LIGHTING OFFICES WITH LEDS: A STUDY ON RETROFITTING SOLUTIONS

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SUMMARY

Global energy consumption is rising and the relative contribution of lighting in buildings to that total is also increasing. In offices, the dominant form of lighting is fluorescent, but this will soon be surpassed in terms of performance by LED lighting, which are already starting to be more widely used. Considering that most buildings and offices are of older building stock, this presents a great opportunity for making energy savings by using more efficient light sources within offices. This thesis investigates the application of LEDs as a retrofitting solution to existing fluorescent lighting systems and assesses their potential to provide an equivalent lighting environment with no adverse effects on performance and investigates their impact on space conditioning load demands and CO2e emissions on a range of case study buildings in the UK.

Savings in lighting cannot only be made through reduced electrical consumption, but also through space conditioning loads, by reduced lighting heat gains. Currently used lighting technology is reaching its limit of performance, whereas LEDs offer the potential to meet energy saving targets with their rapidly improving performance.

LEDs emit most of the heat generated to the back of a luminaire, rather than directly to the occupied space and this can lead to reduced heat gains and thus savings on space cooling demand loads, in addition to the electrical savings due to higher efficacies, for operating them.

In this thesis, simulation software were reviewed that would allow for the lighting specification of custom LED replacement luminaires and assessment of their thermal performance. Methodologies were developed on simulating their light output and designing custom LED replacement luminaires with the use of RADIANCE, thus providing a novel use for this extensively used and validated software. For validation purposes a test room was used where custom LED replacement luminaires were fitted and measured for their performance, where good agreement in predicted and measured results was found.

A visual performance study was also conducted using a range of age groups, to ascertain if there is a difference in task based performance on paper and VDU screens between fluorescent lighting and LED lighting, in an office environment. Subjective opinions on preference between the two light sources was also investigated.

An assessment of space conditioning load demands was performed on five case study buildings, where custom LED luminaires were specified to retrofit the existing fluorescent lighting. Results showed lighting levels and distribution in each building could be replicated with good agreement, offering a cooling load demand reduction, however with an increase in heating load demand. In terms of CO2e emissions, the use of LED lighting instead of fluorescent also proved to be beneficial, providing reductions in emissions.

DECLARATION

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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This thesis is the result of my own independent work/investigation, except where otherwise stated.

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I would also like to thank the Welsh Energy Research Centre for providing funding support through the EU for the Low Energy Design of LEDs (LEDLED) research project, which forms part of the work presented in this thesis. The author of this thesis was the principal investigator of this research project and was the one who conceived the idea, formulated the research questions and prepared the funding application. The aim of this research was to design and develop four LED lighting demonstrator products and assess their potential impact in buildings.

There were four university partner departments in this project, all located within Wales, UK. These were the Department of Optometry and Vision Sciences (Cardiff University), the Department of Electrical and Electronic Engineering (Swansea University), the Department of Chemistry and Material Science (Bangor University) and the Welsh School of Architecture (Cardiff University), which was leading this project. Each department was commissioned by the author to perform a range of tasks required by the project.

The author of this thesis served as both principal investigator in this project and as project manager, with responsibilities ranging from co-ordinating all aspects of the project on a daily basis, devising methodologies, running computer simulations, analysing results and writing reports. A number of research assistants were commissioned by all five departments involved in this project, throughout its duration, to perform a series of tasks setup by this author and other co-investigators, for their respective work packages.

The following list outlines the contributions of others in the work presented here, together with additional information on how this work was used by the author in this thesis:

- Site measurements in a test room:

  This involved the use of lux level meters and temperature measurement devices obtained from the environmental lab of the Welsh School of Architecture. The specification on how measurements should be taken was defined by the author of this thesis, who also took part of the measurements and then used the data obtained to make comparisons between measured and simulated data, as presented in Chapters 6, 7 and 8. I would like to thank Li Qian and Shareful Shickder for their help in this aspect of the work.

- The construction of LED luminaires, as well as combined fluorescent and LED ceiling tile luminaires to be used for testing:

  The Department of Electrical and Electronic Engineering at Swansea University was commissioned to conduct this work, to the specifications provided by the author of this thesis. The luminaires constructed were then placed in a test room for measurements to take place, as described in Chapters 6 and 7.

- Task based performance and perception study:

  The Department of Optometry and Vision Sciences of Cardiff University was

commissioned to run an experiment in a test room, that was specified and setup according to the specifications of the author, by measuring the task based performance of subjects under fluorescent and LED lighting conditions. The author used this data to make comparisons between the two conditions, as presented in Section 7.4, Chapter 7. I would like to thank Rachel North and Andrew Bullyment for their help in this aspect of the work.

In all cases, the author of this thesis oversaw the above work, developed the methodology and setup for experiments, unless otherwise stated in the following chapters.

Finally I would like to thank my parents Dimitris and Niki, for their constant support throughout all my studies, as without their support this would not have been possible.

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Chapter 1. Introduction

1.1 Research Background

Energy demand and greenhouse gas emissions are rising at a global scale and the built environment accounts for a significant portion of that. Within that portion, artificial lighting is a big contributor and, for commercial buildings, lighting represents the largest primary energy consumption (Glicksman 2008). Even though light sources are becoming more efficient, more and more lights are used for interior and exterior applications, thus increasing their contribution to energy consumption and green-house gas emissions.

In the UK, artificial lighting has been reported to account for 17% of an office building total energy consumption (Carbon Trust 2000) and 23% of CO2 emissions in commercial and public buildings (Pout et al. 2002). In the USA, about 14% of all energy consumed in the built environment is spent on lighting. This figure rises to about 25% for offices and 35% for all commercial buildings, according to the US Department of Energy (USDOE 2012a). This presents a potential for significant savings in energy with the use of more efficient light sources.

