recommended solder pad	-	X	X	X
Solder profile	-	X	X	X
Emitter Reel Packaging	-	X	X	X
Packaging Structure	-	X	X	-
Luminous Flux Bins	-	X	-	-
white bin structure	-	X	-	-
x,y coordinates and CCT	-	X	-	-
RMS Voltage Bins (emitter)	-	X	-	-
Forward Current Characteristics	-	-	X	X
Forward Voltage vs. Forward Current, TA =25 ºc	-	-	X	X
Forward Current vs. Normalized Relative Luminous Flux, TA =25 ºc	-	-	X	X
Forward Current vs Wavelength Shift, TA =25 ºc	-	-	X	X
Ambient Temperature vs Allowable Forward Current	-	-	X	X

Table 6.10: LED Module Information by Seoul Semiconductors

6.2.5 Vexica Technology

Vexica[45] is an expert in the design and delivery of energy efficient LED lighting solutions. Their aim is to provide a sustainable and cost effective method of general lighting for years to come. The company focuses on white light as a key growth and development area, but it also develops custom solutions.

The company has developed the Vex-Lumera module[46] which is an OEM LED light engine with remote phosphor that offers manufacturers ease of integration of the latest LED technology. The module delivers excellent quality of light, with high lumen output and high CRI, while it can easily be integrated into luminaires.

[45] http://www.vexica.com/about-us/ 19/4/12
[46] http://www.vexica.com/product/vex-module-3/ 19/4/12

The information available for this module is presented in Table 6.11, where 'x' denotes availability of data.

PRODUCT INFORMATION	VEX LUMAERA
Applications	X
Lumen	X
Power consumption	X
Operating voltage	X
Electrical Data	X
Max ta	X
Driver Type	X
Connections	X
Power (Watts)	X
Input Voltage	X
Optical Data	X
CRI	X
Number of LEDs	X
Beam Angle (Degrees)	X
LED Type	X
Expected Lifetime (Hrs)	X
Mechanical Data	X
Dimensions Module only (mm)	X
Ingress Protection (IP)	X
Weight (KG)	X
Finishes Available	X
DFX	X
Photometry (available on request)	X

Table 6.11: LED Module Information by Vexica

6.2.6 Sharp

Sharp[47] has entered the LED market offering highly functional and reliable products that deliver light that makes objects, people and places look their absolute best. The company has incorporated some of the industry's patented approaches into their LED design and manufacturing. Thus, the Sharp modules offer high Colour Rendering Index and a crucial R9 deep red performance.

For the purposes of this research, the following modules were studied[48]: Mega Zenigatais one of the industry's first LED based solutions for replacing traditional lighting applications. The Mega Zenigata modules offer the advantages of LEDs, plus high lumens per watt as well as Sharp's signature R9 deep red performance. Mini Zenigata is the new module that provides energy-saving replacement solutions for incandescent applications, with enhanced CRI,

[47] http://www.sharpleds.eu/ledfamily.html 24/4/12
[48] http://www.sharpleds.eu/ledfamily.html 24/4/12

efficacy, and lumen output. Zenigata[49] are the high-powered modules that deliver high luminous flux, efficiency, reliability and radiation performance, thus they are ideal for applications that depend upon power and broad coverage. The results are summarized in Table 6.12, where 'x' denotes availability of data and '–' the lack of data.

	Mega Zenigata	Mini Zenigata	Zenigata
PRODUCT INFORMATION	GW5D*E**MR5	GW5BMJxxK04	GW5BQC15L02
Applications	X	X	X
Coding	X	X	X
CCT (K)	X	X	X
Current (mA)	X	X	X
Voltage (V)	X	X	X
Luminous Flux (lm)	X	X	X
Efficacy (lm/W)	X	X	-
CRI	X	X	X
LED chip used	X	-	-
Wattage	-	-	X
Thermal resistance	-	-	X
External dimensions and equivalent circuit	X	X	X
Ratings and characteristics	X	X	X
Absolute maximum ratings	X	X	X
Power Dissipation P	X	X	X
Forward Current IF	X	X	X
Reverse Voltage VR	X	X	X
Operating Temperature Topr	X	X	X
Storage Temperature Tstg	X	X	X
Electro-optical characteristics	X	X	X
Forward Voltage VF	X	X	X
Luminous Flux Φ	X	X	X
Chromaticity Coordinates x,y	X	X	X
Derating curve	X	X	X
Forward Current I F [mA] vs Case Temperature Tc [℃]	X	X	X
Reliability	X	X	X
Test items and test conditions	X	X	X
Temperature Cycle	X	X	X
Temperature Humidity Storage	X	X	X
High Temperature Storage	X	X	X
Low Temperature Storage	X	X	X
Steady State Operating Life	X	X	X
Shock	X	X	X
Vibration	X	X	X
Failure criteria	X	X	X
Quality level	X	X	X
Applied standard	X	X	X
Sampling inspection	X	X	X
Inspection items and defect criteria	X	X	X

[49] http://www.sharpleds.eu/zenigata.html 24/4/12

Supplements	X	X	X
Chromaticity rank table	X	X	X
Rank based on x,y chromaticity coordinates	X	X	X
Chromaticity Diagram	X	X	X
Packing	X	X	X
Label	X	X	X
Indication printed on product	X	X	X
Installation instructions	X	X	X
Precautions	X	X	X
Characteristics diagram (TYP.)	X	X	X
Forward Current vs. Relative Luminous Flux	X	X	X
Forward Voltage vs. Forward Current	X	X	X
Case Temperature vs. Relative Luminous Flux	X	X	X
Case Temperature vs. Forward Voltage	X	X	X

Table 6.12: LED Module Information by Sharp

6.2.7 General Electric (GE)

GE[50] is a leading lighting manufacturer that invents with the vigor of its founder Thomas Edison to develop energy-efficient solutions that change the way people light their world in various settings, including commercial, industrial, municipal and residential.

GE[51] has developed the GE Infusion LED module which is designed to open up new possibilities for the use of long-lasting, controllable, low maintenance LED solutions in various applications that require quality of light. The module is comprised of a printed circuit board (PCB) with an array of high power LEDs that can be easily placed with a simple twist and lock, together with a variety of optical and other accessories. The modules offer high energy efficiency and long lifetime. For the purposes of this current research, the following GE Infusion LED Modules were studied: M1000, M1500, M2000, and M3000.The results are summarized in Table 6.13, where ‘x’ denotes availability of data.

[50]http://pressroom.geconsumerproducts.com/pr/ge/lighting.aspx 24/4/12
[51]http://www.gelighting.com/na/business_lighting/products/led_infusion/content/downloads/GE%20Infusion%20Application%20Guide%20NA.pdf 24/4/12

PRODUCT INFORMATION	M1000	M1500	M2000	M3000
Features	X	X	X	X
Applications	X	X	X	X
Product Code	X	X	X	X
Description	X	X	X	X
Body colour	X	X	X	X
Rated Lumens	X	X	X	X
CCT (Kelvin)	X	X	X	X
CRI	X	X	X	X
Watts	X	X	X	X
SDCM	X	X	X	X
Rated Drive Current	X	X	X	X
Rated Life (hours)	X	X	X	X
Drawings/ Dimensions	X	X	X	X
Mechanical Attachment	X	X	X	X
Electronic Control Gear (ECG)	X	X	X	X
Product List - Collars	X	X	X	X
Optical Design & Performance	X	X	X	X
Optical accessories	X	X	X	X
GE Optics	X	X	X	X
Guidance for Optic Designers	X	X	X	X
Light Emitting Surface (LES)	X	X	X	X
Mating Surface for Optic	X	X	X	X
Use of Diffusers	X	X	X	X
Optics Suppliers	X	X	X	X
Heat Sink Design	X	X	X	X
Temperature Measurements and Thermal Considerations	X	X	X	X
Critical Measurement Points	X	X	X	X
Operation under Built-in Conditions	X	X	X	X
Temperature and Performance	X	X	X	X
Thermal Model	X	X	X	X
Designing a Heat Sink	X	X	X	X
Active Cooling as alternative to Passive Cooling	X	X	X	X
Suppliers of Cooling Solutions	X	X	X	X
Evaluating the Thermal System	X	X	X	X
Beam Angle	X	X	X	X
Twist-in Installation	X	X	X	X
Quality of Light and Performance	X	X	X	X
Lumen Packages	X	X	X	X
Colour Consistency	X	X	X	X
Dimming Options	X	X	X	X
Efficiency	X	X	X	X
Optics	X	X	X	X
Dimming Compatibility	X	X	X	X
Colour Options	X	X	X	X
Global Platform for drivers	X	X	X	X
Design and Engineering	X	X	X	X
Multi-Fixture Compatibility	X	X	X	X
Smaller Working Capital	X	X	X	X
Tool-less Installation	X	X	X	X
Driver Design Choice	X	X	X	X

Design Flexibility	X	X	X	X
Upgradeable Design	X	X	X	X
Polarity Protection	X	X	X	X
Thermal Protection	X	X	X	X
Over-current Protection	X	X	X	X
Reliability and Support	X	X	X	X
Installlation guide	X	X	X	X
Photometric files	X	X	X	X

Table 6.13: LED Module Information by General Electric

6.2.8 Samsung

Samsung[52] offers lighting solutions ranging from display and lighting modules for TVs and mobile devices to lighting engines with integrated optical, thermal and power technologies. In this context, Samsung has developed the LED Area Light Module[53] which is an environmentally friendly light source which has a patented slim design. It is a fluorescent replacement solution for general illumination or for back lighting. Similarly, the Downlight Module[54] is a high performance and high brightness product, ideal for indoor down lighting and lighting of restaurants and retail stores. The results are summarized in Table 6.14, where 'x' denotes availability of data.

PRODUCT INFORMATION	Area Light Module	Downlight Module
Features	X	X
Applications	X	X
Type	X	X
Model Name	X	X
Power Consumption W	X	X
Voltage V	X	X
Luminous flux	X	X
Efficacy lm/W	X	X
CRI	X	X
Beam angle	X	X
CCT K	X	X
Size	X	X
Temperature range	X	X
Lifetime Hrs	X	X
Driver	X	X
Notes	X	X

Table 6.14: LED Module information by Samsung

[52] http://www.samsungled.com/eng/intro/about.asp 9/7/12
[53] http://www.samsungled.com/eng/product/prdFlatPanel(new).asp 9/7/12
[54] http://www.samsungled.com/eng/product/prdDownLight(new).asp 9/7/12

6.2.9 Other companies

Nowadays, there are many lighting manufacturers that develop and manufacture not only LED modules but also LED retrofits in an effort to replace common and traditional lamps. In fact, these companies develop more and more products in an effort to gain share from the vast growing LED market. One can make a quick internet search to find thousands of such manufacturers.

It should be noted that for the purposes of this research, it has been decided to study LED modules, rather than LED retrofits, that can be used by other manufacturers so as to develop a variety of LED luminaires.

6.2.10Information on LED Modules available in the market

Table 6.15 shows that all LED module manufacturers offer information on the features, physical characteristics and applications of their products. They all also offer ordering guidelines, drawings and dimensions. In addition, all LED module manufacturers present data on the colorimentry and CRI of their products.

Most LED module manufacturers give data on the photometry, luminous flux, luminous flux binning, as well as on CCT, colour binning, x/y chromaticity coordinates, and chromaticity diagrams. In addition, most LED module manufacturers provide information on the lifetime, beam angle, electrical data, drive current, forward voltage, power consumption, operating voltage, temperature characteristics, and operating temperature of their products. Similarly, most LED module manufacturers present information on the module housing, mechanical assembly and handling, installation instructions, driver and control options.

Half of the LED module manufacturers offer information on the circuit configuration, efficacy, colour, forward current, absolute maximum ratings, junction temperature, thermal pad temperature, dimming options, and graphs.

The majority of LED module manufacturers do not offer photometric files or information on lumen maintenance, spectral power distribution, power factor, radiation pattern, wavelength, CRI consistency, and colour consistency. Also, most manufacturers do not present data on the thermal class, operating frequency, control options, optics options, heat sink information, current derating curves, and storage temperature. Similarly, most LED module manufacturers do not offer data on the module weight, IP protection, soldering characteristics, driver configuration, reliability tests, and environmental compliance.

	LED MODULE MANUFACTURERS							
LED MODULE PRODUCT INFORMATION	**XICATO**	**PHILIPS**	**BRIDGEL UX**	**SEOULSEM ICON**	**GE**	**VEXICA**	**SHARP**	**SAMSUN G**
Features	YES	YES	YES	YES	YES	YES	YES	YES
Applications	YES	YES	YES	YES	YES	YES	YES	YES
Physical characteristics	YES	YES	YES	YES	YES	YES	YES	YES
Module housing	YES	YES	NO	YES	YES	YES	NO	NO
Module weight	YES	YES	NO	NO	NO	NO	NO	YES
Drawings/ Dimensions	YES	YES	YES	YES	YES	YES	YES	YES
Ordering guide	YES	YES	YES	YES	YES	NO	YES	YES
Lifetime	YES	YES	NO	YES	YES	YES	NO	YES
Circuit configurations	NO	YES	NO	YES	YES	NO	YES	NO
Beam angle	NO	YES	YES	YES	YES	YES	NO	YES
IP protection	YES	NO	NO	NO	NO	YES	NO	NO
Photometry	YES	YES	YES	YES	YES	UPON REQUEST	YES	NO
Lumen maintenance (hrs)	YES	YES	YES	NO	NO	NO	NO	NO
Efficacy	YES	YES	NO	NO	NO	NO	YES	YES
Luminous flux (lm)	YES	YES	YES	YES	YES	NO	YES	YES
Luminous flux binning	YES	YES	YES	YES	YES	NO	NO	NO
Power factor	NO	YES	NO	YES	NO	NO	NO	NO
Photometric files	NO	NO	NO	NO	YES	NO	NO	NO
Colourimetry	YES	YES	YES	YES	YES	YES	YES	YES
CRI	YES	YES	YES	YES	YES	YES	YES	YES
CRI consistency	YES	NO	NO	NO	NO	NO	NO	NO
CCT	YES	YES	YES	YES	YES	NO	YES	YES
Colour code/ bin	YES	YES	YES	YES	NO	NO	YES	NO
Colour consistency	YES	YES	NO	NO	YES	NO	NO	NO
Colour	YES	YES	NO	YES	YES	NO	NO	NO
Chromaticity Coordinates x,y	YES	YES	YES	YES	NO	NO	YES	NO
Chromaticity diagrams	YES	YES	YES	YES	NO	NO	YES	NO
Spectral power distribution	YES	YES	NO	YES	NO	NO	NO	NO

Wavelength	NO	YES	YES	YES	NO	NO	NO	NO
Radiation pattern	NO	YES	YES	YES	NO	NO	NO	NO
Electrical data	YES	YES	YES	YES	YES	NO	YES	NO
Drive current (mA)	YES	YES	YES	YES	YES	NO	YES	NO
Forward voltage	YES	YES	YES	YES	NO	NO	YES	NO
Power consumption	YES	YES	NO	YES	YES	YES	YES	YES
Operating voltage	NO	YES	YES	YES	NO	YES	YES	YES
Thermal class	YES	NO	NO	NO	NO	NO	NO	NO
Forward current	NO	YES	YES	YES	NO	NO	YES	NO
Current derating curves	NO	YES	YES	NO	NO	NO	YES	NO
Operating frequency	NO	YES	NO	YES	NO	NO	NO	NO
Absolute Maximum Ratings	NO	YES	YES	YES	NO	NO	YES	NO
Temperature Characteristics	NO	YES	YES	YES	YES	NO	YES	YES
Junction temperature	YES	YES	YES	YES	NO	NO	NO	NO
Thermal pad temperature	YES	YES	NO	YES	YES	NO	NO	NO
Operating temperature	NO	NO	YES	YES	NO	YES	YES	YES
Storage temperature	NO	NO	YES	YES	NO	NO	YES	NO
Mechanical assembly and handling	YES	YES	YES	YES	YES	NO	YES	NO
Heat sink information	NO	NO	NO	NO	YES	NO	NO	NO
Installation instructions	YES	NO	YES	YES	YES	NO	YES	NO
Soldering Characteristics	NO	YES	NO	YES	NO	NO	NO	NO
Driver/ Control Options	YES	YES	NO	YES	YES	YES	NO	NO
Driver configuration	NO	YES	NO	YES	NO	YES	NO	NO
Dimming options	YES	YES	NO	YES	YES	NO	NO	NO
Control options	YES	YES	NO	NO	YES	NO	NO	NO
Optics options	NO	NO	NO	NO	YES	NO	NO	NO
Graphs	NO	YES	YES	YES	NO	NO	YES	NO
Reliability tests	NO	NO	NO	NO	YES	NO	YES	NO
Environmental compliance	YES	YES	YES	NO	NO	NO	NO	NO

Table 6.15: Product Information on LED Modules available in the market

6.3. LED Luminaires

This section presents the findings of the market research in regard to LED luminaires. The LED luminaire manufacturers studied are Thorn, Targetti, Projection Lighting, Iguzzini, i-LED, Fagerhult, Bega, Philips, Delta lighting and ACDC. The goal was to study not only traditional architectural lighting companies that have entered the LED market, but also newly established lighting companies that have entered directly the LED industry.

6.3.1 Thorn

Thorn Lighting[55] is part of the Zumtobel group, specializing in both outdoor and indoor luminaires and integrated controls. Their aim is to provide products and services that make it easier for customers to specify and install, and to maintain good quality and energy efficient lighting. Thorn offers a variety of LED products[56] for both indoor and outdoor applications. For the purposes of this current research, the following indoor LED luminaires[57] were studied: Baseled, Prospector, and Chalice 190 LED. The results are summarized in Table 6.16, where ‘x’ denotes availability of data and ‘–‘ the lack of data.

[55] http://www.thornlighting.com/com/en/aboutus_about_thorn_f.htm 26/4/12
[56] http://www.thornlighting.com/com/en/products_electronic_catalogue_f.htm 26/4/12
[57] http://www.thornlighting.com/com/en/products_electronic_catalogue_f.htm 26/4/12

PRODUCT INFORMATION	96107393 BASELED 165 WHI BEZELRING WHI	96107961 PROSPECTOR 1x12W LED L927 MT3 SP WHI	96239849 CHALICE 190H ALU LED 2000 HFX CL2 L840
Description	X	X	X
Configuration	X	X	X
Datasheet	X	X	X
Dimensions	X	X	X
Total power	X	X	X
Weight	X	X	X
Polar Curve	X	X	X
IP protection	X	X	X
LED	Cree "True Light"™	Cree "True Light"™	-
UGR	X	-	X
Efficiency (lm/w)	X	-	X
Applications	X	X	X
CCT	-	X	X
CRI	-	X	X
Luminous flux	-	-	X
Optics	-	-	X
Dialux plugin	X	X	X
Relux plugin	X	X	X
Photometry	X	X	X
Light Output Ratio (LOR)	X	X	X
Glare evaluation	X	X	X
Classification	X	X	X
Lamp (LED)	X	X	X
Material/ Finish	X	X	X
Installations/ Mounting	X	X	X
Standards	X	X	X
Specifications	X	X	X
Ordering Guide	X	X	X
Emergency options	X	-	-
Dimming options	X	-	X
Illuminance cones	-	X	-
LED Driver	-	X	X

Table 6.16: LED luminaire Information by Thorn

6.3.2 Targetti

Targetti[58] is the leader of the TargettiPoulsen group of companies that specializes in both indoor and outdoor architectural lighting. Targetti offers products and ad hoc solutions developed in response to specific functional and aesthetic challenges. Their aim is to create through light, more functional and comfortable places.

The company offers a complete and constantly updated range of products, amongst which there are LED products. For the purposes of this current research the following products were studied. The Arc LED[59] which is part of the Arc family which provides superior technical performances and the best optical solutions for both light control and visual comfort. The MiniarcKripton LED[60] which is part of the Miniarc family which is characterized by its small dimensions, making it capable of satisfying any kind of design need. The Monoled RGB[61] which is designed for taking the utmost of LED emission and minimizing the visual impact.The results are summarized in Table 6.17, where ‘x’ denotes availability of data and ‘–‘ the lack of data.

PRODUCT INFORMATION	ARC LED	MINARC KRIPTON LED	MONOLED RGB
Features	X	X	X
Concept	X	X	X
Material	X	X	X
Optics	X	X	X
Mounting	X	X	X
Power supply	X	X	X
Light source	led	led	led
Colour Temperature control	X	-	-
Dimming	X	X	X
Version (fixed, adjustable)	X	X	-
Wattage	X	X	X
Dimensions	X	X	X
IP rating	X	X	X
F class	X	X	X
Insulation class	X	X	X
Feeding voltage	X	-	X
Light effect	X	-	X
Drawings	X	X	X
Photometry	X	X	X
Polar curve	X	X	X
I max	X	X	X
Notes	-	Not fully specified yet	-

Table 6.17: LED Luminaire Information by Targetti

[58]http://www.targetti.com/about-us 27/4/12
[59]http://www.targetti.com/products/65440/arc-led 27/4/12
[60]http://www.targetti.com/products/65471/miniarc-kripton-led 27/4/12
[61]http://www.targetti.com/products/70145/monoled-rgb 27/4/12

6.3.3 Projection Lighting

Projection lighting[62] is a highly dynamic organization, specialized in the development of innovative lighting solutions to suit individual design requirements. The company is dedicated in providing the highest product quality and in meeting the lighting needs of the widest range of applications.

Projection lighting offers a wide range of LED products under the brand name alphaLED[63]. The alphaLED series includes downlights, track lights and spots. For the purposes of this current research, the following products were studied: the Washer, the Pinhole and the Universal Open.The results are summarized in Table 6.18, where 'x' denotes availability of data.

PRODUCT INFORMATION	WASHER DOWNLIGHT	PIN HOLE	UNIVERSAL OPEN
Features	X	X	X
Adjustable/ fixed	X	X	X
Construction/ body colour	X	X	X
Lumens	X	X	X
Beam Angles	X	X	X
CCT	X	X	X
CRI	X	X	X
Driver/ Driver current (mA)	X	X	X
Dimming Option	X	X	X
Emergency Option	X	X	X
Power Consumption	X	X	X
Drawings	X	X	X
Product Selection Quide	X	X	X
Lenses	X	X	X
Photometric Data	X	X	X
File LDT	X	X	X
Lux per 1000lm	X	X	X
Applications	X	X	X
Weight	X	X	X

Table 6.18: LED Luminaire Information by Projection Lighting

[62] http://www.projectionlighting.co.uk/ 27/4/12
[63] http://www.alphaled.co.uk 27/4/12

6.3.4 iGuzzini

iGuzzini[64] is a leading manufacturer of indoor and outdoor luminaires. The company has been designing products in collaboration with leading architects and designers, as well as researchers, doctors, sociologists, and physicists. The company[65] aims at offering the best technological solutions and to constantly invest in research and innovation. The company has received over the years many international awards for innovation, design and eco-sustainability.

iGuzzini offers a variety of lighting equipment, some of which with LEDs. For the purposes of this current research the following products were studied. Pixel Plus[66] and Deep Frame[67] which are recessed luminaires as well as Linealuce[68] which is a wall mounted luminaire. The results are summarized in Table 6.19, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	PIXEL PLUS	DEEP FRAME LED	LINEALUCE WALL MOUNTED LED RGB
Features	X	X	X
Mounting	X	X	X
Colour of LED (neutral or warm white)	X	X	X
CCT	X	X	-
No of LEDs	X	X	X
Power Consumption	X	X	X
Dimensions	X	X	X
Beam angle/ spread	X	X	-
Insullation class	X	X	X
Optics	X	X	X
Adjustability	X	X	-
Standard compliance	X	X	X
ENEC approval	X	X	-
IP protection	X	X	X
Installation instructions	X	X	X
Photometric Data	X	X	X
Polar curve	X	X	X
Illuminances	-	-	X
Control gear	X	X	X
Accessories and components	X	X	-
Body colour	-	X	X
Applications	X	X	X

[64] http://www.iguzzini.com/Company#./Company_profile?&_suid=13360586226390399036506 1804275 3/5/12
[65] http://www.iguzzini.com/Company#./Mission_Vision_Commitment?&_suid=1336058820795 06558558116311333 3/5/12
[66] http://catalog.iguzzini.com/iGuzzini/iGuzzini_Lines_datasheets_int/UK/New2011/Pixel%20Plus_GB.pdf 3/5/12
[67] http://catalog.iguzzini.com/iGuzzini/iGuzzini_Lines_datasheets_int/UK/New2011/Deep%20Frame_GB.pdf 3/5/12
[68] http://catalog.iguzzini.com/Product.aspx?id=IGZBA76 3/5/12

Dimming	-	-	X
Wiring	-	-	X
Total light Output [Lm]	-	-	X
Total power [W]	-	-	X
Luminous Efficacy [Lm/W]	-	-	X
Voltage	-	-	X
Weight	X	X	X

Table 6.19: LED Luminaire Information by Iguzzini

6.3.5 i-LED

i-Led by Linealight Group[69] offers a wide range of LED products. In fact, the company claims a variety of products and patents, which is the result of the continuous evolution in the development of increasingly high-performance products. i-Led offers tailor-made products offering customized solutions to cover the specific needs of each project. At the same time, the company sets high importance to energy-saving and integration.For the purposes of this current research, the following products[70] were studied: Nitum, Navap and Kunda. The results are summarized in Table 6.20, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	NITUM	NAVAP	KUNDA
Features	X	X	X
Finishing	X	X	X
Colour of LED	X	X	X
Power Consumption	X	X	X
Dimensions	X	X	X
Drawings	X	X	X
Constant current mA	X	X	X
Weight	X	X	X
Accessories	X	X	X
Optics (degrees)	X	X	X
Impact resistance	-	-	-
Glass surface temperature	-	-	X
Drive over article	-	-	X
IP rating	-	-	X
Photometric data	-	-	-
Polar curve	-	-	-

Table 6.20: LED Luminaire Information by i-LED

[69] http://www.ciplighting.com/id5.html 3/5/12
[70] http://www.linealight.com/site/uk/download/technical_sheets/ 3/5/12

6.3.6 Fagerhult

Fagerhult[71] is a leading lighting group which creates modern products and exciting energy-efficient and environmentally adapted lighting installations, successfully integrated into the individual environments. The driving force for Fagerhult[72] is the importance of light to human operations and well-being. Thus, the company aims at creating lighting solutions that help people optimize their capacity with minimal influence on the environment.

Fagerhult offers a wide range of indoor and retail lighting solutions. For the purposes of this current research, the following recessed luminaires were studied: Pleiadpower LED[73], Pleion[74], Pleiad LED Washer[75], as well as the wall luminaire LED WL[76].The results are summarized in Table 6.21, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	Pleiad Power LED Fixed	Pleion	Pleiad LED Washer	LED WL
LED chip	-	-	Fortimo/ Lexel	-
Installation	X	X	X	X
Connection	X	X	X	-
Design	X	X	X	X
Reflector	X	X	X	-
Accessories	X	X	X	X
LED ballast/ driver	X	X	X	X
CCT	X	X	X	X
Lumen lm	X	X	X	-
Efficacy lm/w	X	X	X	-
Distribution angle	X	X	X	-
Drawings	X	X	X	-
Photometric data	X	X	X	-
Polar curves	X	X	X	-
Eulumdat	X	X	X	X
IES file	X	X	X	X
Dialux	-	-	X	X
IP rating	X	X	X	X
Class III etc	X	X	X	X
Instructions for use	X	X	X	-
Dimming	-	-	X	-

Table 6.21: LED Luminaire Information by Fagerhult

[71] http://www.fagerhultgroup.com/about-fagerhult/default.asp 3/5/12
[72] http://www.fagerhultgroup.com/sustainability/default.asp 3/5/12
[73] http://www.fagerhult.com/shop/produkt.asp?sprak=1002&kategori_id=3&serie_id=770&produkt_id=3248 3/5/12
[74] http://www.fagerhult.com/shop/produkt.asp?sprak=1002&kategori_id=3&serie_id=769&produkt_id=3246 3/5/12
[75] http://www.fagerhult.com/shop/produkt.asp?sprak=1002&kategori_id=3&serie_id=644&produkt_id=2917 3/5/12
[76] http://www.fagerhult.com/shop/produkt.asp?sprak=1002&kategori_id=8&serie_id=657&produkt_id=2954 3/5/12

6.3.7 Bega

Bega[77] is a well-established company mainly in the field of outdoor illumination. The company has developed and produced high quality luminaires for almost all areas of architecture, taking into consideration the extreme conditions that may occur in outdoor applications. Given that, the company claims to have created the best technology and production processes to more than meet such requirements. Bega products are characterized by reliability, long service life, and economic operation.