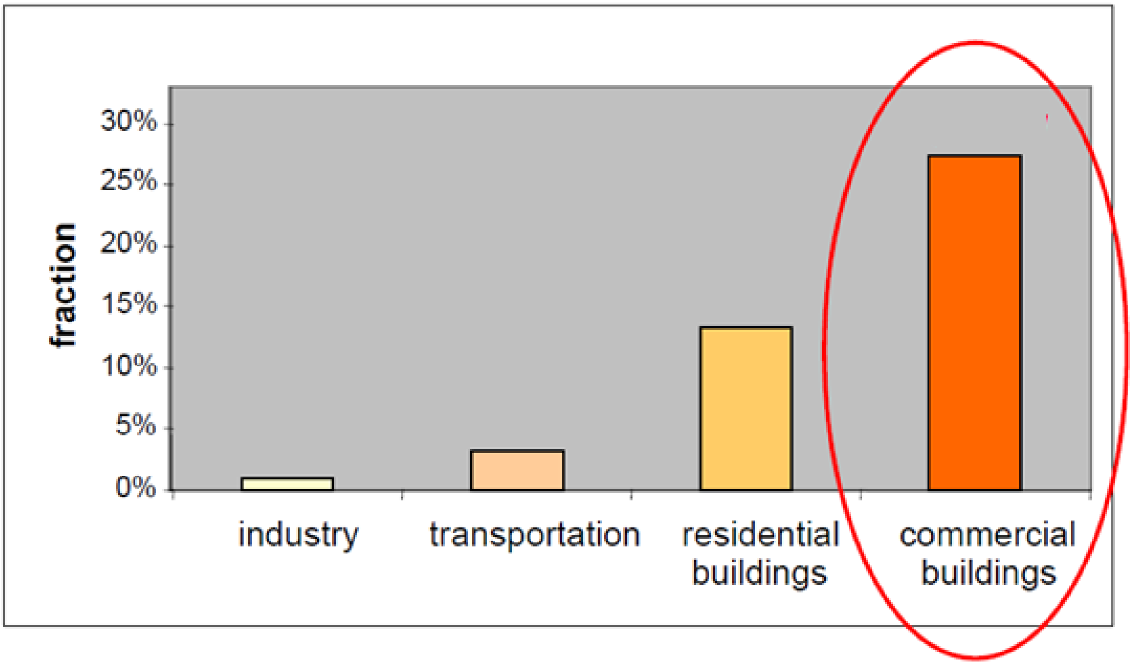

Figure 1.1 The impact of light energy consumption by segment (USDOE 2012)

The incandescent lamp has been in use for more than 100 years, however the technology it employs has not been further improved, so it is not considered possible to make significant energy saving there. This is the main reason incandescent lamps are being phased out in Europe since 2009 through the Ecodesign Directive (2005/32/EC). Fluorescent lighting has improved in efficacy and is still expected to improve some more, but the technology it employs is close to peaking in terms of efficacy (Waide 2010) and hence great saving are not expected from there either.

The lighting technology that has improved significantly over the past few years, and is expected to continue to improve for a number of years to come, is Solid-State-Lighting (SSL) technology in the form of Light Emitting Diodes (LEDs). Improvements in the technology have been made over the past years that have led to greater efficacies, from around 10 lm/W in 1995, to around 90 lm/W in 2011 (USDOE 2012a). The solid state technology employed and the continued development in the field promises even greater efficiencies in the future, as well as flexibility for use in many applications as there is still considered significant room for improvement (Navigant Consulting 2010). This places LEDs at the forefront for wider adoption in buildings so that reductions in energy consumption and emissions can be achieved.

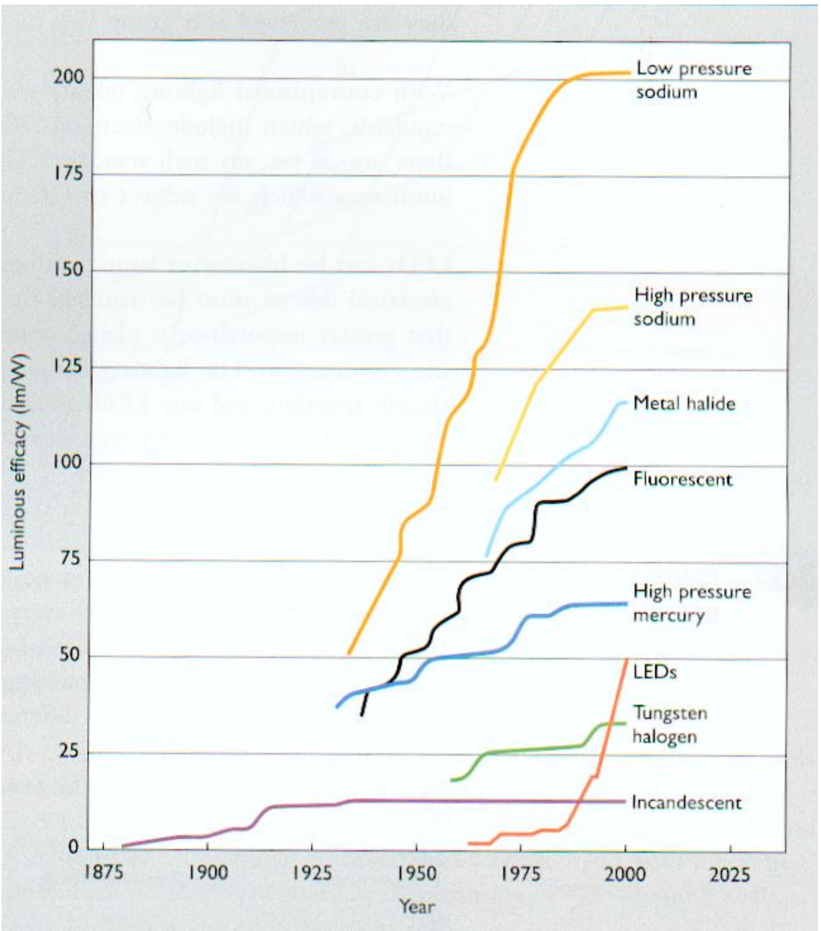

Figure 1.2 Efficacy improvement in the main types of light sources (Forster 2005)
Note: Efficacies from LEDs have improved since 2000

A significant amount of research is being conducted on the improvement of the performance of LEDs, however their potential impact on buildings has not been studied thoroughly. In the context of buildings, literature concentrates on the effect of LEDs on electrical energy consumption. Artificial lighting, and in this case LEDs, also have an impact on heating and cooling loads in buildings, due to their emission of heat into a space. This thesis attempts to fill this gap by focusing on the use of LEDs within offices and investigating their impact on heating and cooling demand loads.

1.2 Defining the Problem

LEDs over the past few years have dramatically improved in their optical characteristics, while continuing to improve every year making them a good candidate for replacing existing lighting technologies. With the ever increasing adoption of LEDs in various industries and the associated economies of scale, costs per unit, which is one of the main barriers towards mass adoption, are expected to reduce (Navigant Consulting 2010). With this in mind, as well the phasing out of incandescent lighting from the market, it becomes obvious that LED lights are going to be one of the dominant light sources in the near future.

A significant amount of research has been conducted on the technology of LEDs and how to improve their optical, thermal and energy performance (Petroski 2002). Some work has been conducted on the application of LEDs in various industries such as the automotive, aerospace and display, among others and how the performance of LEDs compares to existing lighting sources in terms of light output and electrical energy consumption (H. J. Han et al. 2010). Much less has been done on the implications of using LEDs in an architectural context and, more specifically, on the impact of LEDs on whole building energy consumption and comfort. The majority of existing research on LEDs in the context of buildings focuses on light output and electrical energy performance, and compares that to other forms of artificial lighting (Schubert and J. K. Kim 2005) (Humphreys 2008) (J. K. Kim and Schubert 2008) (Arik and Setlur 2010).

This research typically treats LEDs as any another source of light whereas, in a number of aspects, the thermal behaviour of LEDs differs significantly from existing artificial light sources. One of the most significant differences is the way in which heat is dissipated from LEDs. LEDs emit the majority of the heat generated towards the back of the light sources, whereas all other sources emit the majority of the heat towards the direction the light is produced.

This does not have a significant effect when LEDs are used in free-standing luminaires, ones contained entirely within a contained space. It is much more significant, however, when used in luminaires that are installed within a suspended ceiling, above which is a semi-isolated and often ventilated ceiling void. In this case, typical light sources emit a portion of their heat into the main room space below and a portion into the ceiling void above. This is where the real differences between LEDs and other light sources becomes most obvious as, in the case of LEDs, a significantly greater portion of the heat is emitted into the ceiling void.

This offers the potential to significantly reduce heat gains due to lighting within the main space, while also allowing for the potential to remove a lot of this heat directly from the ceiling void before it is able to leak through the ceiling (Figure 1.3). If we also consider that a suspended ceiling system with recessed luminaires is one of the most common forms of ceilings in offices and many other building types within the UK and globally (EIA 2006), as well as the fact that high internal gains within offices means that there is typically a need for cooling for a significant portion of the year, then it is possible to appreciate the potential impact LEDs might have in the reduction of total energy loads in offices. This is not only as a result of reduced electrical lighting loads but through better management of the heat generated by lighting.

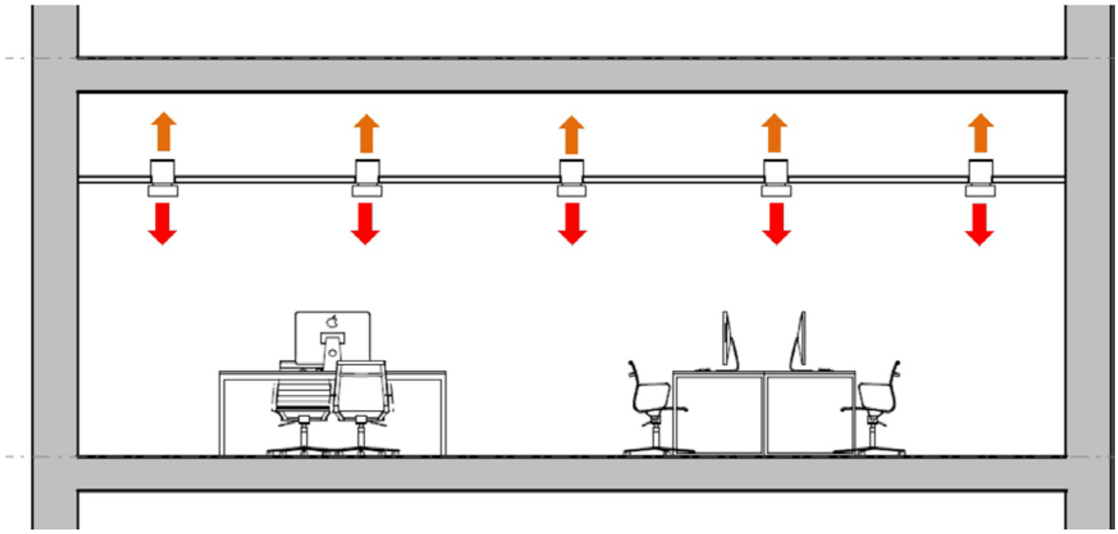

Figure 1.3 Distribution of heat from lighting for a typical office floor with a suspended ceiling system. Red arrows indicate heat from lights emitted into the main room and brown arrow indicate heat emitted from lights to the ceiling void above the room. (image by Author)