For the purposes of this current research, a series of recessed downlights were studied, including the models 6826[78], 6838[79] and 6503[80].The results are summarized in Table 6.22, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	6826	6838	6503
Light distribution (reflector)	X	X	X
IP rating	X	X	X
Power supply	X	X	X
Dimming	X	X	X
CCT	X	X	X
LED	-	-	-
Watt	X	X	X
Lumen	X	X	X
Application	X	X	X
Product description	X	X	X
Safety class (I etc)	X	X	X
Photometric data	X	X	X
Polar curve	-	-	-
Dialux plugin	X	X	X
Eulumdat	X	X	X
IES	X	X	X
DXF	X	X	X
Lux	X	X	X
Drawings/ Dimensions	X	X	X
Installation	X	X	X
Accessories	X	X	X
β = Half beam angle degrees	-		X
Coding	X	X	X

Table 6.22: LED Luminaire Information by Bega

[77] http://www.bega.de/inhalte/en/informationen_unternehmen.php 3/5/12
[78] http://www.bega.de/inhalte/produkt_produkt.php?produkt=6800 3/5/12
[79] http://www.bega.de/inhalte/produkt_produkt.php?pib=6838 3/5/12
[80] http://www.bega.de/inhalte/produkt_produkt.php?produkt=6500 3/5/12

6.3.8 Philips

Philips is dedicated to introducing innovative end-user driven and energy-efficient solutions and applications for lighting[81]. They address lighting needs in various applications indoors and outdoors. With new lighting technologies such as LEDs and the increasing demand for energy efficient solutions, Philips offers groundbreaking lighting solutions. For the purposes of this current research, the following products were studied: the Spot LED[82], the StyLiD[83], and the Turnround[84] downlights.The results are summarized in Table 6.23, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	SPOT LED II	STULID	TURNROUND IP54
Features	X	X	X
Applications	X	X	X
Type	X	X	X
Light source	LUXEON ® K2	X	X
Light colour	X	X	X
Power supply	X	X	X
Power consumption	X	X	X
Optic	X	X	X
Adjustment	X	X	X
Lifetime	X	X	-
Material	X	X	X
Remarks	integrated transformer	-	-
IP code	X	X	X
Safety class	X	X	X
Glow-wire test	X	X	X
Flammability mark	-	-	X
ENEC mark	X	X	-
IK mark	-	X	X
CE mark	-	X	X
CCT	X	X	X
Lifetime to 70% luminous flux	X	X	X
Supply voltage	X	X	X
Beam angle	X	X	X
Luminous flux	X	X	X
CRI	X	X	X
Maintenance of lumen output - L70	X	X	X
Operating temperature range	X	X	X

[81] http://www.philips.com/about/company/businesses/lightinghighlights/index.page 22/5/12
[82] http://download.p4c.philips.com/l4bt/3/323153/spot_led_ii_semi-recessed_323153_ffs_aen.pdf 22/5/12
[83] http://download.p4c.philips.com/l4bt/3/349609/stylid_puredetail_recessed_adjus_349609_ffs_aen.pdf 22/5/12
[84] http://download.p4c.philips.com/l4bt/3/334057/turnround_ip54_334057_ffs_aen.pdf 22/5/12

Driver	X	X	X
Mains voltage	X	X	X
Colour	X	X	X
Connection	X	X	X
Installation	X	X	X
Driver failure rate	X	X	X
Maintenance	X	X	X
Drawings/ Dimensions	X	X	X
Dimming	-	X	X
Luminous efficacy	-	X	-

Table 6.23: LED Luminaire Information by Philips

6.3.9 Delta Lighting

Delta [85] is a global architectural lighting manufacturer that has turned into a trendsetter and market leader over the years. Delta is looking at innovative and contemporary lighting solutions. The company offers a wide range of architectural fittings as well as LEDs. For the purposes of this current research, the following products were studied: the LEDs Swing S1 WW[86], the Grardcarree LED WW SBL[87] and the Dot.com R6NW[88]. The results are summarized in Table 6.24, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	LEDS SWING S1 WW	GRAND CARREE LED WW SBL	DOT.COM R 6 NW 303 05 64
Available colours	X	X	X
Adjustable	X	-	-
LED power supply	X	X	X
mA	X	X	X
CE	X	X	X
IP ranking	X	X	X
Polar curve	X	X	X
LDT file	X	X	X
IES file	X	X	X
No of LEDs	X	X	X
Drawing/ Dimensions	X	X	X
Options	X	X	X
Lens	X	-	X
CCT	X	X	X
Power	X	X	X

Table 6.24: LED Luminaire Information by Delta Lighting

[85] http://www.deltalight.com/#/company/local 22/5/12
[86] http://www.deltalight.com/downloads/pdf_holder/ds_302%2023%200215.pdf 22/5/12
[87] http://www.deltalight.com/downloads/pdf_holder/ds_202%2028%2081028.pdf 22/5/12
[88] http://www.deltalight.com/#/products/product/8822 22/5/12

6.3.10 ACDC

ACDC[89] specializes in LED lighting and cold cathode lighting solutions. The company is dedicated to innovation and design. Its understanding of architectural lighting and its experience in developing high specification lighting solutions made the company a strong player. Their design philosophy is to challenge what is expected, and to push the boundaries of technologies and design, to develop products that are well-engineered and aesthetically brilliant.For the purposes of this current research the following products were studied: Azeta[90], Hurricane 50[91], and Evolution[92].The results are summarized in Table 6.25, where 'x' denotes availability of data and '–' the lack of data.

PRODUCT INFORMATION	AZETA ROUND 105	HURRICANE 50	EVOLUTION
Features	X	X	X
LED type (brand)	Cree XPG, Xicato	Cree XP, Rebel	Cree XP, Rebel
LED Qty	X	X	X
Drive Current	X	X	X
Power Consumption	X	X	X
Input voltage	-	X	X
PFC	X	-	-
Initial Colour Acuracy	X	-	-
Colour Stabilty Over Life	X	-	-
CRI	X	X	X
Initial Lamp Lumen Output	X	X	X
Lamp Lumens per Circuit Wa	X	-	-
Luminaire Lumen Output	X	X	X
Lifetime L70, Based onTM-21	X	X	X
Lumen Depreciation	X	-	-
Adjustable or not	X	X	-
Drawings/ Dimensions	X	X	X
Driver Options	X	X	X
IP protection	X	X	X
Accessories	X	X	X
Models	X	X	X
Light engines	Acdc, Xicato	Acdc, Xicato	Acdc, Xicato
Optics	X	X	X
CCT	X	X	X
Reflector	X	X	X
Trim	X	-	-
Fitting size	X	X	-
Photometric data	-	X	X
Lumen efficacy	-	X	X
Dimming	X	X	X

[89] http://www.acdclighting.co.uk/about 22/5/12
[90] http://www.acdclighting.co.uk/led/azeta 22/5/12
[91] http://www.acdclighting.co.uk/led/hurricane-50 22/5/12
[92] http://www.acdclighting.co.uk/led/evolution 22/5/12

Emergency option	-	X	X
IES file	X	X	X

Table 6.25: LED Luminaire Information by ACDC

6.3.11. Information on LED Luminaires available in the market

Table 6.26 shows that all LED luminaire manufacturers give information in regard to the features, drawings, dimensions, and applications of their products. They also all provide data on the photometry and colour, as well as on the driver options of their fittings.

Most LED luminaire manufacturers offer polar curves and software plugins, while they also provide data on luminous flux and CCT. Most manufacturers also offer information on driving current or operating voltage, power consumption, as well as on dimming options. Similarly, most LED luminaire manufacturers explain the available versions of their fittings (adjustable or fixed) and the beam angle of emitted light (optics), while they indicate the LED quantity in each product and the IP protection. Accordingly, most manufacturers present different accessories, installation instructions, and other information.

Half of the LED luminaire manufacturers offer information on the LED chip/ module that the fittings use. Also, half of the manufacturers provide data on luminous efficacy, illuminance, and electrical classification of their products. And, half of the manufacturers describe the material/ finish of their products.

The majority of LED luminaire manufacturers do not offer information on the lifetime, lumen depreciation, CRI, insulation class, and emergency options of their products. Similarly, they do not offer ordering guidelines or data on the reflectors used, or on the weight of their products and the product standard compliance.

Finally, none of the LED luminaire manufacturers give information on configuration, connection, lumen binning, and colour binning.

	LED LUMINAIRE MANUFACTURERS									
LED LUMINAIRES PRODUCT INFORMATION	**THORN**	**TARGETTI**	**ALPHALED**	**i-GUZZINI**	**i-LED**	**FAGERHULT**	**BEGA**	**PHILIPS**	**DELTA**	**ACDC**
Features	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LED Quantity	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES
LED chip/module	YES	NO	YES	NO	NO	YES	NO	YES	NO	YES
Driving current or operating voltage	NO	YES	NO	YES	YES	NO	NO	YES	YES	YES
Power consumption	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES
Version (Adjustable or fixed)	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES
Material/ finish	YES	YES	NO	YES	YES	NO	NO	YES	NO	NO
Drawings/ Dimensions	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Weight	YES	NO	YES	YES	YES	NO	NO	NO	NO	NO
IP protection	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES
Configuration	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Ordering Guide	YES	NO	YES	NO	NO	NO	YES	NO	NO	NO
Insulation class	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO
Classification electrical	YES	YES	NO	NO	NO	YES	YES	YES	NO	NO
Connection	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Optics/ Lenses/ Beam angles	YES	YES	YES	YES	YES	NO	YES	NO	YES	YES
Reflector (light distribution)	NO	NO	NO	NO	NO	YES	YES	YES	NO	YES
Standard compliance	NO	NO	YES	YES	NO	NO	NO	YES	YES	NO
Applications	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Photometry	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Lumen output/ luminous flux (lm)	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES
Luminous efficacy (lm/W)	YES	NO	NO	YES	NO	YES	NO	YES	NO	YES
Lifetime	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO
Lumen Bins	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Software plugins	YES	NO	YES	NO	NO	YES	YES	NO	YES	YES
Polar curve	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO

Illuminance Lux	YES	YES	YES	YES	NO	NO	YES	NO	NO	NO
Lumen depreciation	NO	NO	NO	NO	NO	NO	NO	YES	NO	YES
Colour	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
CCT	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES
CRI	YES	NO	YES	NO	NO	NO	NO	YES	NO	YES
Colour Bins	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Driver/ Options	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Dimming options	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES
Emergency options	YES	NO	YES	NO	NO	NO	NO	NO	NO	YES
Other	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES
Accessories	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES
Installation instructions	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES

Table 6.26: Product Information on LED Luminaires available in the market

6.4. Binning Systems& Definitions

This section of the research presents the findings in regard to the binning systems that different manufacturers define and use. The major binning systems refer to product binning, luminous flux binning, and colour binning.

6.4.1. PhilipsLumileds

In its literature PhilipsLumileds explains that in the manufacturing of semiconductor products, there is a variation of performance around the average values given in the technical data sheets. For this reason, Philips Lumileds bins LEDs for luminous flux, colour, and forward voltage (Vf).

For the purposes of this research, the Datasheet D61[93] that refers to Luxeon Rebel ES chips is used to analyze the definitions that Philips Lumileds uses. LUXEON Rebel ES is tested and binned at 700 mA, with current pulse duration of 20 ms. All characteristic charts where the thermal pad is kept at constant temperature (25ºC typically) are measured with current pulse duration of 20 ms. Under these conditions, junction temperature and thermal pad temperature are the same.

LUXEON Rebel ES emitters are labeled using a four digit alphanumeric code (CAT code) depicting the bin values for emitters packaged on a single reel. All emitters are chips packaged within a reel are of the same 3-variable bin combination. Using these codes, it is possible to determine optimum mixing and matching of products for consistency in a given application. Reels of LUXEON Rebel ES emitters are labeled with a four digit alphanumeric CAT code following the format ABCD, where:

A = Flux bin (P, Q, R, S etc.)
B and C = Color bin (W0, V0, U0 etc. for LXML-PWx2 series. 7A, 7B, 7C and 7D for LXWx-PWxx series. 5W, 5X, 5Y and 5Z for LXH7-PW40 emitter)
D = Vfbin (P, R, S and T)

Philips Lumileds[94]claims that LUXEON Rebel ES products will deliver, on average, 70% lumen maintenance (L70) at 50,000 hours of operation at a forward current of 1000 mA. This projection is based on constant current operation with junction temperature maintained at or below 135°C. This performance is based on independent test data, Philips Lumileds historical data from tests run on similar

[93]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-white#lumenmaint 30/5/12
[94]http://www.philipslumileds.com/products/luxeon-rebel/luxeon-rebel-white#lumenmaint DS61, 22/5/12

material systems, and internal LUXEON reliability testing. Observation of design limits is required in order to achieve this projected lumen maintenance.

Table 6.27lists the standard photometric luminous flux bins for LUXEON Rebel ES emitters (tested and binned at 700 mA).Although several bins are outlined, product availability in a particular bin varies by production run and by product performance. Not all bins are available in all colours.

Flux Bins	Minimum Photometric Flux(lm)	Maximum Photometric Flux Bin Code(lm)
P	120	140
Q	140	160
R	160*	180
S	180	200
T	200	220
U	220	240
V	240	260
W	260	280
X	280	300

Table 6.27: Luminous Flux Binning by Philips Lumileds

* 170 lm for LXW8-PW40

Philips Lumileds (DS64) defines Colour bins and x, y chromaticity coordinates for the Luxeon Rebel. Figure 6.1 shows the neutral white colour binning system and Table 6.28 shows an example of neutral white chromaticity coordinates. Accordingly, Figure 6.2 shows the cool white colour binning system and Table 6.29 shows an example of cool white chromaticity coordinates. Finally, Figure 6.3shows the warm white colour binning system and Table 6.30 shows the warm white colour binning systems, defined by Philips Lumileds.

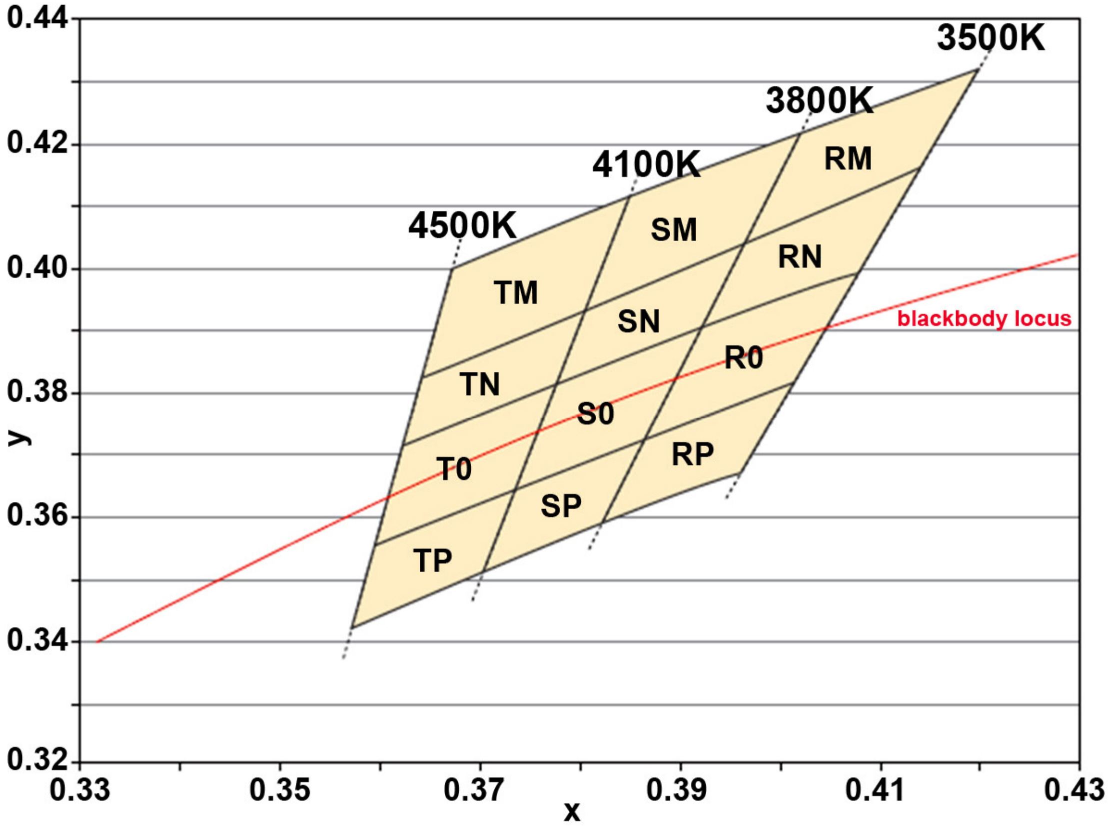

Figure 6.1: Neutral- White Colour Binning by Philips Lumileds

Neutral- White Bin Coordinates							
Bin Code	X	Y	Typical CCT (K)	Bin Code	X	Y	Typical CCT (K)
TM	0.367294	0.400290	4300	SO	0.378264	0.382458	3950
	0.385953	0.412995			0.392368	0.390932	
	0.381106	0.393747			0.387071	0.373899	
	0.364212	0.382878			0.371075	0.365822	
TN	0.364212	0.382878	4300	SP	0.374075	0.365822	3950
	0.381106	0.393747			0.387071	0.373899	
	0.378264	0.382458			0.382598	0.359515	
	0.362219	0.371616			0.370582	0.351953	

Table 6.28: Example of Neutral- White Chromaticity Coordinates by Philips Lumileds

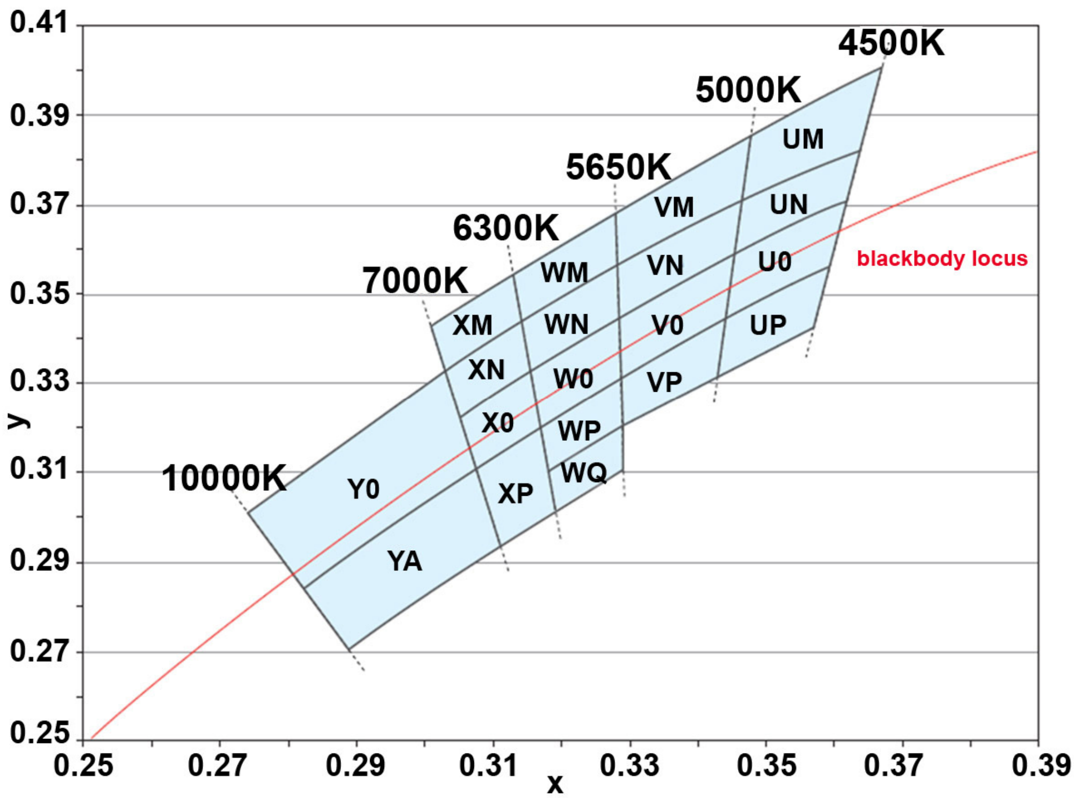

Figure 6.2: Cool- White Binning by Philips Lumileds

Cool- White Bin Coordinates							
Bin Code	X	Y	Typical CCT (K)	Bin Code	X	Y	Typical CCT (K)
YO	0.274238	0.300667	8000	WQ	0.318606	0.310201	6000
	0.303051	0.332708			0.329393	0.320211	
	0.307553	0.310778			0.329544	0.310495	
	0.282968	0.283772			0.319597	0.301303	
YA	0.282968	0.283772	8000	VM	0.328636	0.368952	5300
	0.307553	0.310778			0.348147	0.385629	
	0.311163	0.293192			0.346904	0.371742	
	0.289922	0.270316			0.328823	0.356917	

Table 6.29: Example of Cool- White Chromaticity Coordinates by Philips Lumileds

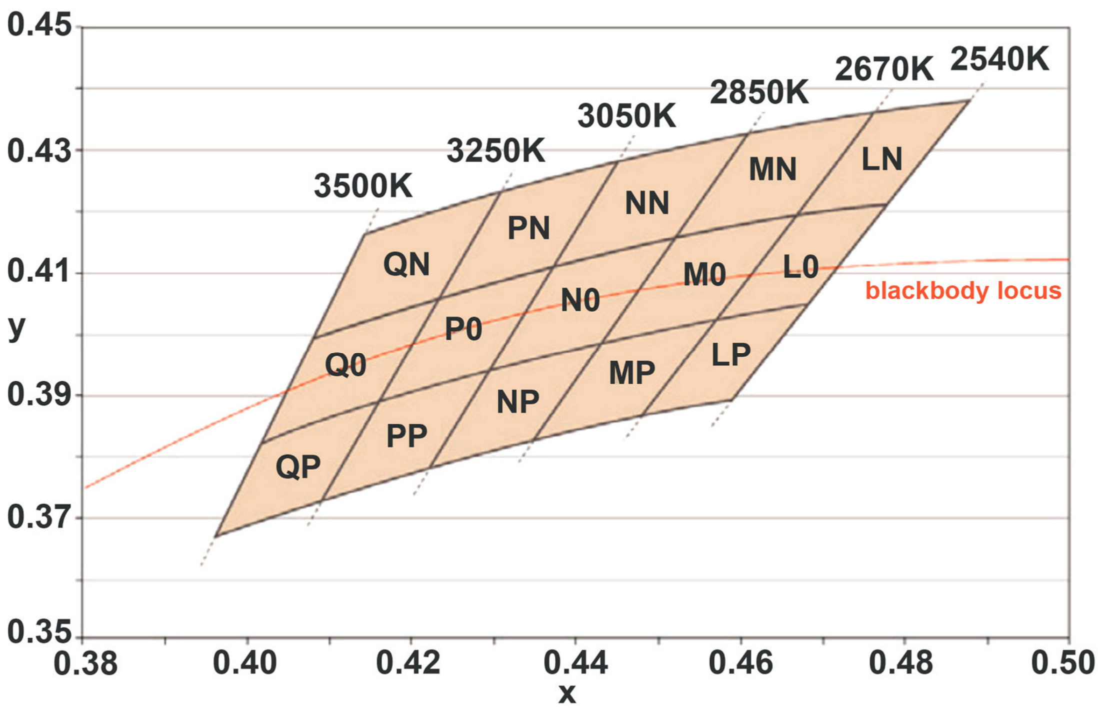

Figure 6.3: Warm- white Binning by Philips Lumileds

Warm- White Bin Coordinates							
Bin Code	X	Y	Typical CCT (K)	Bin Code	X	Y	Typical CCT (K)
QN	0.414776	0.416097	3375	NP	0.429373	0.394281	2950
	0.431186	0.423386			0.443600	0.399111	
	0.423956	0.406472			0.435591	0.383714	
	0.408593	0.399525			0.422124	0.378952	
QO	0.408593	0.399525	3375	MN	0.461404	0.433334	2760
	0.423956	0.406472			0.476733	0.436634	
	0.416487	0.389001			0.467131	0.419632	
	0.402113	0.382156			0.452512	0.416241	

Table 6.30: Example of Warm- White Chromaticity Coordinates by Philips Lumileds

Philips Lumileds also defines Forward voltage bins. It defines minimum and maximum Vf bin values per emitter (tested and binned at 700 mA). Although several bins are outlined, product availability in a particular bin varies by production run and by product performance. The DS61 presents the following Forward Voltage Binning:

Vf Bins		
Bin Code	Min Forward Voltage	Max Forward Voltage
P	2.50	2.75
R	2.75	3.00
S	3.00	3.25
T	3.25	3.50

Table 6.31: Forward voltage binning by Philips Lumileds

6.4.2 CREE

Cree sorts LED chips into bins of radiant flux and dominant wavelength[95]. Examples of standard bins are presented in Table 6.32.

Standard Bins for C*xxx*EZ1000-S*xx*000-2[96]: LED chips are sorted to the radiant flux and dominant wavelength bins. A sorted die sheet contains die from only one bin. Sorted die kit (C*xxx*EZ1000-S*xx*000-2) orders may be filled with any or all bins (C*xxx*EZ1000-0*xxx*-2) contained in the kit. All radiant flux and dominant wavelength values shown and specified are at If = 350 mA. Radiant flux values are measured using Au-plated TO39 headers without an encapsulant.

C450EZ1000- S38000- 2					
Radiant Flux	460mW	C450EZ1000-221-2	C450EZ1000-0222-2	C450EZ1000-0223-2	C450EZ1000-0244-2
	440mW	C450EZ1000-0217-2	C450EZ1000-0218-2	C450EZ1000-0219-2	C450EZ1000-0220-2
	420mW	C450EZ1000-0213-2	C450EZ1000-024-2	C450EZ1000-0215-2	C450EZ1000-0216-2
	400mW	C450EZ1000-0209-2	C450EZ1000-0210-2	C450EZ1000-0211-2	C450EZ1000-0212-2
	380mW	C450EZ1000-0205-2	C450EZ1000-0206-2	C450EZ1000-0207-2	C450EZ1000-0208-2
	445nm	447.5nm	450nm	452.5nm	455nm
	Dominant Wavelength				

Table 6.32: Example of Radiant flux and Dominant wavelength binning by CREE

[95] http://www.cree.com/led-chips-and-materials/chips/chips 30/5/12
[96] http://www.cree.com/led-chips-and-materials/chips/chips/ezbright-gen-ii/ez1000-gen-ii-led 30/5/12

6.4.3 OsramOpto Semiconductors

In its Application notes, Osram provides some basic information on colour and lifetime of LEDs. Take for example the Diamond Dragon. The exemplary median lifetime for a brightness group of the Diamond DRAGON is shown in Table 6.33.

Conditions	Median Lifetime	Unit
If= 1000mA **Tc= 25 degrees C**	>50.000	Operating hours
If=1600mA **Ts= 85 degrees C**	20.000	Operating hours
If= 1800mA **Ts= 125 degrees C** **Tj= 175 degrees C**	200	Operating hours

Table 6.33: Lifetime of Diamond Dragon LEDs by Osram

The Diamond DRAGON[97] is available in all colours of the rainbow, including several variations of white, as indicated in Table 6.34.

LED Type	Colour	Wavelength
LR W5AP	Red	625 nm
LA W5AP	Amber	617 nm
LY W5AP	Yellow	590 nm
LT W5AP	True Green	528 nm
LB W5AP	Blue	470 nm
LD W5AP	Deep Blue	455 nm
LW W5AP	White	X/y= 0.32/ 0.31*
LUW W5AP	Ultra White	X/y= 0.31/ 0.32*
LCW W5AP	Warm White	2700- 4200K **
***Colour coordinate acc to CIE 1937, **Colour temperature**		

Table 6.34: Colour availability of Diamond Dragon LEDs by Osram

To better analyze data from Osram in more detail, the datasheet of Diamond Dragon LUW W5AP was studied. Figure 6.4 shows the cool white chromaticity coordinates of Osram for the Diamond Dragon.

[97] http://catalog.osram-os.com/catalogue/catalogue.do?favOid=0000000400011c6402e30023&act=showBookmark 30/5/12

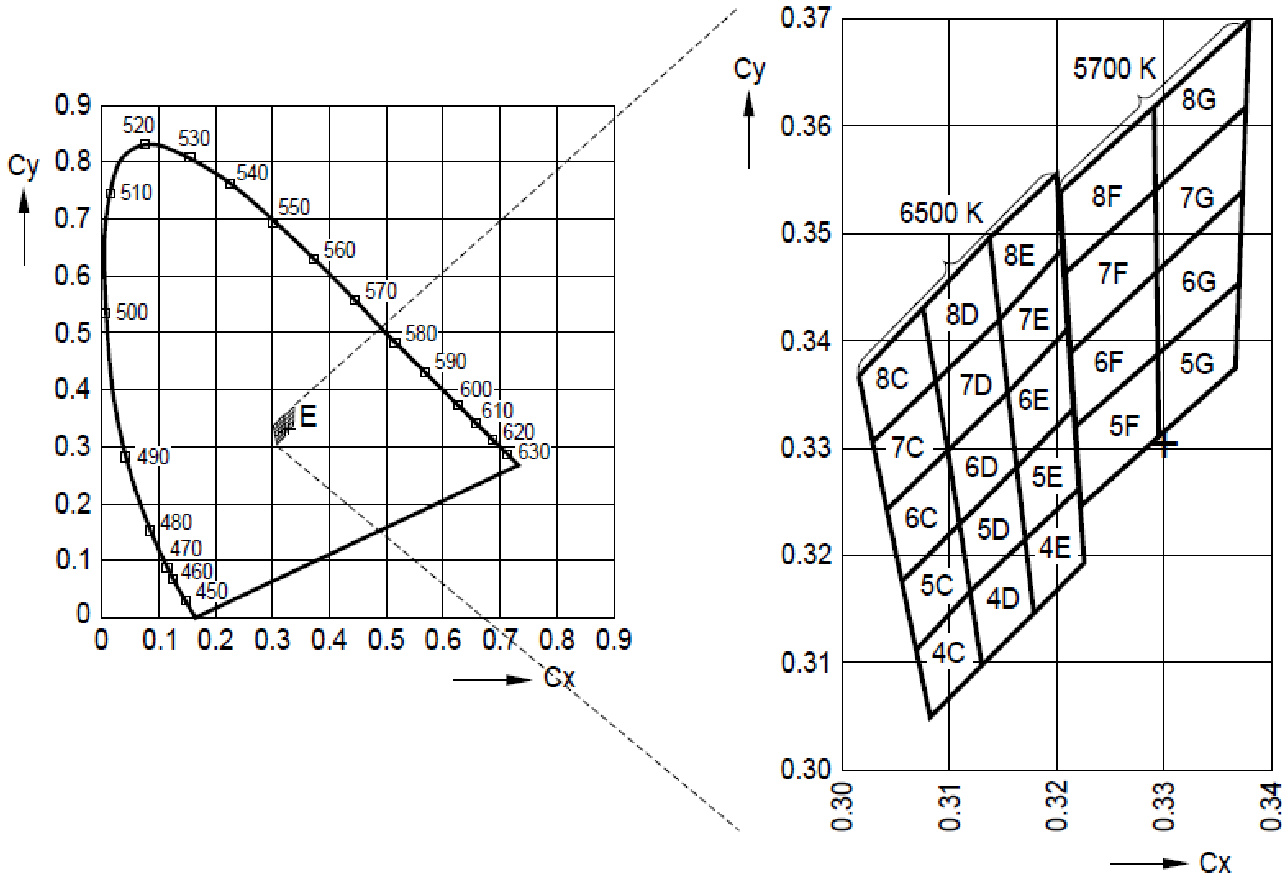

Figure 6.4: Cool white Chromaticity coordinates for Diamond Dragon LUW W5AP by Osram

An example of the x, y coordinates per group is shown in Table 6.35.