The greatest potential for impact in energy reductions with the use of advanced light sources lies in the adoption of more efficient technologies in existing buildings. More specifically with the replacement of existing light sources with more efficient technologies. With the current global recession, coupled with targets on the reduction of carbon emissions, cost effective solutions that address these issues are preferred and are the focus of this thesis. An example of this is the replacement of fluorescent tubes used so widely in office ceiling tile recessed luminaires, with new and more efficient fluorescent tubes, therefore not having to replace the whole luminaire, while maintaining an equivalent light environment. The exact same process though, is not typically possible with LEDs, as LED luminaires require a different design that incorporates heat sinks (among other things), necessitating an alternative design and layout within the luminaire. This is also not helped by the fact that lighting manufacturers are specifically targeting new buildings and offices with their LED luminaire products, thus designing them in a way that makes them unsuitable for direct replacements in existing offices. Therefore, to study the impact of LEDs as replacements for existing lighting technology, custom LED luminaires will have to be built that provide an equivalent lighting environment as an existing fluorescent light source, in order to compare their performance to the most common fluorescent luminaires.

This thesis focuses on this area of research. More specifically, it investigates the lighting characteristics of LEDs and the thermal and energy consequences of replacing existing fluorescents with LEDs. It seeks to quantify the potential impact of LED ceiling tile lighting in terms of heating and cooling energy demand loads in office buildings. Thus the focus is on the application of LEDs as replacements for the most common existing form of ceiling tile lighting in offices (fluorescent strip lighting) and assesses their viability as suitable replacements.

1.3 Aims and Objectives

The fundamental hypothesis in this work is that LEDs can be used as viable direct replacements for existing fluorescent lighting systems in offices, maintaining their lighting layout, for minimal intervention and maximum cost-effectiveness, while providing an equivalent lighting environment that does not adversely affect an occupant's performance or perception, and offering significant opportunities to reduce energy demand, space conditioning loads and CO2 emissions.

Based on this hypothesis, a series of objectives has been set to guide this investigation:

- To review current office lighting technology with an emphasis on fluorescent ceiling tile type technology.

- To review current LED lighting technology, in order to reveal limitations and opportunities of this technology, as well as future trends, so that a prediction can be made as to how efficient they can be in the future and thus assess their potential energy impact now and in the future.

- To develop a method that allows for the design of custom LED luminaires that are capable of replicating existing fluorescent lighting distribution in rooms.

- To test the method developed in the thesis within a real office environment and compare the measured lighting performance under fluorescent and LED replacement lighting conditions.

- To ascertain whether task-based performance and the perception of people is different under LED and fluorescent lighting in a test office environment.

- To predict the energy impact of LED replacement luminaires compared to existing fluorescent and assess their impact in terms of annual heating and cooling loads in a range of case study buildings.

1.4 Method Overview

In order to meet the aims and objectives set for this thesis, a series of tasks were performed which are dealt with and presented in different chapters. This section provides an overview of the methodologies used.

Office lighting technology and LED lighting technology are two areas that provide the background to this work and are dealt with in two separate chapters, forming the main part of the literature review of this thesis. Existing research is presented and the differences between the LED and other lighting technologies are highlighted by reviewing work undertaken in this field.

In order to address the other objectives of this thesis, a series of methodologies were developed. This included the development of a custom LED luminaire, the setup of a test room for validation purposes and for other experiments, and finally the simulation work required to predict the impact of using LEDs as replacement for existing fluorescent office lighting on heating and cooling energy demand loads.

A more detailed outline of the methodologies used in this thesis will be described in Chapter 5.

1.5 Contributions of this Thesis

LEDs are fast becoming one of the dominant light sources in display, automotive and signage applications, and they offer the potential to be the dominant lighting technology in years to come. This is mainly due to their rapidly improving performance in optical, energy and thermal characteristics. It is therefore reasonable to assume that they will become a dominant lighting technology in buildings too.

Extensive work on the development of LEDs and their application can be found in the field of physics, electronics and electrical and lighting engineering. Their potential effect, on the energy demands of buildings, and especially their effect on heating and cooling load demands has not been studied thoroughly and this thesis attempts to fill in that gap, especially in the context of offices.

The work presented in this thesis comprises a series of discreet sections. The following list provides an outline of contributions from the work conducted in this thesis, which closely matches the themes of publications that are currently being produced:

The use of RADIANCE to develop and design custom LED luminaires. The work required for this is a novel application of this extensively used and validated software.

The development of a method to design LED replacement luminaires that can replicate the light levels and output distribution of existing luminaires. The majority of the building stock in the UK, is already 10 or more years old and hence in the context of offices it is more cost effective and energy efficient to replace existing luminaires with equivalent alternative LEDs, rather than redesign the whole lighting system and layout of an existing office.

An assessment of the potential of LEDs to be used as replacements for existing ceiling tile lighting systems, while maintaining the original lighting distribution, as well as not affecting task-based performance and the perception of people.

An assessment of the energy impact of using LEDs as replacements for existing fluorescent lighting in offices

1.6 Outline

The work conducted for this thesis is presented over ten chapters, each dealing with a different topic of the required research. The following paragraphs provide an overview of each chapter.

Chapter 2 provides an overview of office lighting technology, focusing on ceiling tile lighting. Chapter 3 takes an in-depth look at LED technology, starting with how the technology was developed, the optical and thermal characteristics of LEDs and various other of their properties and characteristics.

Chapter 4 discusses the differences between LEDs and other light sources in various aspects of performance and continues by raising the research questions to be answered through experimental work. Chapter 5 outlines the methodology of the simulation and field work to follow.

Chapter 6 deals with the process of simulating artificial lighting in the context of a room using simulation software. The first part reviews suitable software and makes a selection of appropriate software for this thesis. The second part deals with the process of simulating LED lights both as individual LEDs as well as multiple LEDs in a luminaire. Then a methodology is developed for designing custom LED luminaires and devising an IES profile for them. The methodology is then used to design custom LED luminaires that replicate room illumination from existing fluorescent ceiling tile luminaires.

Chapter 7 deals with the setup of a physical office test room, where simulation data is compared to measured values so that the models developed can be validated. A study is also presented that looked into task-based performance of people when under fluorescent and LED lighting, as well as their perception of the lighting conditions.

Chapter 8 deals with the selection of simulation software used to perform thermal analysis, the methodology associated with it and the findings of that work. In Chapter 9, results from the selected case studies are presented. The chapter starts by dealing with the methodology used to select and model each one of the buildings and then presents results for each case study building in turn, concluding by discussing the results for all case studies.

Chapter 10 draws conclusions from the work undertaken in this thesis and provides recommendations for future work in this field.

Chapter 2. Office Lighting

2.1 Introduction

Office lighting accounts for 20% of all electrical energy generated in the world (Humphreys, 2008) and thus presents a great opportunity for making energy savings at a global scale. It is therefore important to understand why artificial lighting consumes so much energy and which lighting technologies are employed in offices, so that areas of improvement can be identified. This chapter aims to provide an overview of regulations and guidance that are used as drivers for artificial lighting performance and then review available lighting technologies. The chapter concludes by identifying one lighting system that shows the greatest potential for LED retrofitting applications.

2.2 Artificial Lighting in Offices

Providing light to offices through daylight is the most efficient, healthy and desirable way of lighting (P. Boyce et al. 2003). However, there are many instances where daylight alone is not enough to provide the required levels of light throughout the occupied spaces of an office. The window sizes, number of windows, building orientation and the form of the building, in combination with the variable light levels provided from the sun and the sky conditions, account for the changing daylight levels encountered within offices which can create a situation where minimum required light levels are not maintained. This is especially true for deep plan offices. In addition to this, associated solar gains are usually admitted to offices together with the daylight. Hence shading and solar heat rejecting glazing systems are often used to minimise solar gains and, as a consequence, the daylight levels within offices are reduced. This typically results in the use of artificial lighting throughout the day in many offices.

Artificial lighting introduces heat gains within a space, together with the lighting that it produces. For offices, this can be a significant proportion of the heat gains within it (Harvey 2009). Advancements in lighting technologies have led to the adoption of fluorescent lighting as the main form of lighting in offices, mainly due to the higher efficacies (lm/W) that can be achieved and longer lifespan compared to incandescent lighting (Forster 2005).

Acoustic ceiling tiles are generally used in offices for two reasons: to lower general noise levels in offices and to hide the exposed ceiling as well as service pipes and cables that are running in the ceiling void. This has led to the design of artificial lighting luminaires that could fit into a typical ceiling tile and, hence, the wider adoption of this type of lighting and luminaire. Fluorescent lighting tubes are very commonly used in such luminaires.

This chapter begins with an overview of regulations and guides that govern artificial lighting design in offices. Then an outline of lighting requirements is provided based on these regulations and guides. Available office lighting technologies are then reviewed. The remaining part of this chapter concentrates on ceiling tile lighting technology, where an overview of their optical and thermal characteristics is provided.

2.3 Lighting Guides and Regulations

Artificial lighting in offices is governed by regulations that provide targets to be met in terms of light levels, energy consumption and safety. Regulations do not cover all aspects of lighting, so there are many supplementary guides available for different types of buildings and spaces that fill this gap. A summary of key regulations and guides relating to this thesis, together with other standards and directives affecting lighting is provided on Table 2.1, with a primary focus on the UK.

Table 2.1 A list of guides and regulations relevant to the UK

Lighting Regulations/Guides	Comments
CIBSE code for lighting 2002	Provides practical guidelines for lighting in a range of environments
European Standard EN 12464-1 (BSI 2002)	Provides standards adopted by 20 European countries. For the UK, this would be BSI 2002. It specifies lighting requirements for indoor workplaces with respect to visual comfort and performance. Tends to correlate very closely to CIBSE code for lighting
CIE (Commission Internationale de L'Eclairage or International Commission for Illumination)	Guidelines and recommendations for lighting for various indoor environments and lighting design can be found
PART L2A 2010: Conservation of fuel and power (New buildings other than dwellings) PART L2B: Conservation of fuel and power (Existing buildings other than dwellings)	Artificial lighting efficacy targets: 55 lm/W or higher (for general office lighting)
EuP & ERP	Energy Related Products directive
BS EN12464: 1	Lighting for work places
BS 5266	Emergency lighting
BS EN15193	Energy Performance of buildings Out of this standard, a measure of performance has been developed called LENI.
BREEAM	Besides factors on energy, environmental factors relating to 'Health and Wellbeing' are also taken into account)

The European Energy Performance Building Directive (EPBD), which is implemented by all EU countries, is a driver for lowering the energy consumption of buildings through the issuing of energy performance certificates for buildings. The European standard EN 15193 (Energy performance of buildings: Energy requirements for lighting - Part 1: Lighting energy estimation), provides the basis for calculating the energy consumption of lighting. More specifically, the LENI (Lighting Energy Numeric Indicator) is used by many EU countries to assess the contribution of light to the overall energy consumption of a building and thus provide certification, by using the following equation as the basis:

LENI = Energy Consumption for lighting / Square metre per year (in $kWh/m^2/a$)

Another driver for reductions in energy use and CO2 emissions is the CRC energy efficiency scheme (UK Environment Agency 2012) launched by the UK government in 2010, that has set some ambitious targets such as an 80% reduction in CO2 emissions by 2050. For these targets to be met significant reductions will need to occur and lighting is one area where significant reductions can be made.