Group	Cx	Cy
4C	0.308	0.305
	0.307	0.311
	0.312	0.316
	0.313	0.310
5C	0.307	0.311
	0.306	0.318
	0.311	0.323
	0.312	0.316
6C	0.306	0.318
	0.304	0.324
	0.310	0.330
	0.311	0.323

Table 6.35: Chromaticity coordinates per group for Diamond Dragon LUW W5AP by Osram

The same datasheet also presents the brightness binning groups for the LUW W5AP as well as the product binning, as indicated in Table 6.36.

Brightness Groups		
Brightness Group	Luminus Flux (lm)	Luminous Intensity (cd)
MY	210… 240	60 (typ.)
MZ	240…280	70 (typ.)
NX	280…330	82 (typ.)
NY	330…390	96 (typ.)
NZ	390…450	112 (typ.)

Table 6.36: Luminous flux binning for Diamond Dragon LUW W5AP by Osram

It also presents an example of Product Binning, as indicated in Table 6.37.

Group Name on Label	
Example: MY- 4C	
Brightness Group	Chromaticity Coordinate Group
MY	4C

Table 6.37: Example of Product Binning for Diamond Dragon LEDs by Osram

Similarly, in the datasheet of the LCW W5AP the following colour binning is defined for warm white, as illustrated in Figure 6.5.

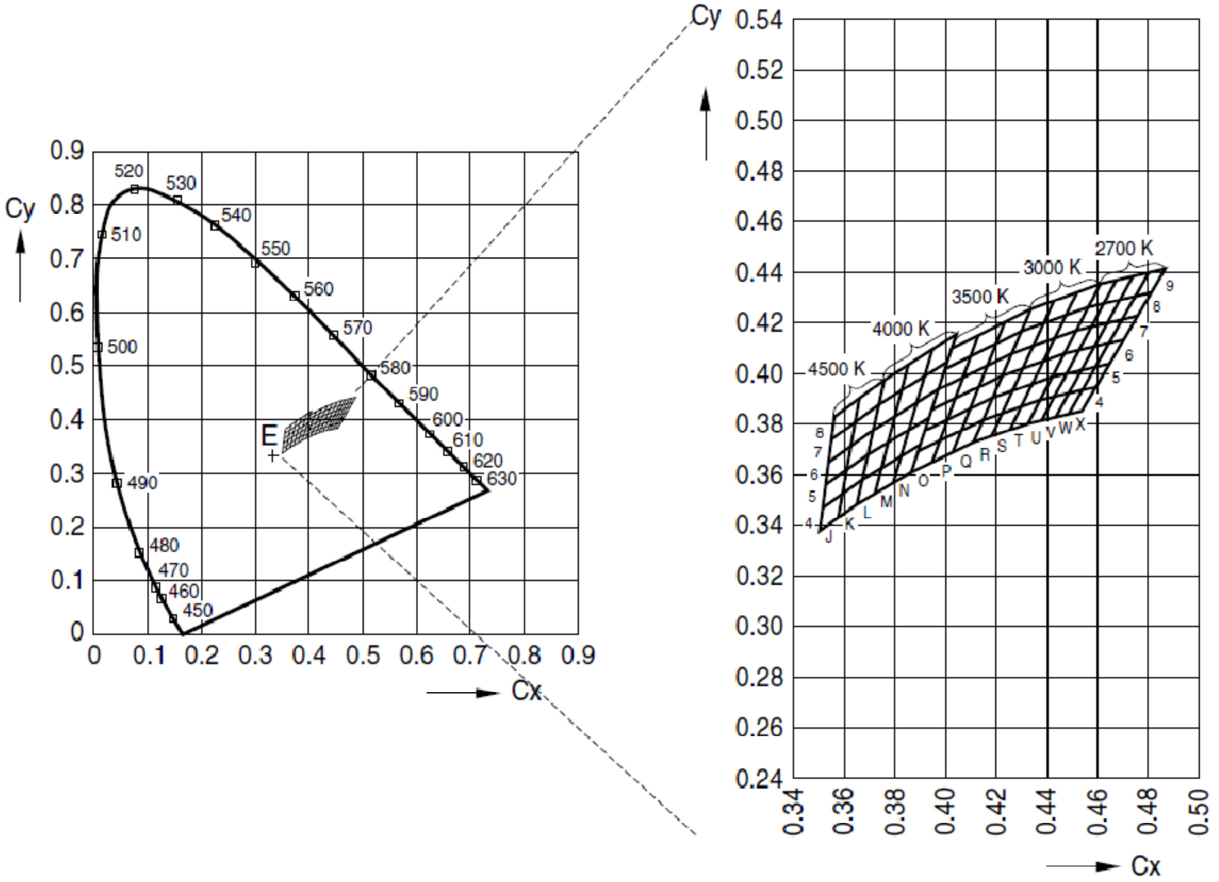

Figure 6.5: Warm white Chromaticity Coordinates for Diamond Dragon LCW W5AP by Osram

6.4.4 EdisonOpto

For the purposes of this research, the EdiPower II series was studied. Edison explains that EdiPower II series provides different colour temperatures and power consumptions[98].

Product binning is mainly realized according to the available colour, power, and lens type. Therefore, a code is generated in the following format, where x1= LED type, x2= emitter type, x3= emitter colour, x4= serial No.1, x5= serial No.2, x6= circuit series, x7= circuit parallel.

EP S x - x xxx
X1 X2 X3 X4 X5 X6 X7

Photometric Luminous Flux Bins are defined for Cool White, Neutral White and Warm White[99], as indicated in Table 6.38.

Group	Min.	Max.	Group	Min.	Max.
A	10	100	N	1790	2330
B	100	130	P	2330	3030
C	130	170	Q	3030	3940
D	170	220	R	3940	5120
E	220	290	S	5120	6650
F	290	370	T	6650	8650
G	370	480	U	8650	11250
H	480	630	V	11250	14620
J	630	820	W	14620	19000
K	820	1060	X	19000	24710
L	1060	1380	Y	24710	32120
M	1380	1790	Z	32120	41750

Table 6.38: Luminous flux binning for EdiPower II by Edison

Notes: Flux is an accuracy of ±10% respectively.

[98] http://www.edison-opto.com.tw/Application/Edison%20Opto_EdiPower%20II%20Application%20note%20_Eng_v1.pdf 30/5/12
[99] http://www.edison-opto.com.tw/Datasheet/EdiPower/Edison%20Opto_EdiPower%20II%20Series_Eng_v2.pdf 30/5/12

Colour bins are defined as shown in Figure 6.6.

Notes: The red line represents the blackbody locus on CIE 1931 graph. Edison maintains a tolerance on x, y colour coordinates, as indicated by the blue boxes.

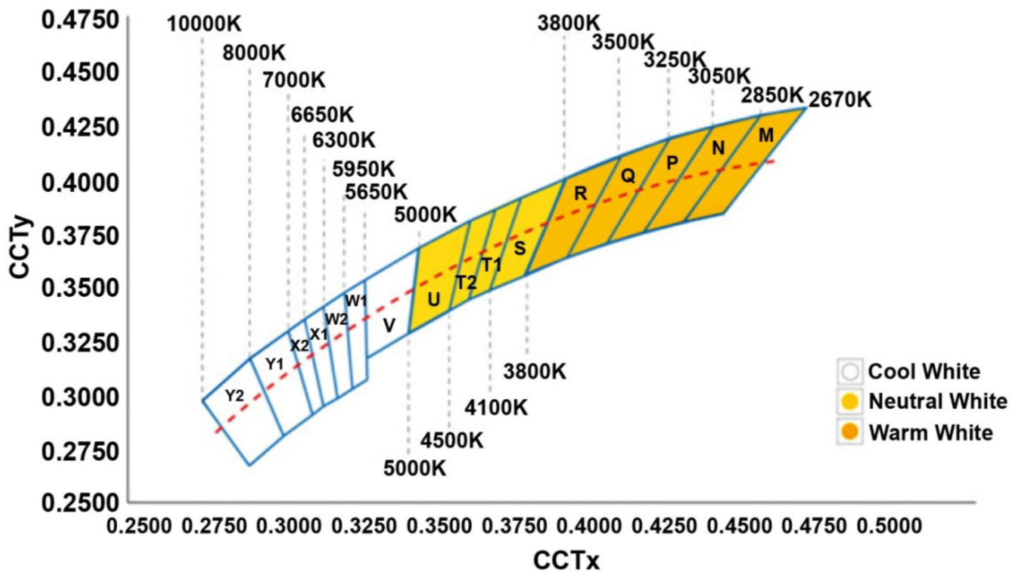

Figure 6.6: Chromaticity coordinates for EdiPower II by Edison

Finally the CCTs for EdiPower II by Edison are defined in Table 6.39.

Group/ CCT (Typ)	X	Y
M (warm white)	0.4614	0.4333
	0.4767	0.4366
	0.4489	0.3875
	0.4355	0.3837
U (neutral white)	0.3469	0.3717
	0.3642	0.3842
	0.3570	0.3425
	0.3433	0.3320
X1 (cool white)	0.3085	0.3383
	0.3147	0.3444
	0.3197	0.3017
	0.3150	0.2979

Table 6.39: Example of CCT bins for EdiPower II by Edison

6.4.5 Xicato

Xicato modules[100] are available in a range of Colour Temperatures: 2700K, 3000K, 3500K and 4000K. This suggests that Xicato does not have colour binning, but it produces in specific CCTs. As illustrated in Figure 6.7: Colour Binning by Xicato
, each Colour Temperature is targeted exactly on the Black Body Locus for perfectly natural white light. Each has a very tight colour point conformity, with a 1 x 2 MacAdam ellipse tolerance, outperforming the ANSI C78.377 standard which equates to a 7 ellipse tolerance.

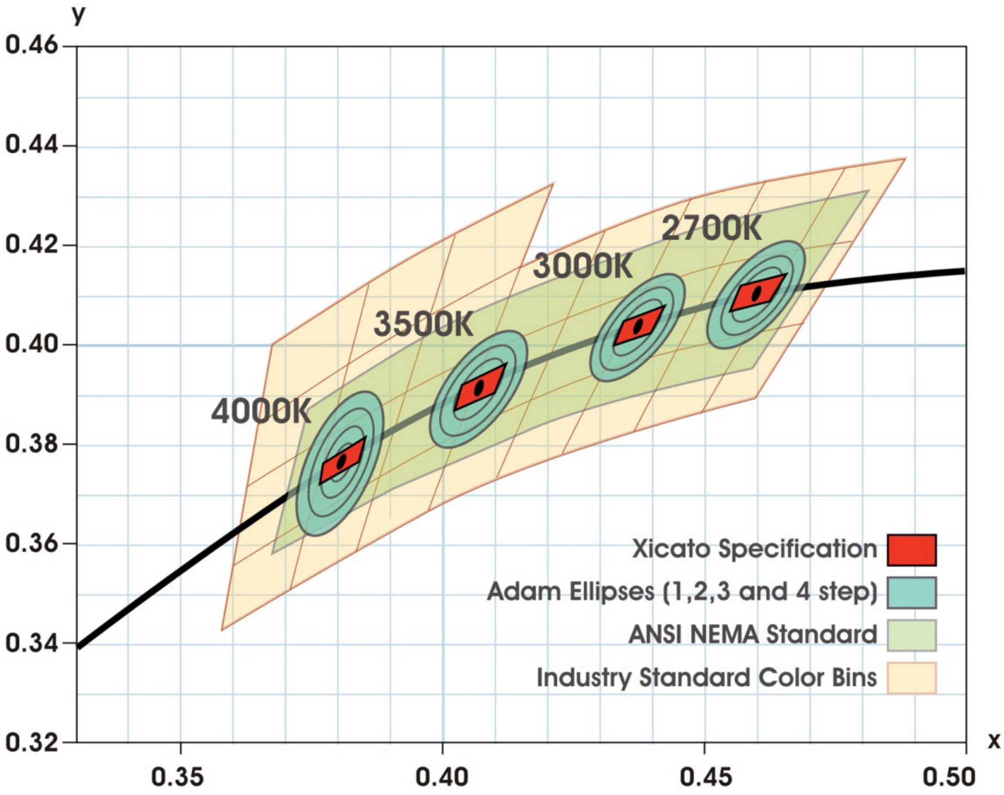

Figure 6.7: Colour Binning by Xicato

With the Artist Series, carefully controlling both the LED and phosphor specification, a CRI of Ra over 95 is achieved, compared to a CRI of Ra over 80 with the standard range. Typically the Colour Rendering Index evaluates only the first 8 pastel reference samples of the conventional CRI metric. The Artist Series is optimized to deliver excellent results for the more saturated and skin colour samples of the CRI reference set. For the deep red R9 reference sample, a value of 96 has been achieved in the 2700K, 3000K and 3500K Artist Series. The R9 value exceeds 85 in

[100] http://www.xicato.com/technology.php 30/5/12

the 4000K Artist Series. These results shown in Table 6.40are compared with halogen, compact fluorescent and compact metal halide lamps.

	Ra	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
Standard XSM	81	80	85	89	81	78	80	86	66	16	64	79	58	81	93	75
Artist Series XSM	98	98	99	98	98	98	97	98	98	96	99	98	88	98	98	98
Typical IR coated Halogen Dichroic	98	98	99	99	99	98	98	99	97	92	97	98	97	98	99	97
Typical Compact Metal Halide	82	90	94	69	82	81	81	87	71	27	59	62	55	93	78	88
Typical Compact Fluorescent	87	91	93	86	91	89	90	88	70	17	76	91	81	93	92	81

Table 6.40: CRI by Xicato

The Xicato patented Corrected Cold Phosphor Technology™ ensures long term maintenance of the phosphor properties, contrary to phosphor on chip solutions, as shown in Figure 6.8.

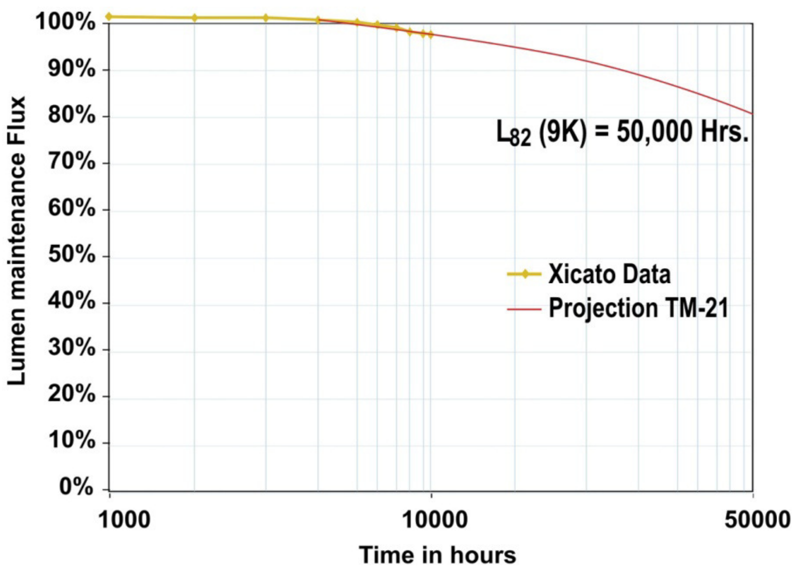

Figure 6.8: Lumen maintenance by Xicato

6.4.6Bridgelux

Bridgeluxclaims in the datasheet of DS14 LS Array[101], that typical manufacturing processes of semiconductor products result in a variation in performance surrounding the typical data sheet values. In order to minimize variation in the end product or application, Bridgelux bins its LED Arrays for luminous flux and colour.

Bridgelux LED Arrays are labeled using a 4-digit alphanumeric bin code. This bin code is printed on the back of each LED Array in the format A B C D, where:

A – designates flux bin (P, Q, R etc.)
B C – designates color bin (P3, P4, Q3, etc.)
D – reserved for future product designations.
All product packaged within a single tube are of the same flux and colour bin combination (or bin code). Using these codes it is possible to determine the best product utilization to deliver the consistency required in a given application.

In addition, Bridgeluxstates that its family of LED Array products will deliver, on average, greater than 70% lumen maintenance after 50,000 hours of operation at the rated forward test current. This performance assumes constant current operation with case temperature maintained at or below 70°C. These projections are based on a combination of package test data, semiconductor chip reliability data, a fundamental understanding of package related degradation mechanisms, and performance observed from products installed in the field using Bridgelux die technology. Bridgelux conducts lumen maintenance tests per LM80. Observation of design limits is required in order to achieve this projected lumen maintenance.

Table 6.41 lists the standard photometric luminous flux bins for Bridgelux LED Arrays (tested and binned at the indicated test current). Although several bins are outlined, product availability in a particular bin varies by product and production run. All production testing and binning (both flux and colour binning) is conducted under pulsed test conditions at Tj = 25°C.

[101] http://www.bridgelux.com/assets/files/DS14%20Bridgelux%20LS%20Array%20Data%20Sheet%20DS14%20051612.pdf 30/5/12

Bin Code	Min lm	Max lm
M	220	240
N	240	265
P	265	295
Q	295	320
R	320	360
S	360	400
T	400	440
U	440	500

Table 6.41: Luminous flux binning for LS Arrays by Bridgelux

Bridgelux defines Colour Bins of warm white as indicated inFigure 6.9:

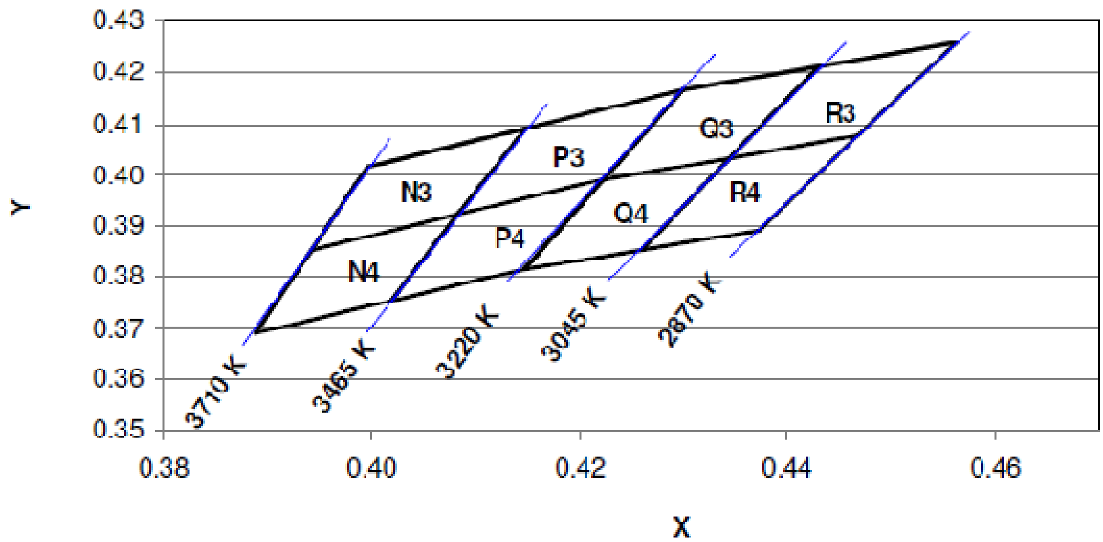

Figure 6.9:Warm- White Colour binning for LS Arrays by Bridgelux

Examples of colour bins and chromaticity coordinates of warm white are shown in Table 6.42.

Bin Code	X	Y	Ansi CCT (K)
N3	0.3943	0.3853	3500
	0.3996	0.4015	
	0.4148	0.4090	
	0.4083	0.3921	
Q3	0.4223	0.3990	3000
	0.4299	0.4165	
	0.4431	0.4213	
	0.4345	0.4033	

Table 6.42: Example of Warm- White Chromaticity Coordinates for LS Arrays by Bridgelux

Bridgelux defines Colour Bins of cool white as indicated inFigure 6.10.

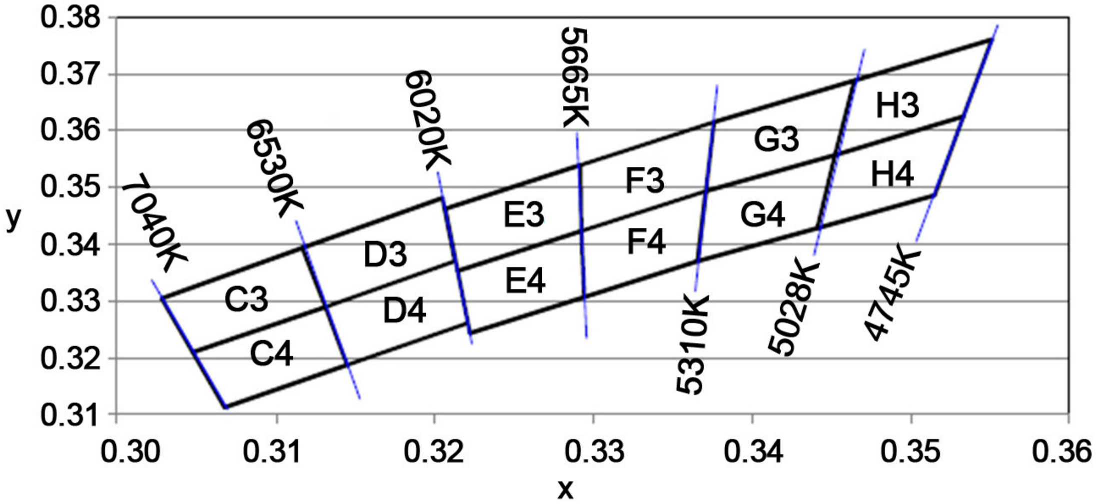

Figure 6.10: Cool- White binning for LS Arrays by Bridgelux

Examples of colour bins and chromaticity coordinates of cool white are shown in Table 6.43.

Bin Code	X	Y	Ansi CCT (K)
C3	0.3048	0.3209	6500
	0.3131	0.3290	
	0.3117	0.3393	
	0.3028	0.3304	
E3	0.3215	0.3353	5700
	0.3293	0.3423	
	0.3292	0.3539	
	0.3207	0.3462	
G3	0.3376	0.3616	5000
	0.3464	0.3688	
	0.3452	0.3558	
	0.3371	0.3493	

Table 6.43: Example of Cool- White Chromaticity coordinates for LS Arrays by Bridgelux

6.4.7 Seoul Semiconductors

Seoul Semiconductors in its Acriche datasheet (A3 series)[102] explains its product binning system as follows:

Full Code of Acriche Series: AX1X2X3X4X5-X6X7-X8X9X10X11X12

Part number: A: Acriche, X1: Colour, X2: Acriche series number, X3: Lens type, X4: Operating Voltage, X5: Type of PCB

Internal number: X6, X7

Code labeling: X8X9: Luminous flux (or Radiant flux for royal blue), X10X11: Dominant wavelength (or x, c coordinates rank code), X12: Operating voltage (emitter only)

Seoul Semiconductors use the luminous flux binning system, show in Table 6.44.

Luminous Flux Bins			
Seoul Sem Flux Bins		Seoul Sem Min lm	Seoul Sem Max lm
S		54	70
T		70	91
U		91	118.50
V	V1	118.50	136
	V2	136	154
W	W1	154	177
	W2	177	200
X	X1	200	230
	X2	230	260
Y		260	340
Z		340	440

Table 6.44: Luminous flux binning for Acriche A3 by Seoul Semiconductors

The colour binning system of pure white is shown in Table 6.45.

Pure White Bin Structure			
Bin	X	Y	CCT (K)
Z2	0.2910	0.3093	8200- 7600
	0.2930	0.3037	
	0.2993	0.3107	
	0.2976	0.3166	
A9	0.3155	0.3120	6500- 6000
	0.3164	0.3046	
	0.3230	0.3110	
	0.3225	0.3190	
C7	0.3440	0.3428	5000- 4000
	0.3433	0.3345	
	0.3500	0.3400	
	0.3514	0.3487	

Table 6.45: Example of Pure White Chromaticity coordinates and CCT for Acriche A3 by Seoul Semiconductors

[102] http://www.acrich.com/en/product/prd/acriche.asp 30/5/12

The colour bins are show in the CIE diagram as in Figure 6.11.

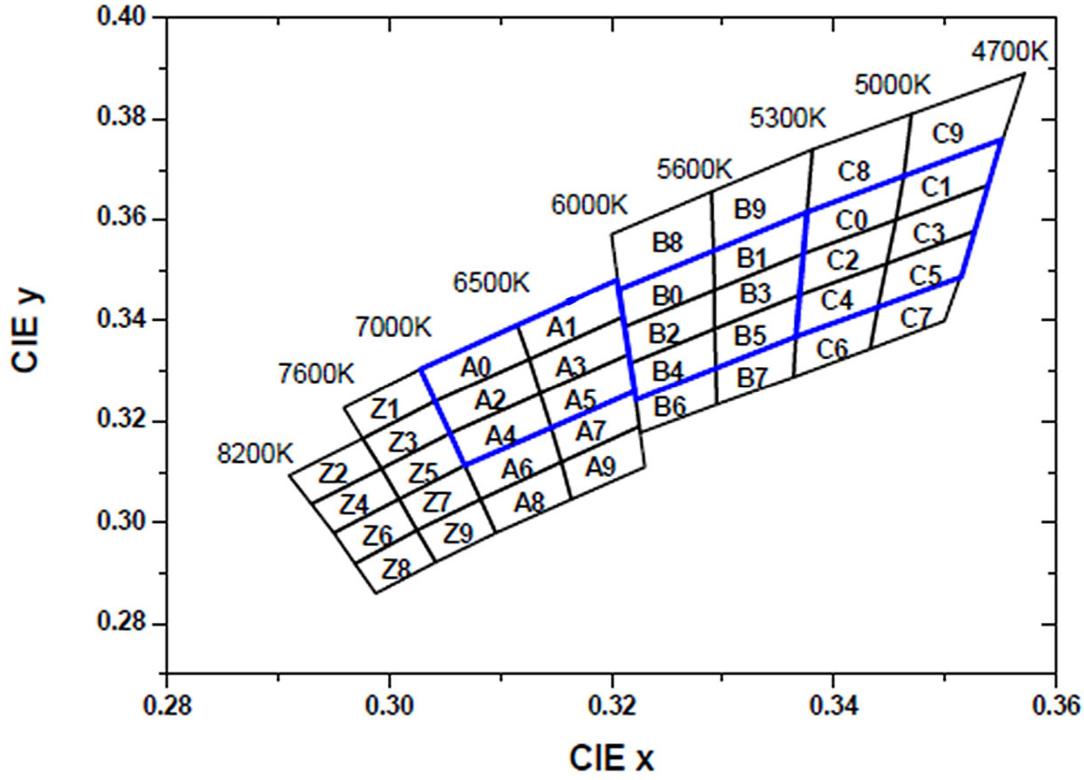

Figure 6.11: Pure white colour binning for Acriche A3 by Seoul Semiconductors

The colour binning system of warm white is show in Table 6.46.

Warm White Bin Structure			
Bin	X	Y	CCT (K)
F8	0.4037	0.414	3700- 3500
	0.3996	0.4015	
	0.4146	0.4089	
	0.4197	0.4217	
F7	0.4017	0.3751	3500- 3200
	0.3983	0.366	
	0.4104	0.3715	
	0.4147	0.3814	
H7	0.4483	0.3919	2700- 2600
	0.4422	0.3805	
	0.4527	0.383	
	0.4593	0.3944	

Table 6.46: Warn White colour binning for Acriche A3 by Seoul Semiconductors

The colour bins are shown in the CIE diagram as in Figure 6.12.

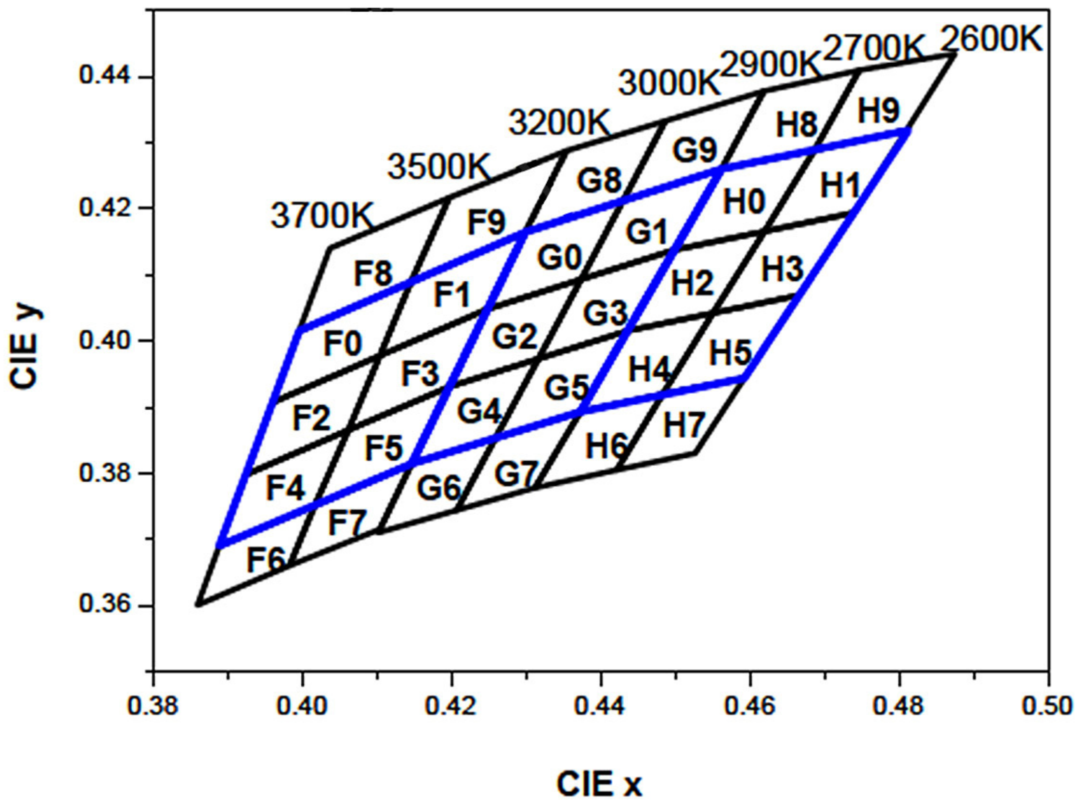

Figure 6.12: Warm- white colour binning for Acriche A3 by Seoul Semiconductors

Seoul Semiconductor uses the voltage binning show in Table 6.47.

RMS Voltage Bins (emitter)	**AX3200 (operating in 110V)**
Bin Code	Voltage (Vf RMS)
A	90.0- 92.0
B	92.0- 94.0
C	94.0- 96.0
D	96.0- 98.0
RMS Voltage Bins (emitter)	AX3220 (operating in 220V)
Bin Code	Voltage (Vf RMS)
A	180.0- 185.0
B	185.0- 190.0
C	190.0- 195.0
D	195.0- 200.0

Tolerance: +-5V

Table 6.47: RMS Voltage bins for Acriche A3 by Seoul Semiconductors

6.5. Comparisons of binning systems

This section compares the binning systems by different manufactures.

6.5.1. Product binning

The findings of section 6.4 indicate that each manufacturer uses its own product binning system. For example:

Philips Lumileds usesthe format ABCD, where A designates the Flux Bin, B andC designate the Colour Bins, and D designates the Forward voltage (Vf) bin.

Osram uses a format such as MY-4C, where MY designates the Brightness Group and 4C designates the Chromaticity coordinate group.

Edison Opto uses a format such as X1X2X3X4X5X6X7, where x1 is the LED type, x2 is the emitter type, x3 is the emitter colour, x4 is the serial No.1, x5 is the serial No.2, x6 is the circuit series, and x7 is the circuit parallel.

Bridgeluxusesthe format A B C D, where A designates the Flux Bin, B and C designate the Colour Bin, and D is reserved for future product designations.

Seoul Semiconductros in its Acriche datasheet (A3 series)[103] expresses its product binning system with a code as follows: AX1X2X3X4X5-X6X7-X8X9X10X11X12, where A is the Acriche LED, X1 designates the colour, X2 designates the Acriche series number, X3 designates the lens type, X4 the operating voltage, X5 the type of PCB, X6 and X7 are for integral use, X8 and X9 designate the luminous flux, X10 and X11 designate the dominant wavelength, X12 the operating voltage.

To sum up, it is evident that each manufacturer defines and uses its own product binning system. Table 6.48indicates the information that different manufacturers incorporate in their product binning code structures, where ‘x’ denotes availability of data and ‘–‘ the lack of data.

[103]http://www.acrich.com/en/product/prd/acriche.asp 30/5/12

PRODUCT BINNING INFORMATION	Philips	Osram	Edison Opto	Bridgelux	Seoul Semiconductors
Flux Bin	X	X	-	X	X
Colour Bins	X	X	X	X	X
Forward voltage bin	X	-	-	-	-
LED type	-	-	X	-	X
emitter type	-	-	X	-	X
Serial number	-	-	X	-	X
circuit series	-	-	X	-	-
circuit parallel	-	-	X	-	-
future product designations	-	-	-	X	-
Lens type	-	-	-	-	X
Operating voltage	-	-	-	-	X
Internal use	-	-	-	-	X
Dominant wavelength	-	-	-	-	X

Table 6.48: Product Binning Information by various manufacturers

6.5.2. Luminous flux binning

The findings of section 6.4 also indicate that different manufacturers have different luminous flux binning systems. The findings are summarized in Table 6.49.

LUMINOUS FLUX BINNING SYSTEMS														
Philips Flux Bins	**Philips Min lm**	**Philips Max lm**	**Osram Flux Bins**	**Osram Min lm**	**Osram Max lm**	**Edison Flux Bins**	**Edison Min lm**	**Edison Max lm**	**Bridgelux Flux Bins**	**Bridgelux Min lm**	**Bridgelux Max lm**	**Seoul Sem Flux Bins**	**Seoul SemMin lm**	**Seoul SemMax lm**
												S	54	70
												T	70	91
						A	10	100				U	91	118.50
P	120	140				B	100	130				V1	118.50	136
Q	140	160				C	130	170				V2	136	154
R	160	180				D	170	220				W1	154	177
S	180	200				E	220	290				W2	177	200
T	200	220				F	290	370				X1	200	230
U	220	240	MY	210	240	G	370	480	M	220	240	X2	230	260
V	240	260	MZ	240	280	H	480	630	N	240	265	Y	260	340
W	260	280	NX	280	330	J	630	820	P	265	295	Z	340	440
			NY	330	390	K	820	1060	Q	295	320			
X	280	300	NZ	390	450	L	1060	1380	R	320	360			
						M	1380	1790	S	360	400			
									T	400	440			
									U	440	500			

Table 6.49: Luminous Flux Binning information by various manufacturers

6.5.3. Colour binning

Section 6.4 shows that different manufacturers use different colour binning systems. Figure 6.13 and Figure 6.14compare the different colour binning systems for cool white by different manufacturers. Similarly, Figure 6.15and Figure 6.16compare the different colour binning systems for warm white by different manufacturers.

The Figures verify that the cool white and the warm white binning systems are not defined in the same way by manufacturers. This is why the schemes in the figures below do not coincide, but have different shapes.

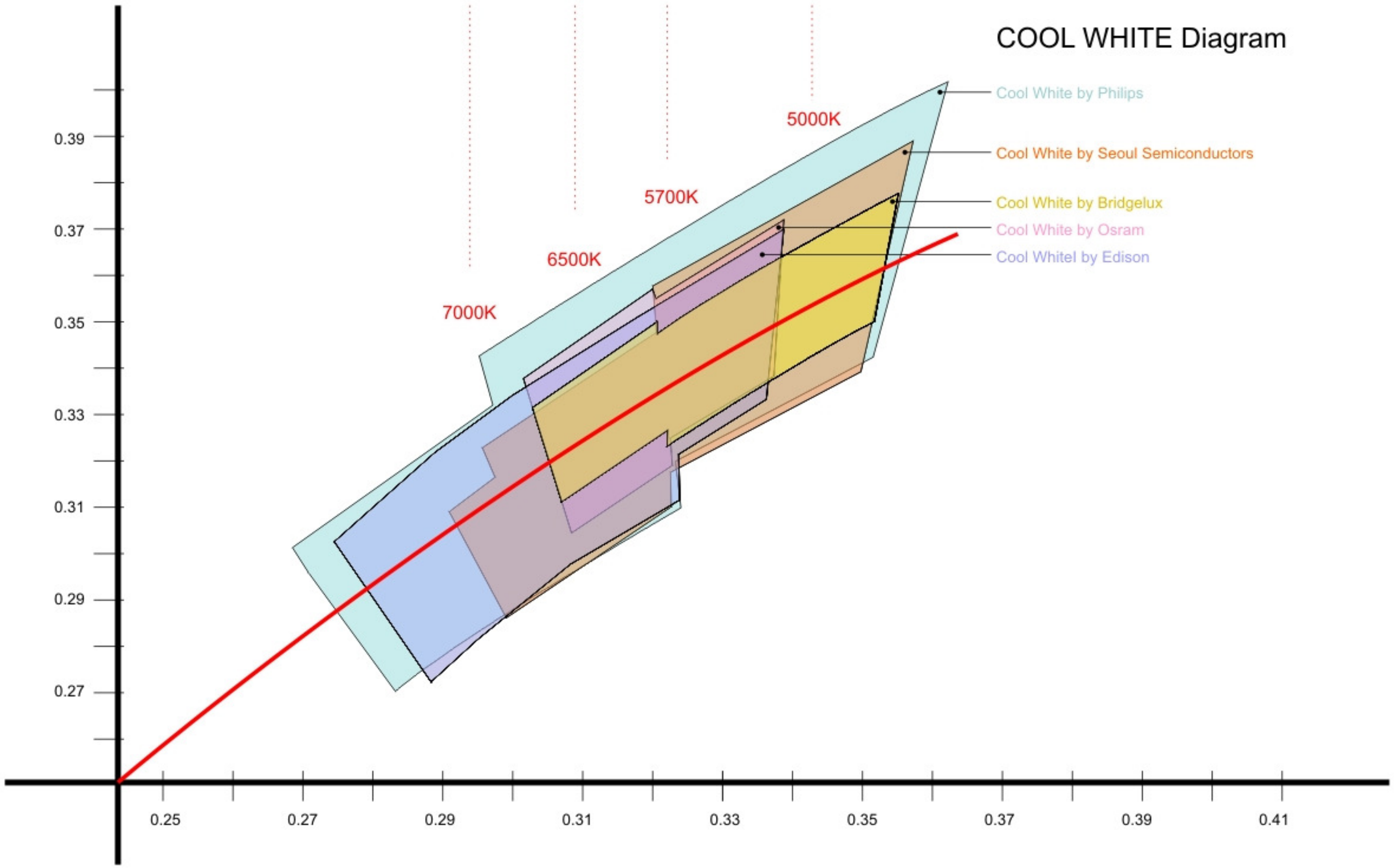

Figure 6.13: Cool white colour binning by different manufacturers (version 1)

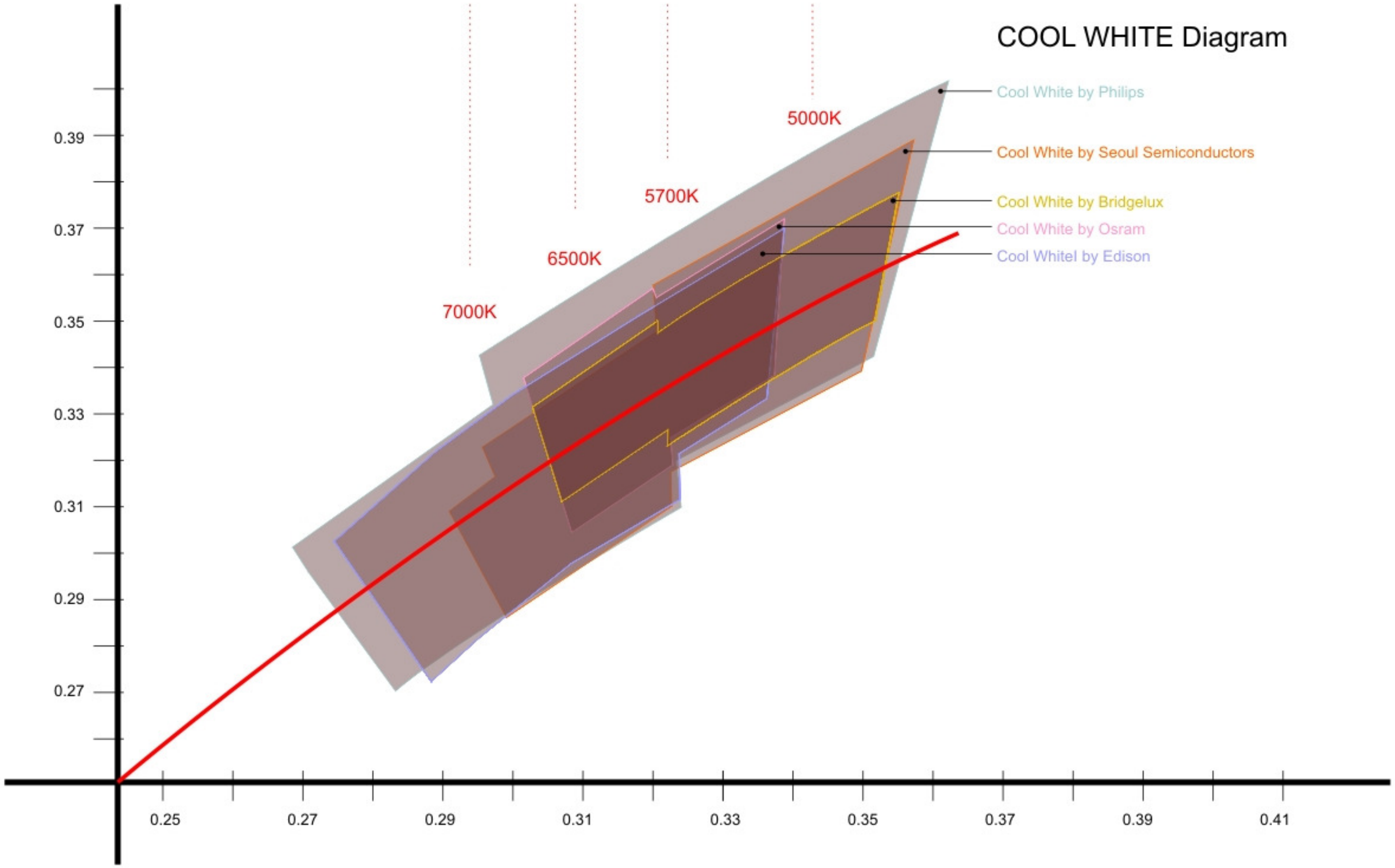

Figure 6.14: Cool White colour binning by different manufacturers (version 2)

)

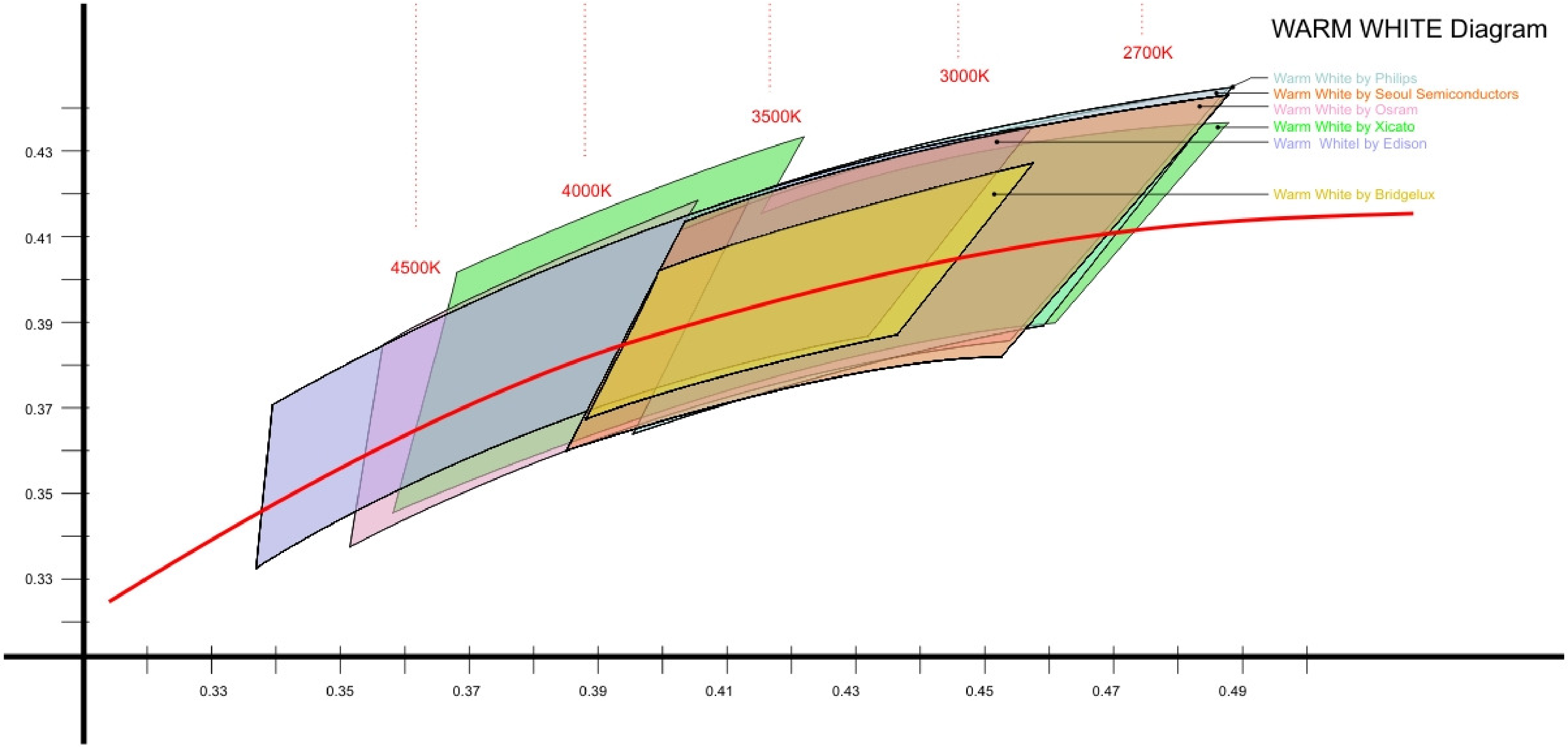

Figure 6.15: Warm White colour binning by different manufacturers (version 1)

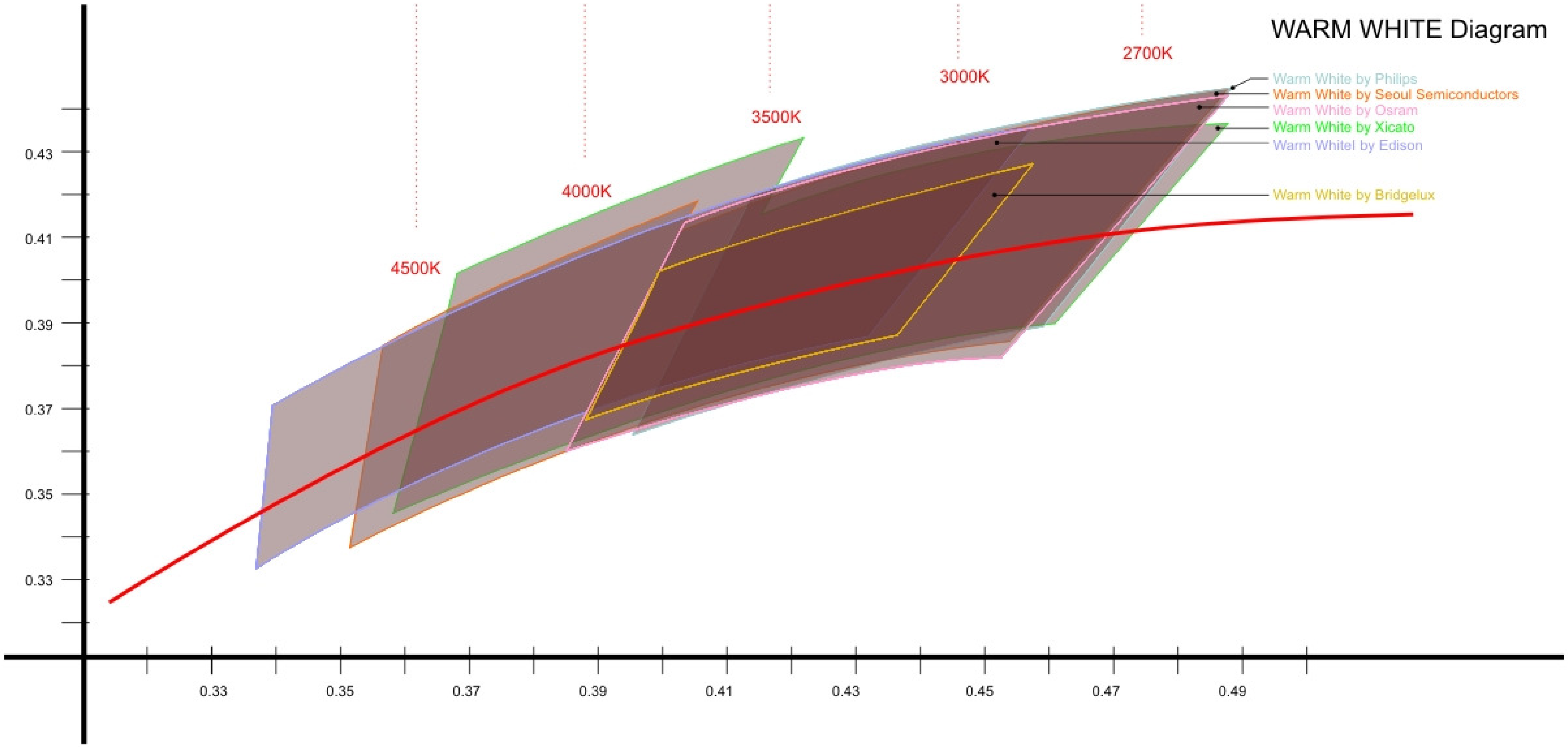

Figure 6.16: Warm White colour binning by different manufacturers (version 2)

Chapter Seven

Completed by January 2014

Analysis/ Discussion

Chapter Seven discusses the use of LED technology in the illumination of the leisure industry, by analyzing the findings of the initial survey (see Chapter 5) and the findings of the market research (see Chapter 6), with reference to the published standards (see Chapter 1).

In addition, Chapter Seven analyzes the information that one group of the LED supply chain considers as important and requires from other groups. It also analyzes the data that is available in the market, given the available standards. The goal is to identify the information that is needed and the information that is actually provided, in the effort to examine the application of LED technology in the leisure industry.

7.1. The illumination of the Leisure Industry

The initial survey (see 5.1.1) found that LEDs are being used by the vast majority of lighting designers for the illumination of the leisure industry. In fact, LEDs are used in applications such asexterior lighting, concealed lighting, decoration lighting, backlighting, indication lighting and special effects. The main products include luminaires with high power LEDs, LED washers, flexible LEDs, linear LEDs, and control systems are used where necessary.

The initial survey (see 5.1.2) also reported that the goal when using LEDs is to provide adequate illumination for the task, as well as light for aesthetics. In the effort to achieve that, the initial survey (see 5.1.3) indicated that RGB LEDs are preferred by lighting designers as compared to monochromatic LEDs (red or green or blue) due to the dynamic colour changes that they offer. White LEDs are being applied in various applications ranging from decorative lighting to general illumination. In fact, the survey reported that the warm white version of LEDs is preferred as compared to the cool version of LEDs, such as warm white MR16 LED lamps that replace halogen lamps.

The case studies presented belowsupport the findings of the initial survey as discussed in section 5.1.3 and demonstrate the wider use of LEDs in various applications in the leisure industry.

Picture 7.1: Alma Hotel, Wandsworth London, UK (Alphaled)

Picture 7.2: Café Zest Meadowhall UK (Gamma Illumination)

Picture 7.3: Harrer Chocolat Café/ Restaurant, Hungary (Linealight LEDs[1])

Picture 7.4: Oltremodo Restaurant Italy (Targetti[2])

[1] http://www.linealight.com/site/uk/projects/all/harrer_chocolate 26/10/13
[2] http://www.targetti.com/ideas-and-inspiration/oltremodo-restaurant 26/10/13

As illustrated, the use of white LEDs is very dominant. On the contrary, the use of RGB LEDs is limited, whereas the use of monochromatic red or green or blue LEDs is even less popular. This has to do with the fact that the trend in the illumination of the leisure industry has changed since the beginning of the research (see 2.6), with lighting designs and installations using more white rather than other colours or dynamic colour changes. Also, over the years developments in the availability of products with white LEDs allowed their wider use (see 1.2 and Annex 9).

7.2. Standards

The recent widespread adoption of LEDs in architectural lighting applications has happened despite the widespread opinion (see 5.1.3) that most manufacturers do not provide sufficient reliable information on their products. For example: the life claims of 100,000 hours originally made by some manufacturers have proved to be false (see Annex 7). There is also the problem that different manufacturers use different binning systems, making it hard to compare such parameters as lumen output (see 6.5.2) and colour point (see 6.5.3) for different suppliers. Another problem is the fact that the colour of white light may differ amongst LEDs of the same manufacturer, as the size of the colour bins is large making different production batches from the same bin appear different (see 6.4).Also manufacturers (see 5.1.3) do not usually offer adequate technical information on their products.

Furthermore, the survey found that there is a belief (see 5.1.3) that data on LEDs is overstated as there have not been many long term studies to check colour consistency and lumen maintenance in real applications. This lack of trust in the data provided for LEDs leads users to test the performance of samples (see 5.1.1) against the nominal specifications of the product to reassure themselves about the light source. This testing is time-consuming, but necessary where the user doubts the veracity of the information provided on a particular product.

The need for reliable data and standard methods for obtaining it was found in the research and is discussed in section 5.1.1. Actually, the initial survey indicated that this is a prerequisite before LEDs have a bright future. For this section of research, it was also important to define what was meant by the term "white". The initial survey (see 5.1.) also reported that, at the time, there were no standards and it was also believed that there has been inadequate research into the use of LEDs. Therefore it was not possible to compare the products from different manufacturers.

However, there have been a number of standards published since the initial survey of Chapter 5, and these are discussed in section 1.3.1.Table 7.1summarizes many of these standards.

Standard	Title	Date
BS EN 62560	Self- ballasted LED- lamps for general lighting services by voltage >50V- Safety specifications	2012
DD IEC/PAS 62612	Self-ballasted LED-lamps for general lighting services- Performance requirements	2009
BS EN 61347-2-13	Lamp controlgear- Part 2-13: Particular requirements for d.c. or a.c. supplied electronic control gear for LED modules	2006
BS EN 62384	DC or AC Supplied Electronic Control Gear for LED modules- Performance Requirements	2006+A1: 2009
BS EN 62031	LED Modules for General Lighting- Safety Specifications	2008
DD IEC/PAS 62717	LED modules for general lighting- Performance Requirements	2011
BS EN 60598-1	Luminaires Part 1: General Requirements and tests	2008 & 2012
DD IEC/PAS 62722-2-1	Luminaire Performance Part 2-1: Particular Requirements for LED luminaires	2011
DD IEC/PAS 62717	LED modules for general lighting- Performance Requirements	2011
IES LM80	Approved Method: Measuring Lumen Maintenance of LED- Light Sources	2008
IES LM79	IESNA approved method for the electrical and photometric measurements of solid state lighting products	2008

Table 7.1: Published standards on LEDs

The recently created standards are now being used by LED manufacturers. For example, many companies now test the lumen maintenance of LEDs using IES LM80 and then use TM-21-11[3] to project the life from the data. Similarly, companies use LM79 to make electrical and photometric measurements of solid state lighting products, luminaires incorporating LED light sources, as well as integrated lamps.Additionally, a number of technical bodies such as the CIE, IEC, IES and CEN are working on further standards in the area (see 1.3.1).

As well as the standards discussed above, there are now new requirements for the energy labeling of lighting products. In the USA the Energy Star system is

[3] IES TM-21-11: Projecting long term lumen maintenance of LED light sources, 2011

used while in Europe energy labels are required by Regulation 874/2012. This supplements the directive 2010/30/EU with regard to energy labeling of electrical lamps and luminaires. Details of this are given in Annex 6.

The standards and methods published have contributed to several improvements. Many manufacturers use the commonly defined definitions of lifetime and lumen maintenance (see Annex 7); claim stable lumen outputs, instead of flux bins (see Annex 7); declare consistent colours and CCTs, instead of colour bins (see Annex 9); and publish reliable photometric measurements (see Annex 8). This generates greater confidence in lighting designers, as compared to their original feelings on LED technology reported in section 5.1.3.

7.3. Lifetime

Initially, lifetime of LEDs was expressed in thousands of hours of operation (usually 100,000 hours). However, LEDs do not fail as traditional light sources, so using the definition of lifetime of conventional sources based on lamp failure[4] is not appropriate (see 1.3.1). On the contrary, the light output of LEDs diminishes over time. The published standard IEC 62612: 2009 (see 1.3.3) states the definition of lumen maintenance of LEDs, which expresses the length of time during which a complete LED luminaire or LED lamp[5] provides more than a percentage of the rated luminous flux under standard test conditions.

Manufacturers apply the lumen maintenance definition and provide a value such as the*L*50 or*L*70, to express estimated operating hours to 50% and 70% of initial light output, respectively. This figure is usually published together with the value B50 or B10 that corresponds to the target statistical confidence interval[6], meaning that 50% or 10% respectively of a sample of LEDs would be expected to have their light output drop below a target lumen maintenance level.

Many companies now test the lumen maintenance of LEDs using the methods IES LM80 and TM-21-11[7] to project the life from the data.As discussed in Annex 7reputable manufacturers such as Xicato and Philips use the L70B50[8] to

[4] http://cool.conservation-us.org/byorg/us-doe/comparing_white_leds.pdf 27/9/13
[5] DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p. 6
[6] http://electronicdesign.com/boards/led-life-standards-and-out-luminaires 23/4/14
[7] IES TM-21-11: Projecting long term lumen maintenance of LED light sources
[8] http://www.lsgc.com/why-leds/lm-80-lumen-maintenance/ 21/4/2013

express the number of hours after which 50% of the sample is giving at least 70% of their original light output under the given set of operating conditions.

The value of L70B50 for 50,000 hours of operation suggests that LEDs last much longer than conventional light sources. Figure 7.1[9] shows cumulative maintenance required over 50,000 hours for different luminaires, and how frequently it is expected to change lamps. In particular, the Tungsten Halogen (TH) lamp has a lifetime of 3,000 hours and 16 replacements, Compact Fluorescent lamps (CFL) and Ceramic Metal Halide lamps (CMH) have a lifetime of 12,000 hours and 4 replacements, while LEDs have a lifetime of 50,000 hours and one replacement.