Targets for energy reductions apply to both new and existing buildings. If we consider that 66% of the predicted 2050 building stock, already exists (Aston and Langdown 2010), then that means most of the savings can be made on refurbishing existing buildings, with lighting being a significant part of that.

The above drivers set the scene for the work conducted in this thesis, where the use of LEDs was explored as replacements to existing office lighting technology.

2.4 Lighting Requirements for Offices

The typical office worker spends one third of their waking time at work (CIBSE 2005), so it is important for them to have a pleasant and comfortable working environment to minimise fatigue and provide conditions conducive to performance and productivity. CIBSE Guide 07 (2005) and BS EN 1246-1 recommend levels for illuminance, limited glare rating and minimum colour rendering for offices, which are summarised in Table 2.2.

Table 2.2 A summary of CIBSE recommendations for offices (CIBSE 2005)

	Maintained Illuminance (lux)	Limited glare rating	Minimum colour rendering Index (CRI)
Filing, copying etc.	300	19	80
Writing, typing, reading, data processing	500	19	80
Technical drawing	750	16	80
CAD work stations	500	19	80
Conference and meeting rooms	500	19	80
Reception desk	300	22	80
Archives	200	25	80

The American IES recommends similar levels, placing office spaces in illuminance category D and requiring 200-500lux (Rea 2000). Unlike CIBSE, it also suggests a maximum illuminance, and that the initial illuminance from general lighting should not exceed 750lux on the horizontal work plane. If there are tasks being performed which require illuminances greater than 750lux, then supplementary lighting should be used to provide the required illuminance.

From current literature, the generally recommended level of illuminance (on the working plane) is 300-500 lux with additional, adjustable, task lighting as and when required. Minimum colour rendering should be 80 CRI with a colour temperature of around 4000°K. It is important that illuminance should be uniform across the working surface.

The above recommended levels are the ones used in the studies conducted in this thesis.

2.5 Available Office Lighting Technologies

The artificial lighting technology currently used in offices, largely depends on the properties of the luminaire selected and the properties of the luminaire itself are largely dependent on the type of light sources that they employ. The following table provides an overview of commonly used light sources in offices, together with less commonly used ones for comparative purposes.

Table 2.3 shows why fluorescent lighting is used so commonly in offices, as the efficacies achieved are very high, together with a much longer life span compared to other sources. LEDs are comparable to fluorescent in certain aspects of performance and better in others, but more details on LED technology will be provided in Chapter 3 and a comparison between fluorescent and LED technology in Chapter 4.

It is important to note that there are differences between efficacy of a light source and efficiency. Efficacy (in lm/W) is the light power of the light output, divided by electrical power in (measured in W). The light power in this case takes into account the sensitivity of the human eye, which is only sensitive to the visible spectrum (400-700nm) with maximum sensitivity to the green wavelength (555 nm). Efficiency of a light source is usually given as a percentage and is defined again as the light power output of the source, divided by the electrical power in. The difference in this case is that the light power considered extends beyond the visible spectrum (Humphreys 2008).

Table 2.3 Properties of various light sources (after: Humphreys (2008) and EnergySavingTrust (2006))

	Fluorescent Tubular	**Compact Fluorescent**	**GLS filament lamp**	**Tungsten halogen filament lamp**
Comments	Composed of a tubular glass envelop. Light is emitted from phosphors which convert energy from a low pressure mercury discharge. The spectral light distribution is tailored by the mix of phosphors and so colour rendering and colour temperature vary Required control gear Contains mercury (3-15ml/tube)	Same as fluorescent tubular *small size *life span depends on whether it is turn on/off a lot, in which case it can significantly shorten	Light is produced by an incandescent filament sealed in a glass bulb, usually containing an inert gas filling Simple operation, no control gear required Ease of dimming Good colour rendering Good lumen maintenance	Filament lamps with a halogen added to the gas filling which prevents evaporated tungsten blackening the bulb and therefore ensures excellent lumen maintenance. Smaller bulb Required control gear
Efficacy (lm/ W)	55-110 lm/W	35-80 lm/W	8-15 lm/W	15-25 lm/W
Life span (hrs) / Average Life??	10,000 - 30,000 hrs	6,000 - 15,000 hrs	500-1,000 hrs	2,000 - 5,500 hrs
Colour rendering	40-100	80-100	90-100	90-100
Colour Temp	2700-6500	2700-6000	2800	3000
Efficiency: light power out (not adjusted for the response of the human eye) / electrical power in	25%	20%	5%	5%

2.6 Ceiling Tile Technology

One of the problems that exist in offices is noise. In order to address that problem, suspended acoustic tiles are typically used to dampen reflected noise by absorbing it. In addition to this, a suspended ceiling tile system allows for all necessary service pipes and cables needed within an office building to be hidden from view. These are some of the reasons why suspended ceilings are used so extensively in buildings around the world and, in particular, offices.

A typical ceiling tile from a suspended ceiling is 600mm x 600m and this is where a light source is usually fitted. A number of design alternatives exist, but the most common ones, consist of a luminaire with the same dimensions that incorporates fluorescent lighting tubes (Figure 2.1).