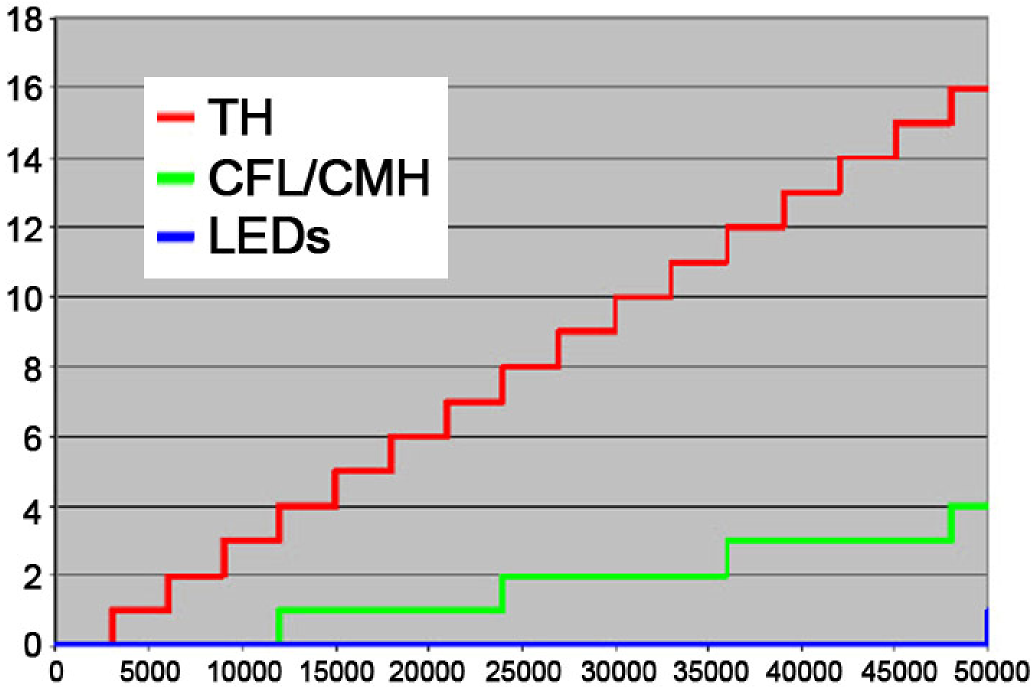

Figure 7.1: Maintenance, number of replacements per hours, of different luminaires

The published standard IEC 62612: 2009 refers to life in combination with the failure rate[10], which is the percentage of a number of tested lamps of the same type that have reached the end of their individual lives, after 6,000 hours of testing. The market research shows (see Annex 7) that most manufacturers do

[9] http://www.hightechnologylighting.com/info/xicato+leds 27/9/13
[10] DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p. 7

not mention the physical failures of Fx at the rated life of 50,000 hours, and do not provide relevant values, such as L70 F10.

Given that, manufacturers do not provide information on[11]Gradual failure fraction (*B*y) that expresses the gradual light output degradation, or on the Abrupt failure fraction (*C*y) that expresses the abrupt light output degradation, as explained in DD IEC/ PAS 62722-2-1:2011.

To sum up, the initial survey as presented in Chapter 5, expresses the need for a uniform and a proper definition of lifetime. The standards and methods published have provided such definition, which reputable manufacturers use to express lifetime and lumen maintenance of their products. Lighting designers can therefore compare the lifetime of different LED products and calculate maintenance requirements.

7.4. Light Output

The initial survey (see 5.1.3) revealed how important it is to have information on the lumen output of LED products, especially when it comes to white light. Nevertheless, this section of the initial research also revealed the belief that not all available white sources have appropriate and constant light outputs.

Light output measurements of the LED should be performed only after stability has been achieved; with different LEDs achieving stability in different times[12]. Once stability has been achieved, luminous intensity distribution shall be measured[13] in accordance with CIE 127: 1997, EN 13032-4, and other related published standards.

The market research (see 6.4) shows that different manufacturers define luminous flux bins with minimum and maximum values, and use different luminous flux binning systems from each other (see Table 6.49, Chapter 6). For instance:

[11] DD IEC/PAS 62722-2-1: 2011,LED modules for general lighting, Performance requirements, p.15
[12]Hatziefstratiou, P. (2005). *Photometry and colorimetry of LED Clusters*. UCL. London. UK
[13] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements

- the X flux bin by Philips corresponds to 280-300lm
- the NZ flux bin by Osram corresponds to 390-450lm
- the F flux bin by Edison corresponds to 290-370lm
- the R flux bin by Bridgelux corresponds to 320-360lm
- the Y flux bin by Seoul corresponds to 260-340lm

This makes it difficult to compare the products from different manufacturers (see 5.1.3).

The market research (see Annex 7) also revealed that over the years, reputable manufacturers such as Philips and Xicato, have advanced their production techniques, for example: by applying remote phosphors, by improving thermal management, by offering better heat sinks. Manufacturers also use the published methods LM80 and LM79 to claim stable outputs- and not luminous flux bins- even for the whole lifetime of their products.

The initial survey (see 5.1.3) in addition found that there is a belief that LEDs are low in power, thus their light output is also very low. However, as technology advances (see Annex 7) reputable manufacturers claim lumen outputs of 400lm, 1000lm, 1300lm, 2000lm, 3000lm, and4000lm, even for the whole lifetime of their LED modules. Such lumen outputs are comparable to the lumen output of conventional light sources. For example: Bridgelux claims[14] that the LED Array has comparable performance to that of 20-100 Watt incandescent and halogen, 7-42 Watt compact fluorescent, and 18-50 Watt High Intensity Discharge (HID) based luminaires and feature increased system level efficacy and service life.

To sum up, as technology and production methods of LED modules improve, manufacturers are able to provide products of high and stable lumens. High and stable lumen outputs allow luminaire manufacturers to design more products with LED modules for demanding applications, such as downlighting and general lighting. Consequently, lighting designers can compare and select reliable LED products in terms of lumen output.

[14]http://www.bridgelux.com/assets/files/DS11%20Bridgelux%20ES%20LED%20Array%20Data%20Sheet%20053012.pdf 20/10/13

7.5. Photometric Data

The initial survey (see 5.1.1) reported the need for photometric data on LEDs. Photometric data include polar curves, luminous intensity values, beam angles, illuminance cones, plugins in IES or LDT files for lighting software such as Dialux or Relux. Suppliers are selected based on their ability to provide quality information and well-documented photometric data.

However, as revealed in section 5.1.2 users do not get photometric measurements for most LED products available in the market. Then again, users believe that the available data is inadequate or unreliable, mainly due to the lack of consistency during the manufacturing processes of LEDs. The market research (see Tables 6.6 &6.15, Chapter 6) verifies the lack of photometric files on LED chips and LED modules, but not on LED luminaires.

In fact, the initial market research revealed that luminaire manufacturers (see Table 6.6, Chapter 6) deliver information on the photometry of their products, but not software plug-ins. In addition, the market research (see Annex 8) revealed that, over the years, reputable LED module manufacturers using advanced production techniques claim reliable photometric data and offer photometric data, polar curves, illuminance cone diagrams, and software plug-ins.

For example, AlphaLED[15] provides LDT files and illuminance cone diagrams for their downlights using the Xicato LED module, as indicated inFigure 7.2.

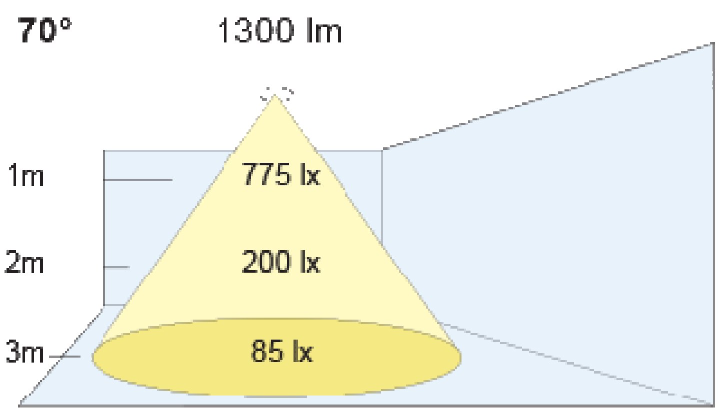

Figure 7.2: Illuminance cone diagram by AlphaLED[16]

[15] http://www.alphaled.co.uk/catalogue/90-series/pin-hole/?x=315&y=163 4/11/13
[16] http://www.alphaled.co.uk/catalogue/90-series/pin-hole/?x=315&y=163 4/11/13

With stable and reliable information on LED modules, luminaire manufacturers are able to offer consistent photometric data on their products. In turn, lighting designers have increased trust on manufacturers and feel more confident to design with LEDs.

7.6. Lumen efficacy

The initial survey (see 5.1.1) revealed that one of the main advantages of LEDs is their high lumen efficacy, calculated from the measured initial luminous flux of the individual LED module divided by the measured initial input power of the same individual LED module [17]. Luminaire efficacy is affected by optical components, ballast or driver efficiency, and thermal management. Given that, LEDs vary in efficiency due to varying constructions and materials[18].

The initial market research (see Table 6.6 &6.15, Chapter 6) reported that most LED manufacturers do not state lumen efficacy of their products. Similarly (see Table 6.26, Chapter 6) not all LED luminaire manufacturers claim such data. Nevertheless the market research (see Annex 7) also indicated that over the years reputable manufacturers including Xicato and Bridgelux, have claimed lumen efficacies of around 100lm/W.

In comparison to traditional light sources, LEDs are inherently directional sources[19] and offer better optical control than traditional energy-efficient sources like fluorescent and metal halide lamps. This allows LED luminaires to direct light where it is needed, efficiently achieving desired illumination levels and uniformity. For that, LED luminaires can achieve higher efficacies in directed light applications such as downlights, than traditional sources.

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[17] DD IEC/PAS 62717:2011, LED modules for general lighting, Performance requirements

[18] http://www.colorkinetics.com/support/whitepapers/evaluating_light_output.pdf 28/11/13

[19] http://cool.conservation-us.org/byorg/us-doe/comparing_white_leds.pdf 27/9/13

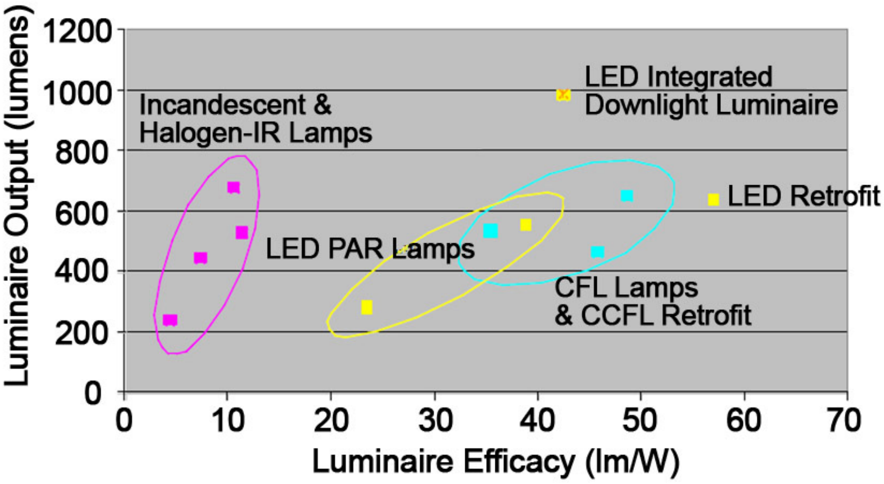


Figure 7.3:Luminaire efficacies with different light sources

Figure 7.3shows a comparison of luminaire efficacies[20] for Recessed Downlights with LED, Compact Fluorescent (CFL), Cold-Cathode Fluorescent (CCFL), Incandescent and Halogen-IR sources (including ballast, driver and thermal losses, where applicable), and demonstrates thatLEDs integrated in downlights have the greatest luminaire efficacy.

Lumen efficacy of LEDs is expected to surpass the efficacy of incandescent, halogen and linear fluorescent lamps, even more in the forthcoming years. Manufacturers have been announcing that LED efficacy will soon reach 150lm/W. Research, as illustrated inFigure 7.4[21]shows that LED luminaires are expected to reach efficacies of 170lm/W by 2020, and 200lm/W by 2025.

[20] http://cool.conservation-us.org/byorg/us-doe/comparing_white_leds.pdf 27/9/13
[21] http://www1.eere.energy.gov/buildings/ssl/sslbasics_whyssl.html#ft_1 29/11/13

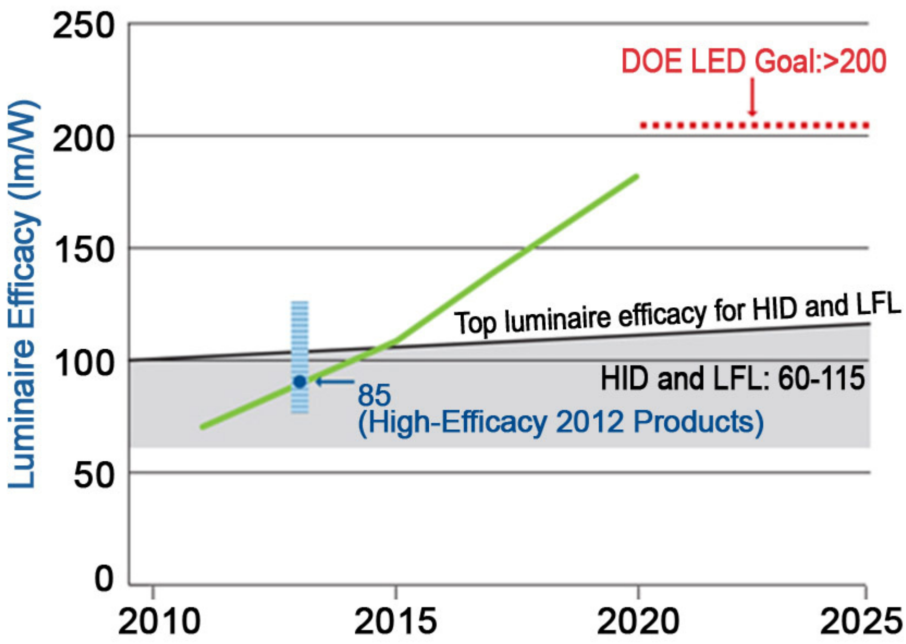


Figure 7.4:Future Projections of Efficacy of LED light sources compared to other sources

In general terms, the lumen efficacy of LEDs is much higher than traditional sources. This is a reason for their further adoption by lighting designers in an effort to create sustainable and energy saving environments.

7.7. White colour consistency &CCT

The initial survey (see 5.1.1) revealed the great need for information related to the white colour emitted from LEDs. In particular, users require information on colour consistency, white colour availability, Correlated Colour Temperature (CCT), colour range availability, and Colour Render Index (CRI) of white LEDs. Yet, this section also reported that there is lack of colour consistency, uniformity, and stability amongst white LEDs, making it hard to further adopt LED technology.

The market research (see section 6.) shows that manufacturers have defined ‘bins’ of colour around the black body curve with similar colour characteristics, in an effort to identify colour properties of their LEDs. Nevertheless, different manufacturers use different colour binning systems and draw different graphs on the CIE chromaticity diagram. Figures 6.14- 6.17 in Chapter 6 clearly demonstrate the different binning systems of cool white and warm white by different manufacturers. This problem makes it hard to compare such parameters as colour point for different suppliers.

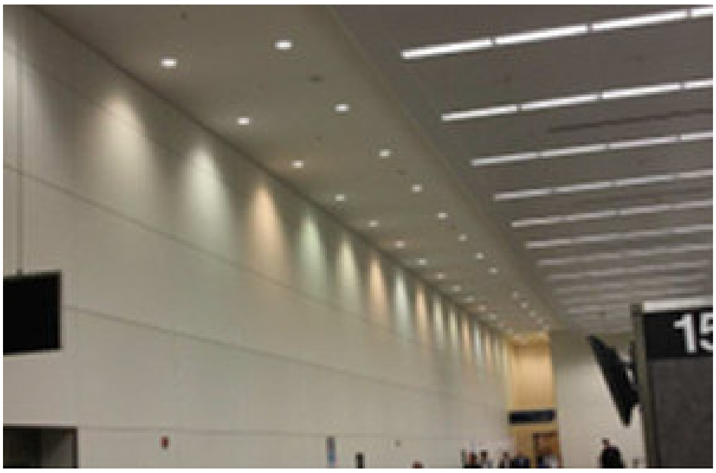
The market research also shows that the colour bins defined by manufacturers may be large or small (see 6.4). Where the size of the colour bin is large, the colour coordinates of white light may differ from one production batch to another, thus the colour may appear different, though from the same bin of the same manufacturer.

Colour may also present shift with time. Colour shift has to do, mainly, with the way that white light is produced from LEDs. In fact, the most common manufacturing technique[22] to produce white LEDs is to homogeneously suspend the phosphor powder in an encapsulating epoxy that is then used to coat the die. The exact shade or colour temperature of white light[23] is determined by the dominant wavelength of the blue LED and the composition of this yellow phosphor. For warm white LEDs red phosphor must be added to the yellow. The thickness of the phosphor coating produces variations in the colour temperature of the LED. Manufacturers attempt to minimize colour variations by controlling the thickness and composition of the phosphor layer during manufacturing. Over time, the blue die and the yellow phosphor degrade. This results in light shifting colour.

Another important parameter in colour shift is heat. As temperature increases, several performance parameters experience a temporary and recoverable shift. In particular, as heat increases, light output (flux) decreases, forward voltage (Vf) decreases, and colour temperature shifts towards blue. Other parameters[24],[25] that affect the colour of emitted light include the LED die itself, the LED junction temperature, variations in operating temperature, variations in the LED current (usually when dimmed), the age of the LED and the degradation over life.

[22] http://www.digikey.com/us/en/techzone/lighting/resources/articles/remote-phosphor-offers-alternative-to-white-leds.html 13/9/13
[23] http://www.photonstartechnology.com/learn/how_leds_produce_white_light 13/9/13
[24] http://ledlight.osram-os.com/wp-content/uploads/2012/02/OSRAM-OS_Application_Guide-Brilliant_Mix_Tech_Note_v1_1_4_2012.pdf 13/9/13
[25] http://www.photonstartechnology.com/learn/how_leds_produce_white_light 13/9/13

The problems related to white light are often evident in architectural installations.An example of such an installation is illustrated in Picture 7.5.



Picture 7.5: Lighting installation with low quality LED products that emit different colour of white light[26].

Standards have been published to address the problems related to the white colour of LEDs. IEC 62612 defines colour by the initial colour temperature value and the rated colour temperature which shall preferably be one of the following six values: 2.700K, 3.000K, 3.500K, 4.000K, 5.000K or 6.500K[27]. In addition, for reference purposes, the standardized chromaticity co-ordinates corresponding to these CCT values have been specified[28].Moreover, the measured actual CCT values are expressed as fitting within one of eight categories, each corresponding to a particular MacAdam ellipse around the related CCT value, i.e. CCTs within a 1-step MacAdam ellipse, 2-step MacAdam ellipse, and so on.

The market research (see Annex 9) shows that reputable manufacturers have been using advanced manufacturing techniques to guarantee colour consistency and colour stability of their LED modules between different production batches and over time. Examples include the 'corrected cold phosphor technology' of Xicato, and the method of controlling the intensity of different coloured LEDs incorporated in a module such as the CREE LMR4 module. Such manufacturers use the published standards to define Correlated

[26]http://xicato.com/technology/color-consistency/ 4/9/13
[27]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p.9,10
[28]DD IEC/PAS 62612:2009 Self-ballasted LED-lamps for general lighting services-Performance requirements, p.9, 10

Colour Temperatures (CCTs) and colour consistency as per the steps of MacAdam ellipses (see Annex 9).

To sum up, the latest LED manufacturing methods show that LED module manufacturers provide specific information in regard to the colorimetry of their modules. Thus, manufacturers claim stable CCTs of 2700K, 3000K, 4000K, 5000K, and 6500K. Similarly, manufacturers claim colour consistency as tight as two or even one MacAdam Ellipse around the colour point on the black body locus. Luminaire manufacturers using such modules are able to claim stability and consistency of their products in terms of colour. Therefore, lighting designers are confident to design with LEDs with uniform outcomes of white in their installations.

7.8. Colour Rendering Index

The initial survey (see 5.1.3) shows the need of a high Colour Rendering Index(CRI) of Ra= 80+, so the colours of materials and surfaces appear natural in the light from LEDs. Colour Rendering Index has been defined as a measure[29] of the ability of a light source to reproduce colours faithfully in comparison with an ideal or natural light source. However, for LEDs with narrow spectrum, the CRI index is not in all circumstances giving a fair representation of the colour appearance. This suggests that further research is needed in regard to the CRI of LEDs.

The market research as presented in Chapter 6shows that some LED chip manufacturers (see Table 6.6, Chapter 6), LED module manufacturers (see Table 6.15, Chapter 6), and some LED luminaire manufacturers (see Table 6.6, Chapter 6) state the CRI of their products.

The market research also indicates that products that emit white light by combining RGB LEDs typically have a CRI of 20-60[30] at the white point. This explains why they are not used in white applications. Products combining a blue

[29]http://en.wikipedia.org/wiki/Color_rendering_index, 4/7/13
[30]http://ledlight.osram-os.com/wp-content/uploads/2009/10/Brilliant_Mix_Professional_White_for_General_Lighting.pdf 15/9/13

LED chip with coating of yellow phosphors typically have a CRI of 70-80[31]. Such products are widely used in architectural applications.

New technologies of producing white light from LEDs achieve a CRI of 90+ or 95+ (see Annex 9). Luminaires using modules of the latest technology have a wider use, not only in the leisure industry, but in other applications that require faithful reproduction of colours, such as retail lighting and museum lighting.

7.9. RGB Colour

The initial survey (see 5.1.1) showed that users are not very interested in RGB LEDs. But when they have to use colour, they prefer to use RGB rather than monochromatic LEDs. In such cases, the initial survey (see 5.1.3) showed that users want to know the colour mixing capabilities of RGB LEDs in order to have a wide colour gamut. In addition, this section of the survey found that users prefer RGB LEDs in one chip, rather than red or green or blue LEDs in arrays. The reason is that RGB in one chip LEDs produce more saturated colours.

Coherent colour changing, colour stability over time, saturation of colours, smoothness in dimming, flexibility in controls, management capabilities, and ease of colour mixing and control, are also important issues in regard to RGB LEDs.

The initial survey (see 5.1.3) also revealed that users do not expect RGB LEDs to give good white colour. RGB LEDs are ideal to create a wide range of saturated colours, but when it comes to white it is less sensible to use RGB LEDs. Research suggests that it is important to define a uniform system for colour measurements of RGB LEDs and to define a uniform binning structure against which comparisons will be made[32]. Although some effort has been made to define a form of metric of colour stability across the beam[33], there is still no published standard available in regard to this issue. Moreover, the market research indicates that no sufficient progress has taken place in regard to RGB LEDs, probably due to the wider use of white light in architectural lighting applications.

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[31] http://ledlight.osram-os.com/wp-content/uploads/2009/10/Brilliant_Mix_Professional_White_for_General_Lighting.pdf 15/9/13

[32] Lighting Industry Liaison Group, “A Guide to the Specification of LED Lighting Products 2012”, October 2012

[33] Hatziefstratiou, P. (2005). *Photometry and colorimetry of LED Clusters*. UCL. London, UK

7.10. Luminaire design& specifications

The initial survey (see5.1.1) reported that users value the design and appearance of LED luminaires, and select fittings that are in coherence with the architectural and ornamental characteristics of the space. Users also select fittings by studying the construction and engineering of fittings to ensure themselves of using reliable products. For example, operating temperature, heat dissipation, thermal management, power consumption, optical systems, beam control, and glare protection are factors that affect decisions about the selection of fittings.

In addition, this section of the survey revealed that the overall performance of the fittings affects selections, including light output, brightness, efficacy, and energy efficiency. Likewise, dimensions, size, mounting capabilities, ease of maintenance, and functionality, are also significant criteria when selecting a LED luminaire.

In an effort to best meet the requirements of users, LED luminaire manufacturers offer in the market a wide range of products, ranging from downlights to pendant luminaires, and from wall washers to linear custom fittings. The products are mainly used in general lighting, decorative lighting, wall washing, and concealed lighting.

Picture 7.6: Kronos Downlight by ELECTRON SA[34]

Picture 7.7: CCT Pendant[35] by Targetti

Picture 7.8:Integrex wall washer by ACDC[36]

Picture 7.9: VarioLED Hydra LD5 by LED linear[37]

The fittings use LEDs[38] that are compact and easy to integrate into fixture design. As discussed in Annex 10, many reputable manufacturers promise to incorporate technological advancements into the existing module designs. Therefore, it will be easy for luminaire manufacturers to up-grade modules[39] easily and effectively without the need to change optical designs as these will remain constant. The same Annex also reports that reputable manufacturers of the Zhaga Consortium have been working on the development of interface

[34] http://www.electron.gr 5/11/13
[35] http://www.targetti.com/products/65622/cctled-pendant-architectural 5/11/13
[36] http://www.acdclighting.co.uk/led/integrex/#.Unv_x9tXvVQ 5/11/13
[37] http://www.led-linear.com/en/products/product-line/product-details/kategorie/varioledtm-hydra-white-ip67/produkt/varioledtm-hydra-ld5-ip67 5/11/13
[38] www.mondoarc.comMondo_ArcMediaPack2014, 28/10/13
[39] www.mondoarc.comMondo_ArcMediaPack2014, 28/10/13

specifications that allow LED light sources from different suppliers to be used interchangeably, without changing the luminaire design.

The findings imply that luminaire manufacturers will be able to design fittings for the future and integrate upgraded LED modules with minimal cost. At the same time, lighting designers and end users will be able to select the LED module they desire in the fitting they like, to best meet their needs.

7.11. Control Capabilities

The initial survey (see 5.1.1) revealed that one of the major advantages of LED is the control capabilities that this technology offers. Dimming and control of light is a desired feature in many applications of the leisure industry. For example: dimming is required in restaurants in order to set a relaxing environment; control of RGB colour is required in bars that aim to boost the interest of guests.

It is recommended[40] to use Pulse Width Modulation (PWM) for dimming LEDs to deliver consistent performance between lighting systems over a broad range of light output levels.Pulse-width modulation[41] (PWM) is a modulation technique that conforms the width of the pulse, formally the pulse duration, based on modulator signal information. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors.

In addition to the above, the driving capabilities of LEDs should be considered. LEDs operate with constant current or constant voltage. A constant current system[42] is a system that can vary the voltage across an electronic circuit to maintain a constant electric current. When a component is indicated to be driven by a constant current, the driver circuit is, in essence, a current regulator and must appear to the component as a current source of suitable reliability. A constant voltage system is a system that maintains constant voltage regardless of the load current. Examples of connection diagrams are illustrated in Figures 1 & 2, Annex 11.

[40] http://bridgelux.com/assets/files/AN12_Electrical_Drive_Considerations.pdf 20/10/13
[41] http://en.wikipedia.org/wiki/Pulse-width_modulation 10/11/13
[42] http://en.wikipedia.org/wiki/Constant_current 10/11/13

When it comes to the operation of RGB LEDs, lighting designers need to consider the polarity. RGB LEDs will only light with correct electrical polarity[43] (common anode or common cathode). When the voltage across the p-n junction is in the correct direction, significant current flows and the LEDs will light. On the contrary, if the voltage is of the wrong polarity, very little current flows, and no light is emitted from the RGB LEDs. This is shown in the drawings of Figure 3, Annex 11.

The market research as presented in Chapter 6 reports that LED module (Table 6.5, Chapter 6) and LED luminaire (Table 6.6, Chapter 6) manufacturers provide information on the dimming and control options of their products, and also provide information on driver options and configurations. Lighting designers use this data to familiarize themselves with the control options that best meet their needs.

As revealed in section 5.1.1, end users usually have little knowledge on LED technology. Therefore, lighting designers need to then educate end users on the control systems of their installations.

7.12. Cost

The initial survey (see 5.1.1.) shows that cost is an important consideration when selecting LEDs. Initially, LEDs had a high purchase cost, especially when compared with conventional light sources. Nevertheless, over time the purchase cost of many LED products has decreased significantly due to the high demand and supply of such products. Examples include the LED Strips and the LED retrofit lamps. The quality of such products needs to be tested and evaluated.

At the same time, a bench test[44] performed in September 2011, compared amongst other factors, the cost of 1000lm LED Modules of reputable manufacturers. The results are shown inTable 7.2. As indicated, LED modules that offer stable and consistent photometry and colorimetry have a very high purchase cost.

[43]http://en.wikipedia.org/wiki/LED_circuit 11/11/13
[44]http://www.mondoarc.com/technology/LED/1008147/1000lm_led_module_bench_test.html 10/11/13

LED module	USD purchase cost
Xicato XSM 8030/1300	39.00
Philips Fortimo DLM 1100	92.00
CREE LMR4 (including integrated power supply)	54.00

Table 7.2: Cost of LED modules from reputable manufacturers

7.13. Coding

The initial survey of Chapter 5implies the need for a consistent system of defining LED products. The DD IEC/ PAS 62717: 2011[45] published standard provides a definition of the photometric code of LEDs. For example, the photometric code 830/359:

- 8: The initial CRI of e.g. 77
- 30: Initial CCT of 3000K
- 3: initial spread of chromaticity co-ordinates within a 3-step MacAdam ellipse
- 5: maintained spread of chromaticity co-ordinates at 25% of rated life (with a maximum duration of 6,000h) within a 5-step MacAdam ellipse
- 9: code of lumen maintenance at 25% of rated life (with a maximum duration of 6,000 hours, in this example: >=0% of the 0h value)

The market research shows that LED module manufacturers use different designation systems that are most convenient to them, and not a system that is consistent to all manufacturers. For example, the part number designation of Bridgelux

B X R A – A B C D E – R RRRR, for Bridgelux LED Arrays[46]
is explained as follows:

[45] DD IEC/PAS 62717:2011,LED modules for general lighting, Performance requirements, p. 34
[46]http://www.bridgelux.com/assets/files/DS11%20Bridgelux%20ES%20LED%20Array%20Data%20Sheet%20053012.pdf 20/10/13

B X R A – designates product family
A – designates colour, C for Cool White, N for Neutral White and W for Warm White
B C – designates LED Array product flux, 04 for a 400 lumen array, 08 for a 800 lumen array, 12 for a 1200 lumen array, and 20 for a 2000 lumen array
D E – designates product family
R RRRR – used to designate product options, 00000 by default
The base product part number (BXRA-ABCDE) is indicated on each individual unit, printed on the bottom of the LED Array.

Similarly, the market research reveals that luminaire manufacturers use ordering systems that best meet their production needs, and not a system that is commonly acknowledged by all manufacturers. For example, the ordering code of Electron SA[47]
KRONOS-27-X1000-FX-95-40-BL-DL
Is explained as follows:

KRONOS – designates the family of downlight
27 – designates the CCT
X1000 – designates the Xicato LED module of 1000lm
FX – designates that the fitting is fixed
95 – designates a CRI of 95+
40 – designates the beam angle of 40 degrees
BL – designates the colour of fitting as black
DL – designates the DALI dimming option

The use of different designation systems and ordering codes makes it very hard to evaluate and compare LED products. Thus, further work needs to be made in an effort to define uniform definitions that manufacturers will apply for their products.

[47] http://www.electron.gr/en/products.html?app=catalog&view=item&id=955&category_id=619 11/11/13

7.14. Marking

Lighting products are expected to have the appropriate markings and certificates. Published standards such as the BS EN 60598: 2012[48] and DD IEC/ PAS 67722-2-1: 2011[49]analytically list such markings (see section 1.4 and 1.6). Given that, LED luminaire manufacturers are expected to provide information, such as:

- Origin of the product
- Rated power
- Rated voltage
- Rated current
- Frequency (Hz)
- Class of electrical protection
- Termination marks when supplied with mains voltage
- Maximum number of luminaires that can be connected
- Symbol not suitable for covering with thermally isolated material
- Instructions for proper installation/ use/ maintenance
- Operating temperature and spacing requirements
- Wiring diagrams
- Special conditions
- Limitations to use
- Warning for suitability for direct mounting on normally flammable surfaces
- Ingress Protection (IP) rate
- Means of adjustment

Similarly, product datasheets should provide information such as:

- Photometry, lumen outputs, polar curves
- Rated life, failure fraction, lumen maintenance
- Rated chromaticity coordinate values both initial and maintained, CCT, CRI
- Lumen efficacy
- Beam angle of emitted light

[48] BS EN 60598 page 30-35
[49] DD IEC/PAS 62722-2-1: 2011, p 8-10

The market research of Chapter 6 shows that in most cases manufacturers provide markings defined by the published standards. In other cases, markings are only available by reputable manufacturers. And in other cases, the requested markings are not available in manufacturers' websites. Table 7.3shows the recommended markings (see sections 1.4 and 1.6)and their availability as identified by the internet market research of Chapter 6, where:

- ✓ Available
- × Not available
- ❖ Available mainly by reputable manufacturers
- ➢ Not applicable

Marking on LED luminaires as per published standards for different applications			
Marking based on IEC documents[50][51][52]	**White**	**Monochromatic (non white)**	**RGB**
Mark of origin	✓	✓	✓
Rated voltage(s) in volts	✓	✓	✓
Rated wattage (W)	✓	✓	✓
Nominal frequency (Hz)	✓	✓	✓
Class of protection Class II or Class III	✓	✓	✓
Type reference by maker	✓	✓	✓
Terminations marked to identify live, neutral and earth for mains supply	✓	✓	✓
Max number of luminaires interconnected	×	×	×
Luminaires not suitable for covering with thermally insulated material	❖	❖	❖
Installation, use and maintenance	✓	✓	✓
Operating temperatures and Spacing requirements	✓	✓	✓
Wiring diagram	❖	❖	❖
Special conditions	❖	❖	❖
Limitations of use	✓	✓	✓
Power factor and supply current	✓	✓	✓
Remote control gear info	✓	✓	✓
Warning for direct mounting on normally flammable surfaces /non-combustible surfaces	❖	❖	❖
IP rating	✓	✓	✓
Protective conductor current	×	×	×
Means of adjustment	✓	✓	✓
Circumstances of use	×	×	×
Rated luminous flux (lm)	❖	❖	❖
Rated life (in h) & lumen maintenance (Lx)	❖	×	×
Failure fraction (Fy)	❖	×	×
Lumen maintenance code	×	×	×
Rated chromaticity coordinate values	❖	❖	❖
Correlated colour temperature (CCT in K)	❖	➢	×
Rated colour rendering index (CRI)	❖	❖	×
Ambient temperature (tp) for a luminaire	✓	✓	✓

[50] BS EN 60598 page 30-35
[51] DD IEC/PAS 62722-2-1: 2011, p 8-10
[52]DD IEC/PAS 62722-2-1:2011, p 9-10

LED luminaire efficacy (lm/W)	❖	×	×
Luminous intensity distribution	❖	×	×
Peak intensity values	❖	×	×
Beam angle	✓	✓	✓
Chromaticity tolerance initial and maintained	❖	×	×
CRI initial and maintained	❖	×	×
Temperature cycling	×	×	×
Optical risk	×	×	×
Risk Group	×	×	×

Table 7.3: Marking on LED luminaires as per IEC publications for various applications

Furthermore, the initial survey (see 5.1.1) revealed that selection of LED luminaires depends on whether the fitting complies with legislative directives, such as CE, EMC, LVD, UL, Rohs.

The CE marking[53] indicates a product's compliance with EU legislation and so enables the free movement of products within the European market. The EMC Directive[54](Electromagnetic Compatibility) first limits electromagnetic emissions of equipment in order to ensure that, when used as intended, such equipment does not disturb radio and telecommunication as well as other equipment. The Directive also governs the immunity of such equipment to interference and seeks to ensure that this equipment is not disturbed by radio emissions when used as intended**.** In addition to that, the LVD [55] ensures that, electrical equipment within certain voltage limits provides a high level of protection for European citizens and may be sold in the Single Market in the European Union. The Directive covers electrical equipment with a voltage between 50 and 1000 V for alternating current and between 75 and 1500 V for direct current. The market research has shown that all products imported or exported from the European Union need and must have the CE and/or LVD marking.

In the USA, LED fittings often need to have UL labelling. UL[56] is a global independent safety science company with more than a century of expertise innovating safety solutions from the public adoption of electricity to new breakthroughs in sustainability, renewable energy and nanotechnology. Dedicated to promoting safe living and working environments, UL helps safeguard people, products and places in important ways, facilitating trade and providing peace of mind.

[53]http://ec.europa.eu/enterprise/policies/single-market-goods/cemarking/about-ce-marking 20/11/13
[54]http://ec.europa.eu/enterprise/sectors/electrical/emc/index_en.htm 20/11/13
[55]http://ec.europa.eu/enterprise/sectors/electrical/lvd 20/11/13
[56]http://www.ul.com/global/eng/pages/aboutul 20/11/13

The Restriction of Hazardous Substances (Rohs) Directive[57] restricts the use of hazardous materials in the manufacture of various types of electronic and electrical equipment.

An example of data availability by manufacturers in regard to markings is illustrated below.

Max Linear System by Aldabra[1]

Picture 7.10: Max Linear System

Applications:	shelves, windows, niches, walls
Setting:	retail showrooms, private houses
Installation:	surface mounted
Material:	natural anodized aluminium - transparent methacrylate
Finishes:	grey anodized aluminium
LED light source:	high power - low power
Optics:	transparent diffuser
Functions:	on-off, dimmable
Features:	lengths up to 3 meters
Power supply:	constant voltage 24Vdc

[57] Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, 2002/95/EC

7.15. Data Availability in the LED Supply Chain

The initial survey (see 5.1.) revealed three major lighting applications:

- Applications that require white light
- Applications that require monochromatic light other than white
- Applications that require RGB light

Section 5.1.2 also investigated the key lighting parameters that need to be taken into consideration in each of the above three applications.

Given the above, the following sections discuss the data that is requested and the data that is available in the LED Supply Chain, with reference to the key lighting parameters of each kind of application. The LED Supply Chain and its main players are defined in section 1.4.

7.15.1 Data Availability on "white" LEDs in the LED Supply Chain

Section 5.1.2 reported that the most important lighting parameters in applications where white light is needed include:

- Correlated Colour Temperature
- Colour consistency between LEDs and through life
- Colour Rendering Index
- Stability characteristics
- Lumen output
- Lumen maintenance

Section 5.2 revealed very high correlations between parameters that are related to white colour:

- lumen output and colour consistency
- colour range availability and colour consistency
- colour consistency and lumen maintenance
- cost and power
- lumen output and lumen maintenance

- colour consistency and white colour availability
- CCT and CRI
- colour range availability and lumen maintenance
- colour consistency and CCT
- control capabilities and white colour availability
- colour range availability and lumen output
- white colour availability and CCT
- LED luminaire design and power

LED Module manufacturers are expected to provide directly to LED luminaire manufacturers, information on:

- CCT, colour binning, colour stability, CRI
- Operating conditions and stability
- Lumen output, lumen maintenance, photometry
- Technical specifications, operating voltage, power consumption, drivers, heat sinks, optics

The market research (see Chapter 6) indicates that reputable LED module manufacturers provide to LED luminaire manufacturers the requested information, at least to the vast majority. At the same time, however, other manufacturers do not offer any kind of information on colour. On the contrary, the binning of white is categorized as:"cool white", "warm white" and "neutral white". These manufacturers usually do not specify lumen output either, yet they talk about replacement of LEDs with common lamps such as incandescent or linear fluorescent.

LED luminaire manufacturers are expected to provide directly to lighting designers information on:

- CCT, colour binning and CRI
- Lumen output, lumen maintenance, life time, and photometry
- Operating conditions and drivers

The market research (see Chapter 6) shows that lighting designers get most of the requested information when they deal with reputable manufacturers. When they deal with non-reputable manufacturers they usually request samples in order to reassure themselves about the specifications of the fittings.

Lighting designers are expected to provide to end users more practical information on LED technology, such as:

- Lifetime
- Power consumption, cost of installation, energy savings
- Consistency and stability of white light between them and over time
- Adequate illumination for the task
- Control systems and capabilities

In general terms, lighting designers provide to end users the requested information, taking into consideration the correlations between different parameters. For example, lighting designers try to deliver information on lumen output and lumen maintenance, on colour availability and CCTs, on CCTs and CRI. They also educate users on the control systems and dimming capabilities of white light.

Taking into consideration the fact that architectural lighting applications are using more and more of white light (refer to section 7.1),data availability on white LEDs becomes fundamental. Therefore, each group of the LED Supply Chain is expected to provide to the rest of the groups the requested information, in an effort to accomplish uniform and homogenous light outcomes.

Table 7.4 summarizes the information on white LEDs that should be available as per section 5.1 and 5.2 in relation to the information that is actually currently available as per the market research of Chapter 6:

✓ Available
× Not available
❖ Available mainly by reputable manufacturers

Data Availability by the different groups in the LED Supply Chain			
White light applications	Module manufacturers to luminaire manufacturers	Luminaire manufacturers to lighting designers	Lighting designers to end users
Lumen Output	❖	❖	❖
Lumen Maintenance	❖	❖	❖
Photometry	❖	❖	❖
Stability	×	×	×
CCT	❖	❖	❖
Colour bins	❖	❖	❖
Colour stability	❖	❖	❖
CRI	❖	❖	❖
Operating Conditions	✓	✓	✓
Beams	✓	✓	✓
Power Consumption	✓	✓	✓
Operating voltage	✓	✓	✓
Drivers	✓	✓	✓
Heat sinks	✓	✓	✓
Tj	✓	✓	✓
Optics	✓	✓	✓
Lifetime	✓	✓	✓
Cost	✓	✓	✓

Table 7.4: Data availability in the LED Supply Chain for white applications

7.15.2. Data Availability on "monochromatic" LEDs in the LED Supply Chain

Section 7.1 revealed that architectural lighting applications are using lately more white and less of other colours. When colour is needed, users prefer RGB LEDs due to the immense control capabilities that they offer, rather than monochromatic LEDs (see 5.1.3). In any case, section 5.1.2 reported that the most important lighting parameters in applications where monochromatic light (other than white) is needed include:

- Colour
- Lumen output
- Lumen maintenance
- Lifetime

Section 5.2 revealed very high correlations between parameters that are related to monochromatic colour (other than white):

- lumen output and colour consistency
- colour range availability and colour consistency

- colour consistency and lumen maintenance
- cost and power
- lumen output and lumen maintenance
- colour range availability and lumen maintenance
- colour range availability and lumen output
- LED luminaire design and power

LED Module manufacturers are expected to provide directly to LED luminaire manufacturers, information on:

- Lumen output and lumen maintenance
- Photometry
- Stability
- Operating conditions, heat sinks
- Beams and optics
- Operating voltage, power consumption, drivers

The market research (see Chapter 6) reveals that not many developments have taken place over the last years in regard to monochromatic LEDs. The majority of manufacturers do not provide polar curves or information on lumen output, lumen maintenance, or colour stability. On the contrary, manufacturers usually provide data on operating voltage, power consumption and drivers.

LED luminaire manufacturers are expected to provide directly to lighting designers information on:

- Lumen output, photometry
- Lifetime, lumen maintenance
- Beams
- Operating conditions
- Drivers

The market research (see Chapter 6) shows that the more information luminaire manufacturers get from LED module manufacturers, the more data they provide to lighting designers. Therefore, luminaire manufacturers usually provide information on lumen output, lifetime, beams, operating conditions and drivers; but they do not provide information on lumen maintenance and photometry.

Lighting designers are expected to select products that are in coherence to the architectural and ornamental elements of the space and provide to end users information on:

- Colour stability and consistency between LEDs and over time
- Lifetime of LEDs
- Cost and power consumption

Lighting designers usually provide the above information to end users.

Table 7.5summarizes the information on monochromatic LEDs that should be available as per section 5.1 and 5.2 in relation to the information that is actually currently available as per the market research of Chapter 6:

✓ Available

× Not available

❖ Available mainly by reputable manufacturers

Data Availability by the different groups in the LED Supply Chain			
Monochromatic applications (non white)	Module manufacturers to luminaire Manufacturers	Luminaire Manufacturers to lighting designers	Lighting designers to end users
Lumen Output	❖	❖	❖
Lumen Maintenance	❖	❖	❖
Photometry	❖	❖	❖
Photometric data	×	×	×
Stability	×	×	×
Colour stability	×	×	×
Operating Conditions	✓	✓	✓
Beams	✓	✓	✓
Power Consumption	✓	✓	✓
Operating voltage	✓	✓	✓
Drivers	✓	✓	✓
Heat sinks	✓	✓	✓
Tj	✓	✓	✓
Optics	✓	✓	✓
Lifetime (LB)	×	×	×
Cost	✓	✓	✓

Table 7.5:Data availability in the LED Supply Chain for monochromatic applications

7.15.3 Data Availability on “RGB” LEDs in the LED Supply Chain

Section 5.1.2 reported that the most important lighting parameters in applications where RGB light is needed include:

- Lumen output
- Lifetime and lumen maintenance
- Control capabilities
- Current rating

Section 5.2 revealed that there are no high correlations between RGB colour mixing and any other lighting parameter. Yet, when it comes to RGB applications, it is important to take into account the following high correlations:

- lumen output and colour consistency
- colour range availability and colour consistency
- colour consistency and lumen maintenance
- cost and power
- lumen output and lumen maintenance
- colour range availability and lumen maintenance
- colour range availability and lumen output
- luminaire design and power
- control capabilities and lumen output
- control capabilities and colour consistency
- control capabilities and stability
- control capabilities and LED luminaire design

LED module manufacturers are expected to provide to luminaire manufacturers information on:

- Lumen output
- Lumen maintenance
- Colour bins for RGB at full power
- Stability and operating conditions
- Current rating, operating voltage
- Power consumption
- Drivers, controls
- Optics and heat sinks

The market research (see Chapter 6) shows that LED luminaire manufacturers do not receive information on stability, lumen output, or lumen maintenance of RGB LEDs. Nor do they get information on the color bins of RGB at full colour. On the contrary, they get information on the operating current or voltage, power consumption, drivers, controls, optics and heat sinks available.

LED luminaire manufacturers are expected to provide to lighting designers information on:

- Lumen output
- Lifetime, lumen maintenance
- Colour availability
- Polarity and controls of RGB LEDs
- Lighting channels, scenes, scenarios, and chasers that can be generated with the appropriate control systems

The market research (see Chapter 6) indicates that lighting designers receive information on the lumen outputs but not photometric curves or colour bins of RGB LEDs. In addition, lighting designers receive a lot of information on polarity, control, and dimming capabilities of RGB LEDs (see 7.11).

Lighting designers are expected to provide information on:

- Size of fittings
- Cost
- Efficiency and power consumption
- Control capabilities
- Ease of use

Lighting designers are also expected to select fittings that are in accordance with the architecture of the space. They are also expected to create dynamic environments with different lighting effects, changes of colours through time, dimming options, according to end user requirements and preferences. Dynamic environments are generated by controlling the colours and intensity of RGB LEDs, through lighting protocols such as the DMX-512 which is traditionally used in the entertainment lighting industry. Finally, lighting designers are expected to educate end users in regard to the capabilities of RGB LED systems; to show them all possible lighting effects and lighting scenarios; to set different lighting scenes; and to provide ease of control.

Table 7.6below summarizes the information on RGB LEDs that should be available as per section 5.1 and 5.2 in relation to the information that is actually currently available as per the market research of Chapter 6:

- ✓ Available
- × Not available
- ⊗ Non available from the majority of manufacturers

Data Availability by the different groups in the LED Supply Chain			
RGB applications	Module manufacturers to luminaire manufacturers	Luminaire manufacturers to lighting designers	Lighting designers to end users
Lumen Output	⊗	⊗	⊗
Lumen Maintenance	⊗	⊗	⊗
Photometry	⊗	⊗	⊗
Photometric data	×	×	×
Stability	×	×	×
Colour bins at full power	×	×	×
Colour stability	×	×	×
Operating Conditions	✓	✓	✓
Beams	✓	✓	✓
Power Consumption	✓	✓	✓
Operating voltage	✓	✓	✓
Drivers	✓	✓	✓
Heat sinks	✓	✓	✓
Tj	✓	✓	✓
Optics	✓	✓	✓
Lifetime (LB)	⊗	⊗	⊗
Cost	✓	✓	✓
Controls/ scenes/ chasers	✓	✓	✓

Table 7.6: Data availability in the LED Supply Chain for RGB applications

7.16. Conclusions

The initial survey of Chapter 5 identified three major applications in the leisure industry: applications that require white light; applications that require monochromatic light (other than white); and applications that require RGB light. The initial survey also specified the key lighting parameters and the product information that is needed to support each application (see also section 1.5).

The analysis (see 7.15) implies that the more information one group has, the more information it distributes to the rest of the groups of the LED Supply Chain. Information request has to do mainly with the photometry and colorimetry of

LED products, as illustrated in Figure 7.5. The market research (see Annexes 7, 8, 9) reveals that reputable manufacturers using LED modules of advanced manufacturing techniques provide consistent and reliable data on the photometry and colorimetry of their products. They also provide information on the lifetime and lumen maintenance, in accordance to published standards.

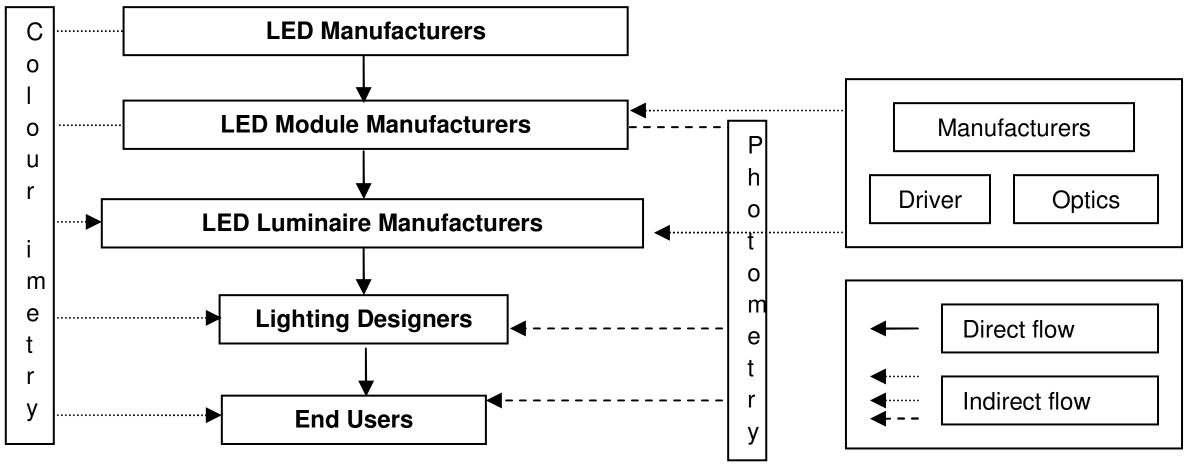

Figure 7.5: Data on photometry and colorimetry required by the main players

Figure 7.5also demonstrates that the major players of the LED supply chain should keep up with developments associated to drivers, optics, heat sinks and other parts related to LED products. At a US Department of Environment industry event [58] looking at LED fixture reliability, interesting data [59] was presented in regard to the failures of a family of outdoor luminaires after a specified period of operation. The total number of failures was 29 out of 5400 outdoor luminaires. The driver (power supply) caused 52% of the failures, a further 31% associated with the luminaire housing and 7% with the driver controls, leaving just 10% associated with the LED chip or module itself.

[58] http://www.mondoarc.com/technology/LED/1008147/1000lm_led_module_bench_test.html 1/11/13

[59] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdfAppalachian Lighting Systems (Ellwood City, PA) 23/11/13

The above suggests that when lighting designers and end users select LED luminaires, they should take into consideration the fact that other parts such as drivers will probably fail first, before the LEDs. In addition to that, and when it comes to the warrantee of LED fittings, lighting designers should also keep in mind that LED technology progresses so rapidly, that the products available today, will probably be old fashioned soon and no longer available. Thus, it will be hard to find spare parts due to the fact that technological developments will be immense.

To conclude, a variety of issues need to be taken into consideration when designing with LEDs and when selecting fittings for architectural lighting applications in the leisure industry, including photometry, colorimety, parts failure rates, and future availability.

Chapter Eight

Completed by April 2014

Conclusions

Chapter Eight discusses the current state and future of LED technology. It also summarizes the information that lighting designers require from other groups in the LED Supply Chain. In turn, it discusses the implications of data availability, and it provides guidelines on how to design with LEDs. Finally, Chapter Eight discusses the limitations of this present research, and depicts areas of future research in relation to LED technology.

8.1. LED Technology

LED Technology has rapidly evolved over the last years. By the end of 2013, a great number of LED modules have become available in the market with high lumen outputs of around 4000lm; high lumen efficacies of 65lm/W for 1000lm LED modules; high CRI of Ra 95+; colour consistency between different production batches of the same manufacturer; constant CCTs over time; long lifetime and lumen maintenance of L70B50. Also, reputable manufacturers have been using the definitions and measuring methods published in standards.

The great availability of technologically advanced modules demonstrates[1] that the market is still embryonic and that companies are still investigating what methods and technologies will provide the best overall performance, production yield, and costs. Yet, the LED modules offered from different manufacturers are not interchangeable. Consequently, luminaire manufacturers need to select which modules to invest in, or alternatively, to develop different series of products with different LED modules.

At the same time, industry initiatives are working on the development of interface specifications that allow LED light sources from different manufacturers to be used interchangeably, without changing the luminaire design. Therefore, in the near future, we could see more luminaires that can adopt the performance upgrades that LED technology brings, enabling users to always have the optimum energy efficient solution in their installation.

But, LED modules are only a part of the luminaire. Luminaire manufacturers have to also take into consideration power supplies, drivers, operating power, heat sinks, optics and lenses, reflectors and diffusers. Power management, thermal management, and optic management are also essential in the development of LED luminaires. The better these issues are studied, the better products will become available in the market.

In any case, solid-state lighting[2] has not yet come close to achieving its full potential. On the contrary, it still has a lot to offer. In fact, it is estimated[3] that switching to LED lighting over the next two decades could save the USA $250 billion in energy costs over that period, reduce the electricity consumption for

[1] http://www.mondoarc.com/technology/LED/1008147/1000lm_led_module_bench_test.html 1/11/13
[2] http://www1.eere.energy.gov/buildings/ssl/sslbasics_randd.html 29/11/13
[3] http://www1.eere.energy.gov/buildings/ssl/sslbasics_whyssl.html#ft_1 29/11/13

lighting by nearly one half, and avoid 1,800 million metric tons of carbon emission. This suggests that a lot of work remains to be done to further improve performance of LEDs and relevant components.

8.2. Lighting Design &Data Availability

The initial survey revealed that lighting designers with a lot of knowledge on LEDs need information on the white colour, including Correlated Colour Temperature (CCT), colour range stability, white colour availability, and Colour Rendering Index (CRI). Over the years, standards have been published to define issues related to colour. The market research revealed that reputable manufacturers have been investing in developing white LEDs with stable CCTs and high CRI. Reputable manufacturers have also been investing in ensuring colour stability over the life of their modules, and between LEDs of different production batches.

Likewise, lighting designers are interested in the lumen output and photometry, lifetime and lumen maintenance of LED products. The standards and methods that have been published are being used by reputable manufacturers with advanced production techniques to claim consistent lumen outputs, photometric data, high lumen efficacies, long lifetime, and lumen maintenance.

Lighting designers with high knowledge on LEDs are interested in colour availability, but they are not very interested in RGB LEDs, mainly because the trend in architectural lighting applications is to use more of white rather than colours. Yet, lighting designers are interested in learning about the control capabilities and control systems of RGB LEDs. The market research revealed that the requested information on RGB LEDs becomes available to lighting designers. In addition, information on luminaire design, power consumption and cost of fixtures is available in the LED Supply Chain, because this information is also important to lighting designers and end users.

To sum up, the research reveals that, over the years, committees and organizations have published standards and methods on issues that are of interest to the lighting community. At the same time, the research shows that manufacturers have been researching on the colorimetry and photometry of LEDs, providing stable products with advanced characteristics.

8.3. Lighting Design Implications

Lighting designers meet the lighting objectives of the leisure industry, by using the wide range of LED products that are available in the market. Actually, lighting design schemes often generate the need of developing and producing new LED products that best meet the project requirements.

To begin with, LEDs attract attention from a distance. Take for example the building facades, as indicated in Picture 8.1.In such lighting designs, it is very important to take into consideration light pollution.

Picture 8.1: Intercontinental & Crown Plaza Hotels, Dubai, UAE[4]

[4] http://www.colorkinetics.com/showcase/installs/Intercontinental-Hotel-Dubai 18/1/2014

LEDs guide visitors to the building and to certain points, as illustrated inPicture 8.2.

Picture 8.2: Hotel Diplomat[5], Stockholm, Sweden

LEDs help make a good first impression, as illustrated inPicture 8.3.

Picture 8.3: Alma Hotel, London, UK[6]

[5]http://www.acdclighting.co.uk/projects/hotel-diplomat-sweden/#.UthTfttXvVQ 18/1/14
[6]www.alphaled.co.uk 18/1/14

LEDs create the appropriate ambience, as illustrated in Picture 8.4.

Picture 8.4: Private Residences, Crete, Greece[7]

LEDs reinforce the emotions of building users, as illustrated in Picture 8.5.

Picture 8.5: Starbucks, Dresden, Berlin[8]

[7]www.electron.gr 18/1/14
[8]http://www.erco.com/projects/hospitality/starbucks-at-the-altmarkt-4999/en_us Photographer Edgar Zipper, Berlin, 18/1/14

LEDs create distinct changes in atmosphere and mood to suit the different occasions, as illustrated in Picture 8.6.

Picture 8.6: Hotel Albuquerque, New Mexico, USA[9]

LEDs generate visual comfort and visual interest, as illustrated in Picture 8.7.

Picture 8.7: Morimoto Restaurant, Philadelphia, Pennsylvania USA[10]

[9]http://www.colorkinetics.com/showcase/installs/Hotel-Albuquerque 18/1/14
[10]http://www.colorkinetics.com/showcase/installs/morimoto 18/1/14

LEDs are integrated and in balance with the architecture and interior decoration, as illustrated in Picture 8.8.

Picture 8.8: Park Hotel, Athens, Greece[11]

LEDs create a consistent and unite whole, as illustrated in Picture 8.9.

Picture 8.9: Ernst- August- Carree, Brasserie Bruxelles, Hanover[12]

[11] www.electron.gr 18/1/14
[12] http://www.erco.com/projects/hospitality/ernst-august-carree-brasserie-bruxelles-1290/en_us photographer Frieder Blickle, Hamburg, 18/1/14

LEDs provide good visual conditions for building users, as illustrated in Picture 8.10.

Picture 8.10: Hansel Bakery, Barcelona, Spain[13]

LEDs provide security and personal safety, as illustrated in Picture 8.11.

Picture 8.11: Expasa Gozaisho Restaurant, Yokkaichi city, Mie Japan[14]

[13] www.alphaled.co.uk 18/1/14
[14] www.yamagiwa.co.jp 18/1/14

LEDs establish a sustainable environment, as illustrated in Picture 8.12.

Picture 8.12: Fardig Betong, Konferenscenter, Sweden[15]

LEDs offer more than just lighting, as illustrated in Picture 8.13.

Picture 8.13: Light rails- an artistic light installation, Birmingham, Alabama, USA[16]

[15]http://www.erco.com/projects/hospitality/faerdig-betong-konferenscenter-5048/en_us
Photographer Tomas Södergren, Morrum 18/1/14
[16]http://www.colorkinetics.com/showcase/installs/LightRails 18/1/14

To sum up, lighting designers have a very interesting tool- LED technology- at their disposal in order to achieve the lighting objectives of the leisure industry. Not only that, but this tool also allows them to make unique lighting designs, create impressive lighting schemes, generate energy efficient installations and green environments, offer controllable ambiences, and present new products in the market.

8.4. Re-inventing Lighting design with LEDs

Lighting design with LEDs, as in the case of any light source, should aim at enabling performance of visual tasks. Given that, the quantity of light is important, and depends on the function of the space, the users, and the interaction between the users and the space[17]. The provision of illumination could be assessed in terms of illuminance values measured on the 'visual task plane', which is actually the horizontal work plane[18].