Figure 2.1 Examples of ceiling tile luminaires (source: Thorn Lighting)

Due to the gridded nature of the ceiling tiles, luminaires are typically spaced at regular intervals, so that a uniform illumination is achieved throughout the office floor (Figure 2.2).

Figure 2.2 Examples of ceiling luminaires placed at regular intervals

As such, luminaires typically employ a series of light sources within them, their light output being the result of the combined effects of the total number of light sources along with reflections that occur within the luminaire housing itself, and the potential filtering of light in case a diffuser is present in front of the luminaire. Therefore, the light properties of a fluorescent ceiling tile luminaire, when considered as a unit, will differ from the properties of a standalone fluorescent tube. Considering that there are so many different designs and configurations for ceiling tile type luminaires incorporating numerous light sources, it is usually the manufacturers who provide the necessary information after testing their products for performance.

As in the case of light output from a luminaire, the same is true for the thermal and energy properties of the luminaire. The efficacy, for example, of a single standalone fluorescent tube will differ from a fluorescent ceiling tile luminaire (when considered as a unit) as the fluorescent lights are contained within a metal housing. Heat emitted from the fluorescent tubes will be partly contained within the luminaire housing, partly emitted into the space below along with the light, and partly emitted towards the back of the luminaire and into the ceiling void. The use of multiple fluorescent tubes also necessitates the use of control gear, which itself emits heat. Therefore, there is a need to define thermal and energy properties of whole luminaires in order to better describe performance. It is manufacturers or independent labs who provide such information, although information of this type is usually scarce.

2.7 Conclusions

This chapter has reviewed the various existing office lighting technologies that are widely available and used in offices around the world. It became obvious that due to stricter regulations on the energy consumption, carbon emissions and overall sustainability of buildings, fluorescent lighting with its higher efficacies and longer life has become the dominant light source used in offices. Still though, as targets for energy and carbon emissions become stricter, better performing light sources are needed. The following chapter reviewed the lighting technology that promises to address a lot of these issues.

Chapter 3. LED Technology

3.1 Overview

Light emitting diodes (LEDs) have become common today and are used as lamps for indicators in various devices, as well for specific task or general illumination. They are used to produce light in a range of wavelengths, thus making them suitable for many applications. Technological developments have led to greater improvements in the devices and thus LEDs are now being considered for wider adoption, as they can be durable, flexible and have the potential for even greater improvements in their performance in the near future. This means that the use of LEDs is important because they are capable of meeting the growing needs of lighting for different systems and machines, while lowering energy consumption.

Recent developments in their performance have allowed for a wider adoption in the lighting industry and provided a promise to make them one of the dominant light sources as they are capable of providing light at different wavelengths with high levels of brightness, among other characteristics. This chapter starts by looking into the history of LEDs, how they work and how they managed to evolve to their present state. It also looks thoroughly at the optical and thermal and energy characteristics of LEDs, as well as the various ways that they can be configured within a luminaire. Finally, the chapter concludes by considering the future of LEDs.

3.2 History of LEDs

The idea of LEDs began with a phenomenon known as electroluminescence. This phenomenon was discovered by Henry Joseph Round, a famous British scientist. He did this using silicon carbide and whisker detectors, but the light produced was not powerful enough to be used in any application, so it was initially abandoned (Zheludev 2007). Having developed the idea in 1907, the first successful LED was created by Oleg Losev, when electric current was passed through silicon carbide crystals and zinc oxide, used in radio receivers. The findings were published in a paper called "*Luminous carborundum detector and detection with crystals*" in 1927 (Losev 1927). Losev went on to publish a range of papers in the field which went largely un-noticed.

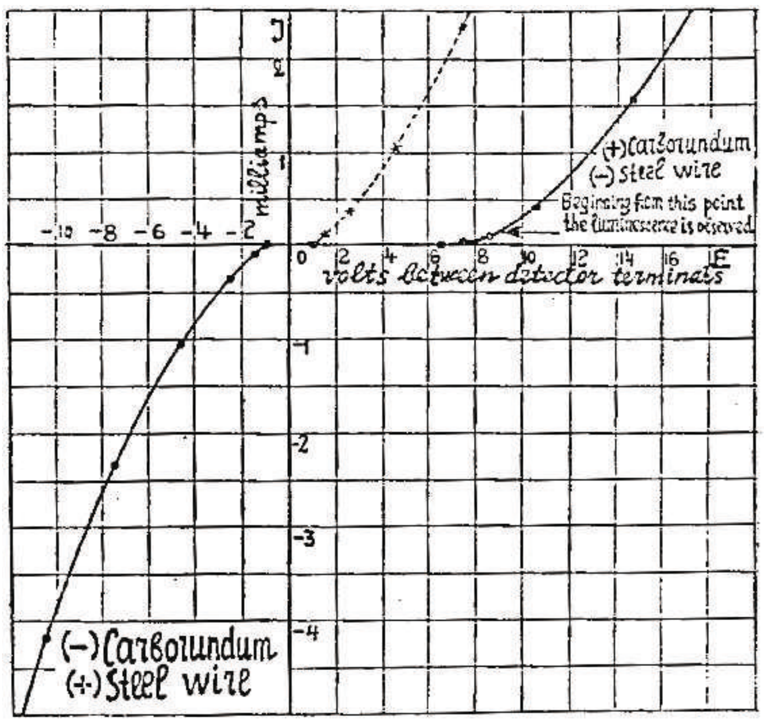

Figure 3.1 I-V characteristics of a carborundum [silicon carbide] detector, indicating the onset of light emission (Losev 1928)

Later in 1961, two experimenters from America, Gary Pittman and Robert Biard from Texas Instruments realised that GaAs ware capable of emitting infrared light whenever electric current was passed. This made it possible for Texas Instruments to receive the patent for the first infrared LED.