At the same time, lighting design with LEDs should also consider 'quality of light'. It is a fact that there is no general agreement on what exactly 'Lighting quality' is. Actually, lighting quality may be the most talked about, but least understood concept in lighting research and lighting design[19]. In general terms, however, lighting quality is a term used to describe all the factors in a lighting installation not directly connected with the quantity of illumination[20]. Parameters that contribute to the quality of lighting include[21]glare, flicker rate, illumination uniformity, and luminance distributions.

To begin with, great attention should be placed on glare, because this can be a serious problem to the users of a space. To be more specific, since LEDs are mainly point sources, they could cause discomfort glare when looking at the source, resulting in an instinctive desire to look away from the bright LED source

[17] T.M. Chung John Burnett, Lighting Quality Surveys in Office Premises, Indoor+ Built Environment, 2009; 9: p.335-341, Dec 17, 2000
[18] Cuttle C, 'A new direction for general lighting practice, Lighting Research and Technology 45: 22,2013
[19] Veitch JA, Newsham GR: Determinants of lighting quality. I: State of the science. J IES1998; 27: p. 92-106, 1998
[20] Stein B, Reynolds JS: Mechanical and Electrical Equipment for Buildings, ed. 8, New York, Wiley, p. 940, 1992
[21]T.M. Chung John Burnett, Lighting Quality Surveys in Office Premises, Indoor+ Built Environment, 2009; 9:335-341, Dec 17, 2000

or difficulty in seeing a task[22]. Similarly, LEDs could cause disability glare impairing the vision of the task as compared to its surrounding even without necessarily causing discomfort. Measurements of glare in LED installations could be realized using the Unified Glare Rating (UGR[23]) system which considers luminance levels and evaluates and limits the psychological direct glare from luminaires.

Accordingly, it is important to take into consideration the exposure to flicker by LEDs. The reason behind that is that flicker[24] is known that can cause (in particular at frequencies between 3 Hz and 55 Hz) photo- sensitive epileptic seizures in various forms depending on the individual and his visual pathology, the contrast, the wavelength and the viewing angle or distance. Research[25] has shown that LEDs under mains voltage manifest the most extreme cases of flicker and that in pulsing mode the overall impression is of higher brightness which is an opportunity for energy savings. The results also show that flicker is not visually perceptible especially with a white background. In an effort to limit flicker, LED fittings should use LED power supplies, converters, and dimmers without flicker[26].

Uniformity[27] of lighting in the leisure industry is not as important as in other lighting applications such as office lighting. On the contrary, it is most usual to achieve emphasis by concentrating light on areas of particular interest, such as the bar in a restaurant or the reception in a hotel.

Luminance distributions are quite important in the leisure industry. On the one hand, it is important to illuminate properly limited areas such as the tables on a coffee shop. On the other hand, it is also important to illuminate each area carefully so that the eye is led smoothly from one area of emphasis to another[28], in order to properly achieve order and coherence.

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[22] "CIE e-ILV: 17-330 disability glare" 18/1/14
[23] http://div3.cie.co.at/?i_ca_id=575&pubid=110CIE in publication 117 4/12/13
[24] http://en.wikipedia.org/wiki/Photosensitive_epilepsy 4/12/13
[25] http://www.scirp.org/journal/opjKitsinelis S, Arexis-Boisson L, Zhang Yuan, Zissis Georges, 'LED Flicker: a drawback or an opportunity?', Optics and Photonics Journal, 2013, 3, 63-66 doi:10.4236/opj.2013.31010 Published Online March 2013
[26] http://www.electron.gr/en/products.html?app=catalog&task=category&id=586 18/1/14
[27] Peter Jay and Partners, 'Review: Subjective criteria for lighting design', Lighting Res. Technol. 34,2, p. 87–99, 2002
[28] Peter Jay and Partners, 'Review: Subjective criteria for lighting design', Lighting Res. Technol. 34,2, p. 87–99, 2002

In addition to the above, lighting quality is also affected by many other non-photometric factors such as the room surfaces, the colour of the room, the layout of the furniture, and how the space is used. In fact, in the leisure industry the surroundings[29] are often of low reflectance, room surfaces have colours, while specific objects are well lit compared to the generally low illumination levels, creating visual interest.

Finally, lighting quality has to do with improved levels of visual comfort and satisfaction of the users in the space. In relation to visual comfort, important considerations[30] are the dimming linearity, dimming stability, and strobe effect of LED drivers. In relation to the satisfaction of users, important considerations are to educate the users on the LED installation and explain the control capabilities.

To sum up, there is not a widely accepted lighting quality index that takes into consideration all of the above parameters, thus it is difficult to evaluate if a light installation is a quality lighting installation or not. However, when realizing lighting designs with LEDs, it is very important to take under consideration all the above mentioned issues.

8.5. Guidelines on lighting design with LEDs

Quantitative measurements, such as lumen output and lumen efficacy, as well as lifetime and lumen maintenance are all important issues to consider when designing with LEDs. In relation to that, the appropriate levels of lighting must be achieved in order to be able to perform the task, whether that is to guide the guest, to work on the lobby, to eat in a restaurant, to attract attention from a distance, to create points of visual interest, and so on. In addition, it is important to consider factors such as Correlated Colour Temperature, Colour Render Index, and colour stability.

At the same time, however, lighting design with LEDs should go beyond that. Lighting design with LEDs should create glare free and flicker free environments, with the appropriate luminance distributions and points of visual

[29]Cuttle C, 'A new direction for general lighting practice, Lighting Research and Technology 45: p. 22, 2013

[30] Jieqiong Song, Liqing Tong, Minhua Qian, Yaojie Sun and Yandan Li, Comprehensive Evaluation System for LED Driver Concerned of Visual Comfort, Research Journal of Applied Sciences, Engineering and Technology 6(6): 943-949, 2013

interest. It should provide environments of visual comfort and satisfaction to end users.

Given the above, the following guidelines shall be taken into consideration when designing with LEDs:

- ***Lighting Design Considerations:***
- ✓ Quantity of light
  - Lumen output
  - Lumen efficacy
  - Lumen maintenance
  - Lifetime
  - Photometric data
- ✓ Quality of light
  - Colour consistency amongst LEDs and over time
  - CCT and CRI
  - Glare
  - Flicker
  - Uniformity vs points of visual interest
  - Luminance distributions
  - Other non- photometric factors
- ✓ Visual comfort and satisfaction
- ✓ Energy efficiency and power consumption
  - Sustainability
  - Cost and energy savings
- ✓ Obtrusive light

- ***LED luminaire selection criteria:***
- ✓ Consider appropriate product based on the project requirements
- ✓ Think of product reliability
- ✓ Take into consideration all product components, not just the LED
- ✓ Think of warranty and future spare part availability
- ✓ Select manufacturers that you trust
- ✓ Design new LED fitting to meet your requirements when possible

- ✓ Show other installations with similar products to make the client understand the effect and product capabilities
- ✓ Request from manufacturers the data you need (photometric, colorimetric)
- ✓ Think of control capabilities

- ➢ ***Lighting Design Implications with LEDs:***
- ✓ Keep up with latest developments
- ✓ Respect your application and do lighting for effect to achieve aesthetics or lighting for the task to achieve required lumens for the task
- ✓ Combine your background with your imagination (i.e. bring your background in entertainment lighting into architectural lighting designs)
- ✓ Feel free to design: LED capabilities are immense
- ✓ Educate end users

- ➢ ***Advice on Data availability and Standards:***
- ✓ Demand the information you need from others in the LED Supply Chain
- ✓ Encourage the development of standards against which to compare lighting products
- ✓ Support the development of guidelines on photometric and colorimetric systems

- ➢ ***General considerations:***
- ✓ Participate in future research on LEDs

8.6. Limitations and Recommendations

This research discussed the use of LED technology in the leisure industry. It identified the implications of the adoption of LEDs. It discussed key issues of

LED technology and revealed important considerations that need to be taken into account when designing with LEDs. Also, the present research analyzed the information that is needed and the information that is provided by the major players of the LED Supply Chain.

This research is of interest to lighting designers who use LED technology in their designs. It is also of interest to manufacturers who invest in developing new LED products and who are interested in providing the data that different groups of the LED supply chain require. Furthermore, it shall be of interest to end users and others who want to familiarize themselves with LED technology.

It is acknowledged that the present thesis deals with a very rapidly changing technology. Therefore, by the time the thesis comes to its end, there are probably going to be even more developments and improvements in the technology of LEDs. This suggests that the findings of this research must be handled with care and in relation to the technology and product availability at the end of 2013.

Similarly, since LED technology[31] is still in its early stages, requirements for measuring conditions and appropriate measurement techniques may be subject to change at any time as the SSL technologies advance. Therefore, standards on LEDs need to be constantly reviewed and updated. Standards allow comparisons of LED products between them, as well as with conventional sources. Only with accurate and updated standards will there be reliable information available within the LED Supply Chain. And only then will LED technology be further trusted and adopted.

At the same time, research should take place in regard to the quality of light in LED applications, and especially in the 100% LED lighting installations which become more popular over the years. Research needs to relate to issues such as glare, flicker, uniformity, luminance distributions, visual comfort and satisfaction of LED installations. Studying the quality of light is of particular interest not only for the leisure industry, but also for other application areas such

[31] LM79-2008: IESNA approved method for the electrical and photometric measurements of solid state lighting products

as office lighting, retail lighting, hospital lighting, where LEDs are being used as retrofits.

Furthermore, LED is a new and fast emerging technology with wide use and immense capabilities, but not much research has been made in relation to humans. In particular, research has to examine the effects of LEDs on human health and human behavior. For instance, research should focus on the effects of blue light emitted from LEDs in the circadian rhythm. Such a research, in combination to the fact that LEDs are controllable, could mean that in the future, by tuning the emitted light of white LEDs, the circadian rhythm can be affected, thus the productivity of employees could be controlled in an office environment. Similarly, it has been suggested [32] that light therapy can be an effective treatment of mood disorders, suggesting that light is able to affect mood in the long term. Therefore, the effects of LED technology on mood disorders could also be studied.

To conclude, the lighting community needs to further study the quantity and quality of LED light in various lighting design installations; it has to develop guidelines for data availability based on the requirements of the major players of the LED Supply Chain; it needs to update standards against which to evaluate and compare LEDs; and it should research on the effects of LED technology on human behavior and human health. Since LED technology is a fast growing technology that will be further adopted in the future, research on the field by the lighting community must be prompt and constant, starting from now in order to catch up with the latest developments!

[32] Spectral quality of light modulates emotional brain responses in humans, Vandewalle, G ; et all, Proceedings of the National Academy of Sciences of the United States of America, Vol.107 (45), p.19549-54, Peer Reviewed Journal, 2010

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Annex1

Pilot Questionnaire

Annex 1 presents the cover letter and first questionnaire that was used as a pilot study. The purpose was to receive comments not only on the questions posed on LED technology and lighting design in the leisure industry, but to also check the validity of the questions.

Lighting Design and LED Technology

Dear Lighting Designer,

I am an MPhil/ PhD student at University College London (UCL), carrying out a survey on Lighting Design and the use of LED Technology.

In the purposes of this study, please find attached a Questionnaire that you are kindly requested to answer. Your replies will be kept anonymous. Completed questionnaires will be treated with the strictest confidentiality.

The questionnaire should take about fifteen minutes to complete. Please answer questions in the space provided, or circle the appropriate answer, or put an **x** in the appropriate scale.

Once you have completed the questionnaire, please return it by email at p.hatziefstratiou@ucl.ac.uknot later than October 28th 2008.

Thank you for your assistance and cooperation.

Best Regards,

Penny Hatziefstratiou
MPhil/ PhD Student
UCL

General Questions

1. What kind of projects do you handle as a lighting designer?

___

___

___

2. In which countries or areas have you worked?

___

LED Technology

3. Do you use LED technology, and if yes in which kinds of applications?

___

___

___

4. What do you think of the use of LEDs in today's environment?

___

___

___

5. What do you think is the future of LED technology?

___

___

___

6. How literate are different groups of people in terms of LEDs?
Please complete the table by putting an **x** in the appropriate box.

Group of people / Knowledge	Little	Moderate	A lot
Lighting Designers			
Architects			
Electrical engineers			
Contractors			
End users			
Others (please specify)			

7. How do you learn about the available LEDs, LED luminaires, and the latest LED developments?

___

___

___

8. What are the major criteria when selecting aLED Luminaire?

____

____

____

9. What are the major criteria when selecting a LED luminairemanufacturer?

____

____

____

10. What kind of information do you require from LED Manufacturers and how much do you value this information? Please complete the table by putting an **x** in the appropriate box.

Information / Value	Very low	Low	Moderate	High	Very High
Colour availability					
Lumen					
Colour consistency					
Lumen maintenance					
Stability					
Control capabilities					
Lifetime of LEDs					
RGB colour mixing					
White colour					
CCT					
CRI					
LED luminaire design					
Cost					
Other (please compete)					

Lighting Design

11. Please describe *your* lighting design process.

____

____

____

12. How do you value the cooperation of the lighting designer with others?

Group of people/ Cooperation	Low	Moderate	High
Architect			
Electrical engineer			
Owners			
Luminaire manufacturers			
Quests			
Others (please specify)			

Lighting Design in the Leisure Industry

13. If the leisure industry is defined as hotels, bars and restaurants, what are the objectives of lighting in the leisure industry?

____

____

____

14. What important issues should be considered when generating lighting design schemes in the leisure industry?

____

____

____

15. What are the End User requirements and expectations in the leisure industry in terms of lighting and lighting design?

____

____

____

16. According to your personal view, please refer to some good lighting design schemes in the leisure industry.

____

____

____

LED Technology in the Leisure Industry

17. Do you use LEDs in lighting designs in the leisure industry? Please circle the appropriate box.

Yes	Sometimes	No

   a. If no, what kind of lamps do you usually use in different applications? Please provide examples.

____

____

____

   b. If yes or sometimes, in which kinds of applications do you use LEDs?

____

____

____

c. If yes or sometimes, what kind of LEDs do you use for various applications?

____

____

____

18. In general, what are the capabilities offered by LEDs in the leisure industry?

____

____

____

19. Do you use RGB LEDs? Where and why?

____

____

____

20. Do you use White Colour LEDs? Where and why?

____

____

____

21. How do you take decisions on which LEDs to use?

____

____

____

22. How confident do you feel about using LED Technology in your designs and why?

____

____

____

23. What important consideration should be taken into account when using LEDs in the leisure industry in the following applications?

a. White colour

____

b. RGB

____

c. Single colour

____

24. What lighting goals should be achieved when using LEDs in the following applications?

    a. White colour

    ____

    b. RGB

    ____

    c. Single colour

    ____

25. According to your personal view, please refer to some good LED lighting design schemes in the leisure industry.

    ____

    ____

    ____

Please indicate about yourself (please circle as appropriate):

Sex	Male	Female	
Age	18-30	31-45	46 or above

What is your background?

____

Please write your name if you like (but not necessarily).

____

THANK YOU FOR TAKING THE TIME TO COMPLETE THIS QUESTIONNAIRE

Annex 2

Initial Survey- Questionnaire

Annex 2 presents the cover letter and the questionnaire that was distributed to lighting designers and other users, in order to perform the initial survey on lighting design and LED technology.

Letter

Dear Lighting Designer,

I am a PhD student at University College London (UCL), carrying out a survey on Lighting Design in the Leisure Industry and the use of LED Technology.

In the purposes of this study, please find attached a Questionnaire that you are kindly requested to answer. Your replies will be kept anonymous. Completed questionnaires will be treated with the strictest confidentiality.

The questionnaire should take about 10 minutes to complete. Please answer questions in the space provided, or put an **x** in the appropriate scale.

Once you have completed the questionnaire, please return it by email at p.hatziefstratiou@ucl.ac.uk the soonest possible.

You are more than welcome to forward this Questionnaire to other lighting designers that you think could be interested in participating in this survey.

Thank you for your assistance and cooperation.

Best Regards,

Panagiota (Penny) Hatziefstratiou
PhD Student
UCL

Lighting Design and LED Technology

LED Technology

1. Do you use LED technology and if yes in which kinds of applications?

2. What do you think of the use of LEDs in today's environment?

3. What do you think is the future of LED technology?

4. How literate do you think are different groups of people in regard to LEDs? Please complete the table by putting an **x** in the appropriate box.

Group of people / Knowledge	Little	Moderate	A lot
Lighting Designers	( )1	( )2	( )3
Architects	( )1	( )2	( )3
Decorators	( )1	( )2	( )3
Electrical Engineers	( )1	( )2	( )3
Contractors	( )1	( )2	( )3
End Users	( )1	( )2	( )3
Other (please specify:)	( )1	( )2	( )3

5. How do you learn about the available LEDs, LED Luminaires and the latest LED developments?

6. What are the major criteria when selecting a LED luminaire?

7. What are the major criteria when selecting a LED luminaire manufacturer?

8. What kind of information do you require from LED Manufacturers and how much do you value this information? Please complete the table by putting an **x** in the appropriate box.

Information/ Value	Very Low	Low	Moderate	High	Very High
Colour range (colour availability)	( )1	( ) 2	( )3	( )4	( )5
Lumen output	( )1	( ) 2	( )3	( )4	( )5
Colour consistency	( )1	( ) 2	( )3	( )4	( )5
Lumen maintenance	( )1	( ) 2	( )3	( )4	( )5
Stability	( )1	( ) 2	( )3	( )4	( )5
Control capabilities	( )1	( ) 2	( )3	( )4	( )5
Lifetime of LEDs	( )1	( ) 2	( )3	( )4	( )5
RGB colour mixing	( )1	( ) 2	( )3	( )4	( )5
White colour availability	( )1	( ) 2	( )3	( )4	( )5
Correlated Colour Temperature (CCT)	( )1	( ) 2	( )3	( )4	( )5
Colour Render Index (CRI)	( )1	( ) 2	( )3	( )4	( )5
LED luminaire design	( )1	( ) 2	( )3	( )4	( )5
Cost	( )1	( ) 2	( )3	( )4	( )5
Power of LEDs	( )1	( ) 2	( )3	( )4	( )5
Other (please specify:)	( )1	( ) 2	( )3	( )4	( )5

Lighting Design in the Leisure Industry

9. If the leisure industry is defined as hotels, bars and restaurants, what are the objectives of lighting in the leisure industry?

10. What important issues should be considered when generating lighting design schemes in the leisure industry?

11. What are the End User requirements and expectations in the leisure industry in terms of lighting and lighting design?

12. According to your personal view, please refer to some good lighting design schemes in the leisure industry.

LED Technology in the Leisure Industry

13. Do you use LEDs in lighting designs in the leisure industry?

( )1 No
( )2 Frequently (*Please skip to Question 13.3*)
( )3 Yes(*Please skip to Question 13.3*)

13.1 If No, what kind of lamps do you usually use in different applications?

13.2 If No, what are the limitations that make you not use LEDs? (*Please skip to Question 23*)

13.3 If yes or frequently, in which kinds of applications do you use LEDs?

13.4 If yes or frequently, do you use RGB LEDs? In which applications and for what reasons?

13.5 If yes or frequently, do you use white LEDs? In which applications and for what reasons?

13.6 If yes or frequently, do you use single coloured LEDs? In which applications and for what reasons?

14. What kind of LED products do you use? (select with an **x** all that apply)

( )1 LED Wall Washers	( )2 LED Spotlights
( )3 LED Lamps	( )4 Flexible LEDs
( )5 High power LEDs	( )6 Low power LEDs
( )7 Decorative LEDs	( )8 Downlights with LEDs
( )9 LED Parcans& Moving Heads	( )10 Linear LEDs
( )11 LED Displays	( )12 IP protected LEDs
( )13 Control Systems for LEDs	( )14 Other (please specify:)

15. In which applications do you use LEDs? (select with an **x** all that apply)

( )1 Exterior lighting	( )2Interior lighting
( )3 General illumination	( )4Accent lighting
( )5 Concealed lighting	( )6 Decoration lighting
( )7 Illumination of special constructions	( )8Highlighting
( )9 Backlighting	( )10Indication lighting
( )11Illumination of epigrams	( )12Special effects
( )13Emergency lighting	( )14Other (please specify:)

16. What capabilities are offered by LEDs?

17. What are the limitations of LEDs today?

18. What are the barriers for the further adoption of LEDs?

19. How do you take decisions on which LEDs to use?

20. How confident do you feel about using LED Technology in your designs and why?

21. What important considerations should be taken into account when using LEDs in the leisure industry in the following applications?

21.1 White colour?

21.2 RGB colour?

21.3 Single colour?

22. What lighting goals should be achieved when using LEDs in the following applications?

22.1 White colour?

22.2 RGB colour?

22.3 Single colour?

23. According to your personal view, please refer to some good LED lighting design schemes in the leisure industry?

General Questions

24. What kind of projects do you handle?

25. In which countries or areas have you worked?

26. Please select your gender.

( )$_1$ Male ( )$_2$ Female

27. Please select your age group.

( )$_1$ 18-30 ( )$_2$ 31-45 ( )$_2$ 46 or above

28. Please write in your background.

29. Please indicate your job title (Please select with an **x**one).

( )$_1$ Independent Lighting Designer
( )$_2$ Lighting Designer in a Lighting Manufacturer
( )$_3$ Architect
( )$_4$Decorator
( )$_5$ Electrical Engineer
( )$_6$ Student
( )$_7$Employee in lighting company
( )$_8$ Other (please specify:)

30. Please write in your name if you like (but not necessarily).

31. Please write in the name of your office/ company and your email (but not necessarily).

Thank you for taking the time to complete this questionnaire and for participating in this survey.
Please send completed questionnaires to p.hatziefstratiou@ucl.ac.uk

Annex 3

Form in Access

A Form was developed in Access, in order to include the replies of all participants. Annex 3 shows an example of the Form, by presenting the replies of one participant.

Record No.: 1

Q1: Interior and exterior

Do you use LED technology and if yes in which kinds of applications?

Q2: They have their place, certain applications are good, but it's still the wild west

What do you think of the use of LEDs in today's environment?

Q3: I think when the dust settles, there will be some good products and applications to use them

What do you think is the future of LED technology?

Q4: How literate do you think are different groups of people in regard to LEDs?

Lighting Designers

- ○ Little
- ○ Moderate
- ● A Lot

Architects

- ○ Little
- ● Moderate
- ○ A Lot

Decorators

- ● Little
- ○ Moderate
- ○ A Lot

Electrical Enginnee

- ○ Little
- ● Moderate
- ○ A Lot

Contractors

(•) Little ( ) Moderate ( ) A Lot

End Users

(•) Little ( ) Moderate ( ) A Lot

Q5: DOE, manufacturers, Reps

How do you learn about the available LEDs, LED Luminaires and the latest LED developments?

Q6: Color, Color match, Binning, Warranty (must be 5+ years), quality of a manufacturer (they'll follow through if there are problems), heat dissipation

What are the major criteria when selecting a LED luminaire?

Q7: That we have a good rep, a 5+ yr. warranty and a lighting manufactuer that is well established so that they will take care of problems,components,driver

What are the major criteria when selecting a LED luminaire manufacturer?

Q8: ☐What kind of information do you require from LED Manufacturers and how much do you value this information?

Colour Range

( ) Very Low ( ) Low ( ) Moderate ( ) High (•) Very High

RGB Colour Mixing

( ) Very Low ( ) Low (•) Moderate ( ) High ( ) Very High

Lumen Output

( ) Very Low ( ) Low ( ) Moderate (•) High ( ) Very High

White colour Availability

( ) Very Low ( ) Low ( ) Moderate ( ) High (•) Very High

Colour Consistency

( ) Very Low ( ) Low ( ) Moderate ( ) High (•) Very High

CCT

( ) Very Low ( ) Low ( ) Moderate ( ) High (•) Very High

Criterion	Very Low	Low	Moderate	High	Very High
Lumen Maintenance	○	○	○	●	○
CRI	○	○	○	○	●
Stability	○	○	○	●	○
Luminaire Design	○	○	○	●	○
Control Capabilities	○	○	○	●	○
Cost	○	○	●	○	○
Lifetime	○	○	●	○	○
Power of LEDs	○	○	●	○	○

Q9: Dimmability, sparkle, contrast,

If the leisure industry is defined as hotels, bars and restaurants, what are the objectives of lighting in the leisure industry?

Q10: Try not to make it look too boring

What important issues should be considered when generating lighting design schemes in the leisure industry?

Q11: Low maintenance, low energy, dramatic tendencies

What are the End User requirements and expectations in the leisure industry in terms of lighting and lighting design?

Q12: -

According to your personal view, please refer to some good lighting design schemes in the leisure industry.

Q13: ☐☐Do you use LEDs in lighting designs in the leisure industry?

LED use: ○ No ○ Frequently ● Yes

Q13.1: -

☐If No, what kind of lamps do you usually use in different applications?

Q13.2: -

☐☐If No, what are the limitations that make you not use LEDs?

Q13.3:	Up lights, wall grazing, path lights, marker lights	□□□If yes or frequently, in which kin applications do you use LEDs?
Q13.4:	Sometimes – bar / restaurants, cinema	□□If yes or frequently, do you use RGB LEDs? Ir which applications and for what reasons?
Q13.5:	When ever possible for low maintenance and energy	□□□If yes or frequently, do you use white LEDs? In wh applications and for what reasons?
Q13.6:	no	□□□□If yes or frequently, do you use single coloured LI which applications and for what reasons?

Q14: ☐What kind of LED products do you use?

- (●) LED Wall Washers
- (●) LED Spotlights
- ( ) LED Lamps
- (●) Flexible LEDs
- (●) High Power LEDs
- ( ) Low Power LEDs
- ( ) Decorative LEDs
- ( ) Downlights with LEDs
- ( ) LED Parcans, Moving Heads
- (●) Linear LEDs
- (●) LED displays
- (●) IP LEDs
- (●) Control Systems

Q15: ☐☐In which applications do you use LEDs?

- (●) Exterior lighting
- (●) Interior lighting
- (●) General lighting
- (●) Accent lighting
- (●) Concealed lighting
- (●) Decoration lighting
- ( ) Special construction lighting
- (●) Highliting
- (●) Backlighting
- (●) Indication lighting
- ( ) Lighting of epigrams
- (●) Special effects
- ( ) Emergency lighting

Q16:	Narrow beamspreads, long throw, color addative (instead of subtractive), sometimes smaller packaging. Lower maintenance	What capabilities are offered by LEDs?
Q17:	Heat, heat, heat. Driver locations and failures, color shifts in the phospheres, color consistency	What are the limitations of LEDs today?
Q18:	A point source, not an ambient source	What are the barriers for the further adoption of LEDs?
Q19:	Reputable LED manufacturer in an reputable lighting manufacturer's fixture	How do you take decisions on which LEDs to use?
Q20:	Medium. We've had a number of problems from a number of different manufacturers	How confident do you feel about using LED Technology in your designs and why?

Q21: What important considerations should be taken into account when using LEDs in the leisure industry in the following applications?

Q21.1:	Possibly to buy a percentage more than are needed in case of unforeseen damage to maintain the similar look	☐White colour?
Q21.2:	None come to mind	☐☐RGB colour?
Q21.3:	None come to mind	☐☐☐Single colour?

Q22: ☐What lighting goals should be achieved when using LEDs in the following applications?

Q22.1:	It depends on the application	☐White colour?
Q22.2:	It depends on the application	☐☐RGB colour?
Q22.3:	It depends on the application	☐☐☐Single colour?
Q23:	Wall washing either lighting up from a banquet or down a wall. Cove lighting, marker lights for hallways	☐☐According to your personal view, please refer to some good LED ligl design schemes in the leisure industry?
Q24:	Hospitality, Commercial, Retail, Municipal, High-end residential	☐What kind of projects do you handle?
Q25:	US	In which countries or areas have you worked?

Q26: ☐☐Please select your gender

Gender

- ○ Male
- ◉ Female

Q27: ☐☐Please select your age group

Age group

- ○ 18-30
- ◉ 31-45
- ○ 46 or above

Q28:	BFA, degree in interior design, worked for an MEP firm, LD for the past 20 years	Please write in your background.

Annex 4

Replies to Questionnaire in Excel

Annex 4 presents the replies of the participants, which were extracted in an Excel file from the Access form.

The replies to the Questions that were 'open', are partially seen in the excel file. Detailed answers are available on the actual completed Questionnaires of the participants.

The replies to the Questions that required specific answer, should be considered taking in mind the following:

Q14.1- Q14.6:

3 = A lot of knowledge

2 = Moderate knowledge

1 = little knowledge

Q8.1- Q8.14:

5 = Very high importance

4 = High importance

3 = Moderate importance

2 = Low importance

1 = Very low importance

Q13

Q13.1- Q13.2:

3 = Yes

2 = Frequently

1= No

Q14.1- Q14.13:

0 = Yes (use)

-1 = No (do not use)

Q15.1- Q15.13:

0 = Yes (use)

-1 = No (do not use)

Q26:

2 = Female

1 = Male

0 = No answer

Q27:

3 = 46 or above

2 = 31 to 45

1 = 18 to 30

0= No answer

Q29.1- Q29.8:

0 = Yes

-1 = No

The data file is included on the CD that comes together with the printed thesis, under the file name “Appendix 4”. It shows the responses to the Questions of the Questionnaire, with the exception of Question Q30 and Q31, which relate to personal details of the participants and are treated under confidentiality.

Annex 5

Formulas in Excel

Formulas were developed in excel file, in the effort to investigate statistical results from the Questionnaire responses. The data file is included on the CD that comes together with the printed thesis, under the file name “Appendix 5”.

Table A.5.1 shows the statistical figures of the level of importance of lighting parameters depending on level of knowledge, where Reply 5= very high importance, 4= high importance, 3= moderate importance, 2- low importance, 1= very low importance

Designer 3= a lot of knowledge, 2= moderate knowledge, 1= low knowledge

Table A.5.2 shows an example of random perturbation for Q8.8 and Q8.11 to make the scatter diagrams.

Annex 6

Developments in standards

A supplementary research was performed in the end of 2013 in an effort to investigate major developments in regard to standards. The research reported as major developments the Energy Star program and the EU directive on Energy Labeling.

The ENERGY STAR[1] is an Environmental Protection Agency (EPA) voluntary program that helps businesses and individuals save money and protect the climate through superior energy efficiency. The ENERGY STAR label was established to reduce greenhouse gas emissions and other pollutants caused by the inefficient use of energy; and to make it easy for consumers to identify and purchase energy-efficient products that offer savings on energy bills without sacrificing performance, features, and comfort.

In addition to the above, the European Union has recently published the EU 874/2012[2] Regulation which supplements the Directive 2010/30/EU with regard to energy labeling of electrical lamps and luminaires, including LEDs. The Regulation defines how to calculate the energy category of products and gives guidelines on how to present requested data. Examples are shown in the figures below.

Figure A.6.1 shows the label for luminaires containing only non-replaceable LED Modules. Figure A.6.2 shows the label for luminaires containing both non-replaceable LED Modules and sockets for user- replaceable lamps.

[1] http://www.energystar.gov/index.cfm?c=about.ab_index 20/11/13
[2] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0874&qid=1400923575150&from=EN 1/5/14

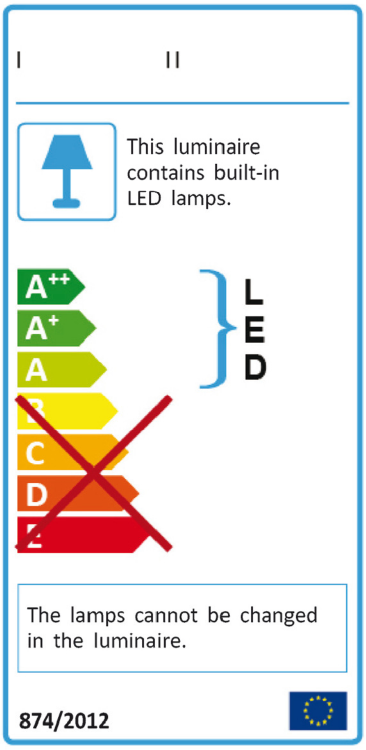

Figure A.6.1: Energy efficiency label for luminaires containing only non-replaceable LED Modules

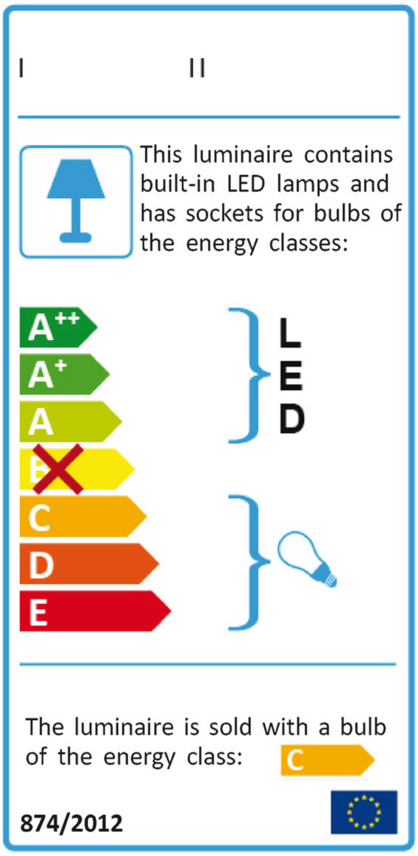

Figure A.6.2: Energy efficiency label for luminaires containing both non-replaceable LED Modules and sockets for user- replaceable lamps

Annex 7

Developments on Photometry and Lifetime

A supplementary market research was performed in the end of 2013, in order to investigate the developments on the photometry and lifetime of LED modules. Table A.7.1 indicatively shows the findings of the market research in terms of lumen output, lumen efficacy, lifetime, and lumen maintenance of LED modules.

	LED Module manufacturers					
Data	Xicato	Philips	Bridgelux	CREE[1]	Sharp	GE
	XSM Standard Series[2]	Fortimo Gen3[34]	ES Series[56]	LMR4	Mini Zinegata[7]	Infusion G3[89]
Lumen range (lm)	400- 3000 Tcase 70ºC	1100-2800	430- 2670 Tcase 70ºC	700-1000	270-1650 Tcase 25 ℃	850-3825
Lumen efficacy (lm/w)	70-95	74-90	71-124 Tj 25ºC	58-62.5	60-105.9	75-106.1
Lifetime Hrs	B50 L70 over 70 % after 50,000 hours	B50 L70 point Tc point of 65° C.	> 70% lumen maintenance after 50,000 hours of operation at or below Tc 85°C	L70 at 35,000 hours	50,000 hours at top performance[10]	L85 at 50,000 hours

Table A.7.1: Information on photometry & lifetime of LED modules, available by reputable manufacturers

[1] http://www.cree.com/led-components-and-modules/products/modules/integrated/lmr4 1/11/13
[2] http://xicato.com/xsm-led-module/specification 10/10/13
[3] http://www.usa.lighting.philips.com/connect/LED_modules/dlm_downlight.wpd 10/10/13
[4] http://www.usa.lighting.philips.com/pwc_li/us_en/connect/LED_modules/assets/LE-6180.pdf 10/10/13
[5] http://www.bridgelux.com/products/ledarray_es.html 10/10/13
[6] http://www.bridgelux.com/assets/files/DS23%20Bridgelux%20ES%20Star%20Array%20Data%20Sheet%20DS23%20120312.pdf 10/10/13
[7] http://www.sharpleds.com/minizenigata.html 10/10/13
[8] http://www.gelighting.com/LightingWeb/na/solutions/highlights/infusion-led-module/overview 10/10/13
[9] http://www.gelighting.com/LightingWeb/na/images/94568-GE-LED-Infusion-Module-Gen3-Sell-Sheet_tcm201-59936.pdf 10/10/13
[10] http://www.sharpleds.com/resources/2013_LED_Product_Brochure.pdf 23/10/13

Xicato with its corrected cold phosphor technology offers multiple flux packages from 400, 700, 1000, 1300, 2000, to 3000lm. The lumen efficacies, depending on the drive current of 350, 500, 700, 1050mA, vary: from 70 to 92lm/W for the Standard series, from 47 to 59lm/W for the Artist series, and from 67 to 88lm/W for the Vibrant Series. Also, it offers greater than 70% lumen maintenance after 50,000 hours of operation.

Bridgelux offers multiple flux packages from 400 to 2200 lm for the ES LED Array series. The drive current can either be 250, 500, 600, 700, 1050, 1200mA. The lumen efficacy varies from 71- 124 lm/W. Bridgelux LED Arrays leverage the Company's proprietary Metal Bond Technology[11] (MBT), which has demonstrated a reduction in thermal resistance which is beneficial to the lighting system by increasing light output and reducing heat sinking requirements. In addition, in order to minimize variation in the end product or application, Bridgelux bins its LED Arrays for luminous flux. In particular, Bridgelux LED Arrays are labeled using a 4-digit alphanumeric bin code: A B C D, Where: A – designates flux bin (P for 1200 - 1320 lm, Q for 1320 - 1380 lm, R for 1380 - 1530 lm etc.) Bridgelux[12] projects that its family of LED Array products deliver, on average, greater than 70% lumen maintenance after 50,000 hours of operation. Bridgelux conducts lumen maintenance tests per LM80.

The Philips Fortimo[13] LED Downlight Module is equipped with a special remote phosphor technology that enables very high levels of LED efficacy. The lamp and driver have been developed and rigorously tested in combination with each other, including key enhancements like thermal protection for the module. Additionally, the module has been successfully implemented using LM80 guidelines. As a result, they provide a great light distribution and lumen output of 1100 to the expanded 2800lm package, while efficacy which is 74-90lm/W can be upgraded and implemented when available.

The Cree LMR4 module[14] utilizes the proprietary TrueWhite technology with an active feedback system which varies the proportion of intensity from the three

[11] http://bridgelux.com/about/products.html 20/10/13
[12] http://www.bridgelux.com/assets/files/DS11%20Bridgelux%20ES%20LED%20Array%20Data%20Sheet%20053012.pdf20/10/13
[13] http://www.lighting.philips.com/us_en/connect/led_modules/dlm_downlight.wpd 23/10/13
[14] Mondo_ArcMediaPack2014, 28/10/13

red and seven white LEDs incorporated into the light engine. The power spectral density of the LMR4 is different from the other LED modules available in the market due to the inclusion of the red LEDs. The white LEDs used within this module appear to be the popular larger die XPG emitters that provide much higher efficacies than standard 1mm die equivalents. The Cree LMR4 is the only LED module which has an integrated LED driver, offering flux packages of 700 or 1000lm, lumen efficacies of 58-62.5lm/W and 70% lumen maintenance after 35,000 hours of operation.

Sharp LED modules[15] utilize multiple LED die placed in a unique pattern to allow for even light distribution. The Mini Zenigata product family gives a new meaning to "compact," with approximately 1/3 (38%) the surface area of Mega Zenigata models and a significant reduction in the emissive area. This can simplify the development of optics that direct the light in a luminaire, and provide an overall better "look and feel" from the light produced. This range of modules offers a lumen output of 270- 1650lm, lumen efficacy of 60-105.9 lm/W, and 50,000 hours of operation.

GE[16] offers a wide range of lumen packages[17] from 850 to 4,500 lumens to meet a variety of lighting needs, including narrow punch beam angles (Infusion NPM) and recessed downlighting applications (Infusion DLM). There is also a comprehensive range of high efficacy of 75-106.1lm/W and lumen maintenance of L85 at 50,000 hours. The Infusion range is tested with LM79 & LM80[18].

[15] http://www.sharpleds.com/ledevolution.html 23/10/13
[16] http://www.gelighting.com/LightingWeb/na/images/94568-GE-LED-Infusion-Module-Gen3-Sell-Sheet_tcm201-59936.pdf 2/11/03
[17] http://www.gelighting.com/LightingWeb/na/solutions/highlights/infusion-led-module/overview/#1 25/10/13
[18] http://www.gelighting.com/LightingWeb/na/solutions/highlights/infusion-led-module/overview/ 2/11/13

Annex 8

Developments on Photometric Data

A supplementary market research was performed in the end of 2013, in order to investigate the developments in the availability of photometric data of LED products.

The market research revealed that reputable LED module manufacturers provide photometric data on their products. An example is presented in Figure A.8.1 below.

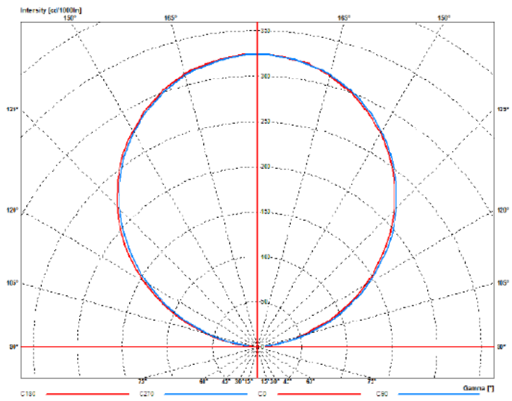

Figure A.8.1: Polar Curve for Fortimo G3 by Philips

In more detail, the market research reported that:

- Philips offers photometric data for its Fortimo Gen 3 system, including[1] IES, LDT, PHL files, as well as polar curves.
- CREE offers IES files for its LMR4 LED Module.
- GE has available polar curves with different optics.
- Xicato also offers photometric data for its LED modules with different optics upon request, though not available on the company website.
- Sharp does not present photometric data on its website.

[1] http://www.lighting.philips.com/us_en/connect/led_modules/dlm_downlight.wpd 23/10/13

The market research also revealed that luminaire manufacturers using modules of reputable manufacturers provide photometric data and software plug-ins. For example:

ACDC lighting[2] provides LDT files, illuminance cone diagrams for (seeFigure A.8.2), and polar curves (seeFigure A.8.3) for LED washers.

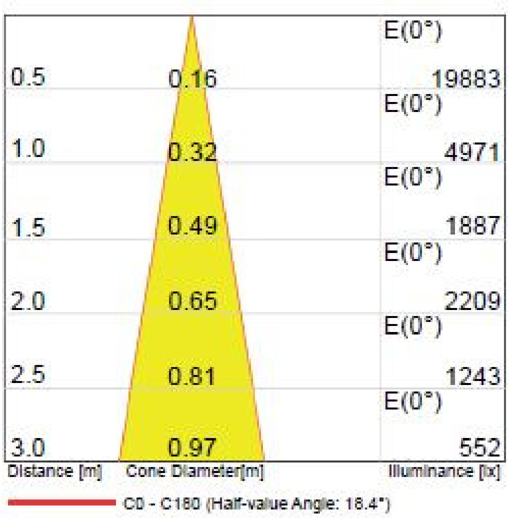

Figure A.8.2: Illuminance cone diagram of Integrex by ACDC

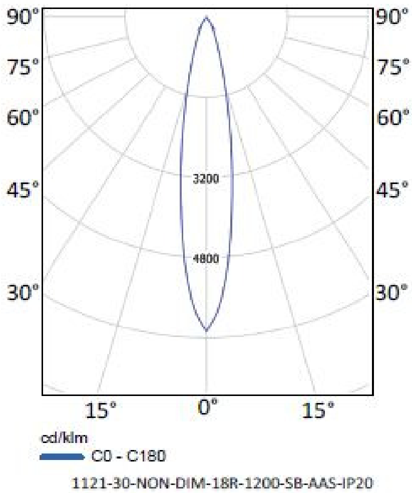

Figure A.8.3: Polar curve of Integrex by ACDC[3]

[2]http://www.acdclighting.co.uk 5/11/13

Similarly, Targetti[4] offers polar curves (see Figure A.8.4) for LED Pendant luminaires.

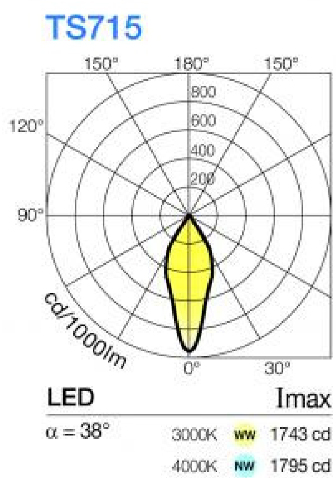

Figure A.8.4: Polar curve of CCT Pendant luminaire by Targetti[5]

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[3]http://www.acdclighting.co.uk/led/integrex/#.Unv_x9tXvVQ 5/11/13
[4]http://www.targetti.com/ 4/11/13
[5]http://www.targetti.com/products/65622/cctled-pendant-architectural 5/11/13

Annex 9

Developments on Colorimetry

A supplementary market research was performed in the end of 2013, in order to investigate the developments on the colorimetry of LED products. The market research revealed the developments in the manufacturing methods that allow manufacturers to claim stable colours between LEDs and over time.

One way to achieve colour stability is by separating the phosphor from the LED and by making sure that the phosphor stays cool. An example of such technology is the "corrected cold phosphor technology'[1] by Xicato[2] where the phosphor is separated from the LED, allowing control of the wavelength variation and heat. By 'tuning' the module in the manufacturing process assures colour consistency of one McAdam Ellipse over the life of the LED modules. Xicato also ensures a high CRI[3] of up to 95+.

Similarly, the Fortimo module by Philips is also a module that employs remote phosphor technologies where the phosphor is placed away from the LED die. The system maintains colour consistency within 3 standard MacAdam ellipses, with CCTs of 3000K, 3500K and 4000K. The Fortimo module also has CRI increased to a minimum of 80.

The ES LED Array[4] products by Bridgelux are constructed of an array of high power LED die boded onto an aluminium substrate and encapsulated in a proprietary phosphor compound[5]. The ES LED Array series has CCTs of 2700K, 3000K, 3500K, 4000K, 5000K, 5600K and CRI of 70, 80, and 90. Yet, in order to minimize variation in the end product or application, Bridgelux bins its LED Arrays for colour (P3, P4, Q3, etc.). Using these codes it is possible to determine the best product utilization to deliver the consistency required in a

[1] http://www.xicato.com/technology/corrected-cold-phosphor-technology%C2%AE, 4/7/13
[2] http://xicato.com/technology/corrected-cold-phosphor-technology® 18/9/13
[3] http://xicato.com/technology/color-rendering 18/9/13
[4] http://www.bridgelux.com/assets/files/DS11%20Bridgelux%20ES%20LED%20Array%20Data%20Sheet%20053012.pdf 20/10/13
[5] http://bridgelux.com/assets/products_portfolio/AN14ReliabilityDatasheet.pdf 20/10/13

given application. Given that, Bridgelux provides Graphs of White (Warm, Neutral, Cool) Test Bins in xy Colour Space, as well as xy Bin Coordinates and Associated Typical CCT.

GE Infusion[6] maintains incredibly consistent colour quality of 2700K, 3000K, 4000K from module to module. The colour point stabilizes by 1000 hours and is maintained within 2 MacAdam ellipses. The socketable system design ensures consistent thermal performance, and this in turn means that color consistency can be easily translated through to the luminaire. The LEDs achieve an exceptionally stable CRI across all colour ratings, which is as high as CRI of 90.

Another method that has been developed in an effort to control the colour emitted from LED modules, is to use two or more LED colours and to control the intensity of them. For instance, the CREE TrueWhite Technology[7] mixes the light from red and unsaturated yellow LEDs to create beautiful, warm, white light. An active feedback system varies the proportion of intensity from these LEDs incorporated into the light engine (which has integrated LED driver).This patented approach enables colour management to preserve high colour consistency around the specified colour temperature and over the life of the product. This way, the LEDs achieve CCTs of 2700K, 3000K, 3500K and 4000K; and a colour consistency of 2-4 MacAdam Ellipses.TheCree TrueWhite Technology also enables a CRI of at least 90 while maintaining high luminous efficacy.

The Mini Zenigata COB[8] LEDs by Sharp incorporates a blue LED die with a proprietary mixture of green and red phosphors to ensure that the LEDs deliver the R9 “deep red dazzle.” An accurate deep red rendering, that provides a warm and vibrant visual aesthetic. All Sharp LEDs meet or exceed CRI[9] of 80.In addition, all the new Sharp Zenigata COB products[10] are tested via the new Single Bin, 3-Step process of Sharp, which eliminates the need for traditional binning. Rather than using the traditional method of testing at 25°C to predict

[6] http://www.gelighting.com/LightingWeb/na/solutions/highlights/infusion-led-module/overview/#1 25/10/13
[7] http://www.cree.com/LED-Components-and-Modules/Tools-and-Support/FAQs 1/11/13
[8] http://www.sharpleds.com/minizenigata.html 23/10/13
[9] http://www.sharpleds.com/ledevolution.html 23/10/13
[10] http://www.sharpleds.com/ledevolution.html 23/10/13

performance at 90°C (very hot), Sharp tests LEDs at 90°C to ensure performance to specification in every module.

The developments on the colorimetry of LED modules are summarized in Table A.9.1, which shows that LED Module manufacturers claim specific CCTs, such as 2700K, 3000K, 4000K, and 5000K. In addition, although some manufacturers still offer CRI of 70 or 80, other manufacturers claim a CRI of 80+ or even 90+. Similarly, although some manufacturers still allow tolerances in their colour consistency, other manufacturers claim a tight colour consistency of two or even one MacAdam Ellipse around the colour point on the black body locus.

	LED Module Manufacturers					
Data	Xicato	Philips	Bridgelux	CREE	Sharp	GE
	XSM Standard Series[11]	Fortimo Gen3[12][13]	ES Series[14]	LMR4[15]	Mini Zinegata[16][17]	Infusion[18][19]
CCT range (Kelvin)	2700, 3000, 3500, 4000	2700, 3000, 3500, 4000	2700, 3000, 3500, 4000, 5000, 5600	2700, 3000, 3500, 4000	2700, 3000, 3500, 4000, 5000, 6500	2700, 3000, 4000
CRI	80	80	70, 80, 90	80, 90	80-93	80, 87
Colour Consistency	1 x 2 SDCM	3 SDCM	3 SDCM	2, 4 MacAdam ellipses	X,y tolerance: + - 0.005	2, 4 MacAdam ellipses

Table A.9.1: Information related to colour, available by LED Module manufacturers

[11] http://xicato.com/xsm-led-module/specification 10/10/13
[12] http://www.usa.lighting.philips.com/connect/LED_modules/dlm_downlight.wpd 10/10/13
[13] http://www.usa.lighting.philips.com/pwc_li/us_en/connect/LED_modules/assets/LE-6180.pdf 10/10/13
[14] http://www.bridgelux.com/products/ledarray_es.html 10/10/13
[15] http://www.cree.com/LED-Components-and-Modules/Tools-and-Support/FAQs 1/11/13
[16] http://www.sharpleds.com/minizenigata.html 10/10/13
[17] http://www.sharpsma.com/sites/default/files/Documents/Shared/Web/Downloads/SP_Specification/lighting/mini-zenigata/GW6BGSxxHED-E.pdf 10/10/13
[18] http://www.gelighting.com/LightingWeb/na/solutions/highlights/infusion-led-module/overview 10/10/13
[19] http://www.gelighting.com/LightingWeb/na/images/94568-GE-LED-Infusion-Module-Gen3-Sell-Sheet_tcm201-59936.pdf 10/10/13

Annex 10

Developments on Luminaire design

A supplementary market research was performed in the end of 2013, in an effort to depict the latest developments in regard to luminaire design. The market research revealed that many manufacturers claim that LED modules will be easy to replace as the technology advances, so as to facilitate luminaire manufacturers in their product designs.

For example: Philips 'future proof' promise[1] for their Fortimo LED systems, that as energy efficiency advances are made in LEDs, and as new bins become available, these will be incorporated into the Fortimo LED Modules[2], offering higher efficacies without changing the dimensions, shape or lumen output of the system. This allows luminaire manufacturers to switch easily between one Fortimo LED module generation and the next, with minimal disruption and cost to their luminaire design and production processes, as well as to plan and design new luminaire ranges for the future.

Similarly, the GE Infusion modules[3] have a twist and lock installation which allows the entire LED module to be removed and upgraded easily, without additional hardware. Likewise, the Bridgelux LED Arrays[4] have been uniquely designed to be easily assembled into lighting fixtures. It can actually be directly mounted to a heat sink without a secondary substrate or circuit board. This results not only in a simple plug and play design but also in an industry leading low system level thermal resistance.

Finally, the market research reported some industry initiatives in regard to LEDs, under the Zhaga[5] Consortium. The Zhaga is a global consortium of companies from the international lighting industry. Its overall aim is to develop interface

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[1] http://www.lighting.philips.co.uk/subsites/oem/product_pages/fortimo/philips-fortimo-led-systems.wpd 23/10/13
[2] http://www.usa.lighting.philips.com/connect/LED_modules/dlm_downlight.wpd 4/11/13
[3] www.mondoarc.comMondo_ArcMediaPack2014, 28/10/13
[4] http://bridgelux.com/assets/products_portfolio/AN15ReflowSolderingBridgeluxArrays082509.pdf 20/10/13
[5] http://www.zhagastandard.org 5/11/13

specifications (referred to as “Books”) that allow LED light sources from different suppliers to be used interchangeably, without changing the luminaire design. In turn, this should accelerate the adoption of LED lighting solutions in the marketplace.

Zhaga members aim to develop interface specifications that cover the physical dimensions, as well as the photometric, electrical and thermal behavior, of LED light engines; to ensure that Zhaga-compliant products are in line with global standards, upgradeable and future proof; to make Zhaga-certified products easily identifiable and traceable; to promote the use and benefits of Zhaga-compliant LED light engines for all applications in general lighting; to actively share their experiences and work closely together to increase customer confidence in specifying and purchasing interchangeable LED light engines. Zhaga-compliant products will be commercially available from multiple suppliers, and will be able to continuously benefit from the performance upgrades that LED technology brings.

In turn, the Zhaga consortium should bring lower Research & Development costs to the companies involved; greater product diversity; easier procurement; less risk; new markets and new options; easier upgrades; and cost- effective replacements.

Annex 11

Operation and Control of LEDs

The market research that was performed in the end of 2013, reported information in regard to the operation and the control capabilities of LEDs. The market research shows that LEDs operate in constant current (CC) or in constant voltage (CV), and can be dimmable.

Figure A.11.1 illustrates a diagram of dimmable constant current LEDs, in serial connection.

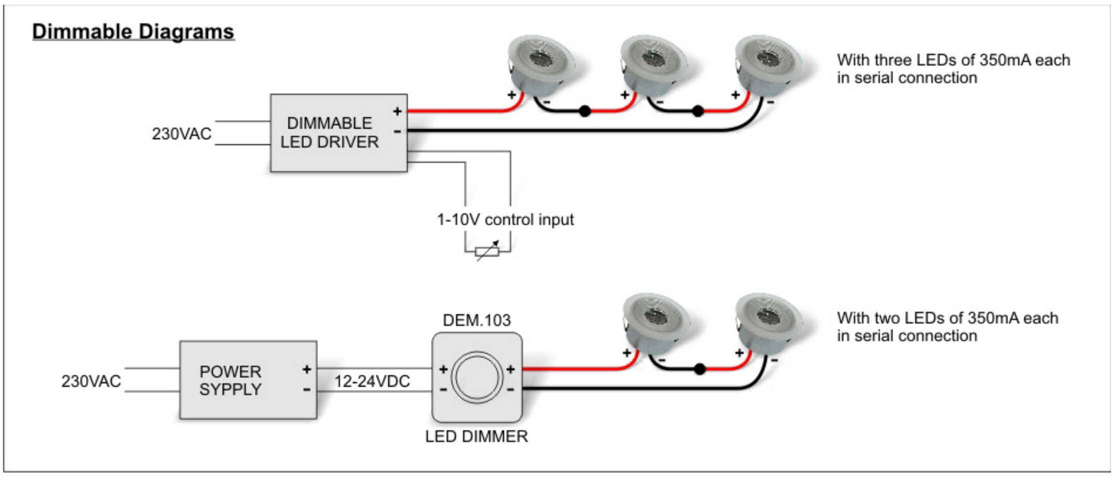

Figure A.11.1: Constant Current connection of LEDs (Electron SA[1])

[1] http://www.electron.gr15/1/14

Figure A.11.2 illustrates correct and wrong diagrams of non-dimmable constant voltage LEDs, in parallel connection.

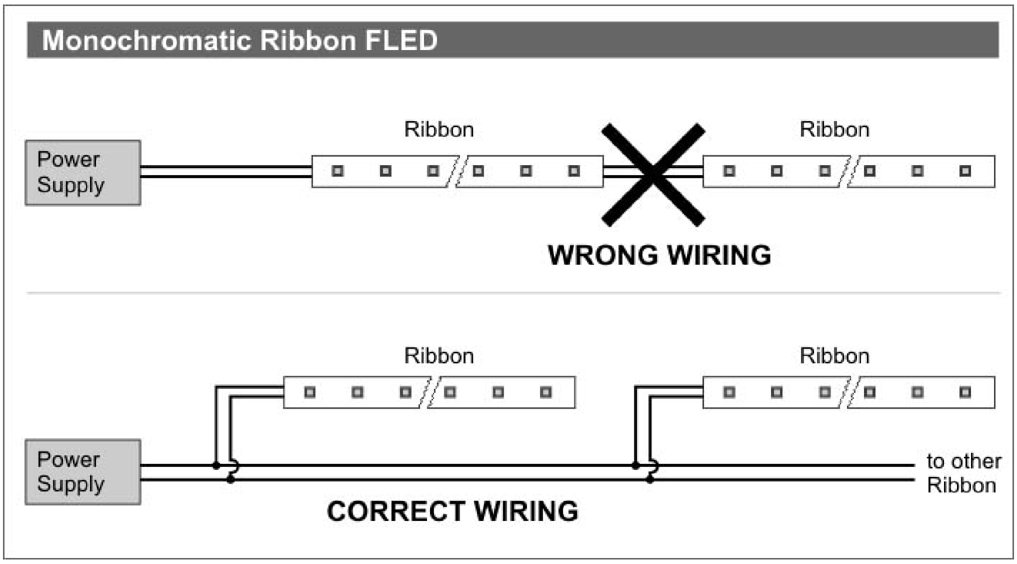

Figure A.11.2: Constant Voltage Connection of LEDs (Electron SA)

RGB LEDs are common cathode (CC) or common anode (CA). Figure A.11.3 illustrates connection diagrams of common cathode and common anode RGB LEDs operating at 24VDC.

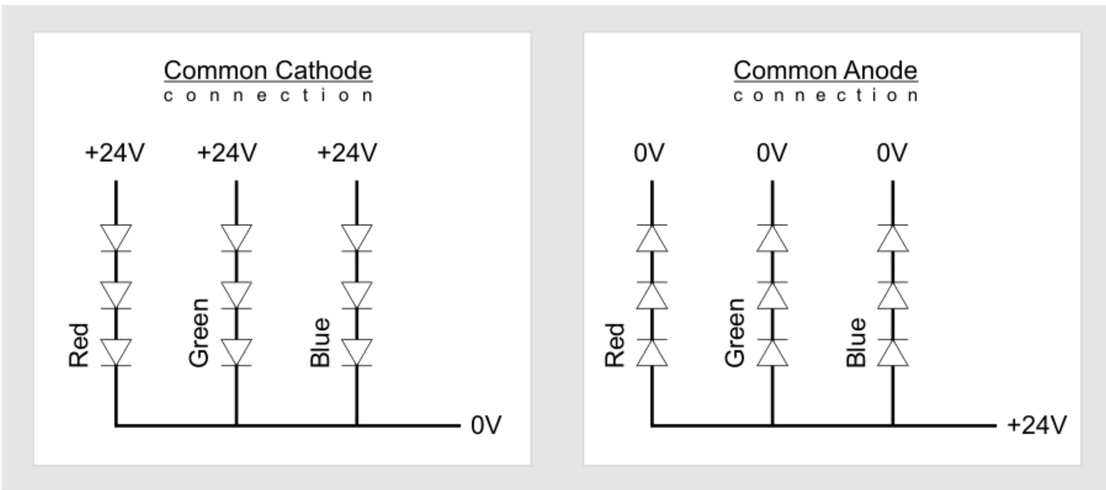

Figure A.11.3: Common Cathode & Common Anode LEDs (Electron SA)