An employee of General Electric, Nick Holonyak made the first visible spectrum LED in 1962. Having developed the first practically visible spectrum, he has since then been considered by many as the founding father of the light-emitting diode (LED). His student, George Craford made the first invention of the yellow LED while at the same time managing to improve the brightness of the red-orange and red LEDs in 1972 (Zheludev 2007).

Another milestone in the development of LEDs was the use of Gallium Aluminum Arsenide (*GaAlAs*) materials that emitted light with ten times more brightness than before. This, allowed LEDs to be used in medical application, in fibre optic data transmission and bar code scanners. However, wider adoption was not possible, as LEDs emitted light in the red 660nm wavelength, thus limiting their use. During this period, laser diodes were also being developed and with the combination of both technologies, Indium Gallium Aluminum Phosphide (*InGaAlP*) was used in LEDs. It was thus possible to produce orange, yellow, green and red LEDs (Schubert 2006).

With such developments it became possible for the LED technology to be more widely adopted. Future developments on LEDs helped improve brightness, colour and efficacy. In 1976, Thomas P. Pearsall from Bell Telephone Laboratories, created the first high-efficiency, high-brightness LEDs for fibre telecommunications, by inventing a new set of semiconductor materials for fibre transmission.

After their successful development, the first LEDs were used to replace neon indicators and incandescent lamps. However, in the 1980s, LEDs were very expensive and therefore made most of the equipment expensive. Further improvements in the technology made it possible for them to be used in radios, telephones, calculators and TVs (Forster 2005). Still though, there was room for improvement in order to achieve more efficient and powerful LEDs, through continuous testing and research on LED materials and associated technologies, which has led to current LEDs, that are capable of being used for general illumination purposes, as will be discussed in the following sections.

3.3 Working Mechanisms of LEDs

An LED light source is a small chip comprised of layers of semi-conducting material. LED packages may contain just one chip or multiple chips that are mounted on a heat-conducting material called a heat sink and all enclosed in a lens. This LED device can be used separately or in arrays to produce light. LEDs when mounted on a circuit board can be programmed to include lighting controls such as dimming, light sensing and pre-set timing. The circuit board is mounted on another heat sink to handle the heat from all the LEDs in the array. The system is then encased in a lighting fixture or an “LED bulb” package.

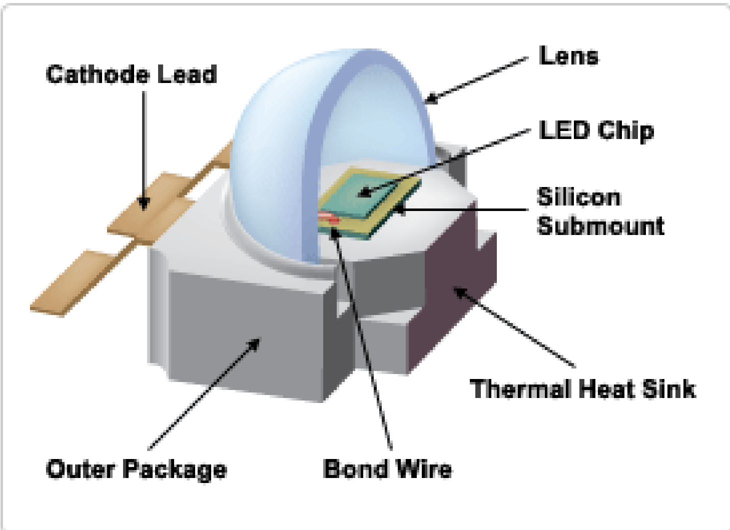

Figure 3.2 Section trough an LED (source: Energy Star)

The working mechanism of an LED to produce light lies in the semiconducting material it is made of. An LED consists of a chip made of a semiconducting material. The material is usually doped with some impurities in order to create the P-N junctions, which are made of p-type and n-type semiconductor materials placed in contact with each other. For other types of diodes, current tends to flow easily from the anode or the P-side to the N-side, also known as the cathode. However, this does not take place in the reverse. This process is what makes it possible for the semiconductor to function as a LED (Humphreys 2008). Holes and electrons, also known as charge carriers, flow into the P-N junction directly carrying different voltages. The moment the electron meets the hole, it falls into a low energy level thus causing it to release some energy. This kind of energy is released in the form of photons.

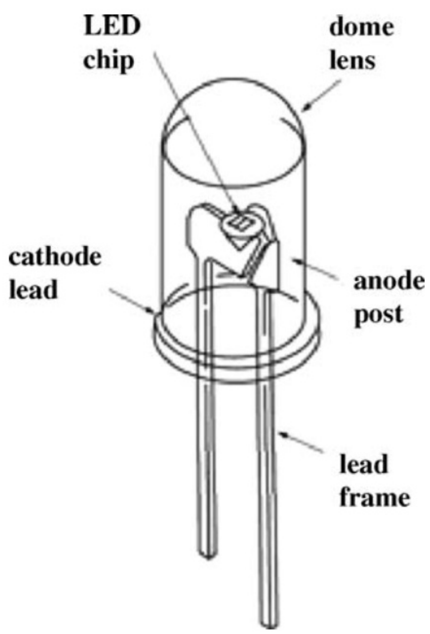

Figure 3.3 Structure of an LED (Yeh and Chung 2009)

In the emission of light from an LED, the wavelength is crucial, as it determines the colour temperature of the light produced. The colour of the LED will usually depend on the band gap of the material that is used in the formation of the P-N junction. In germanium or silicon diodes, the holes and electrons recombine through the use of non-radiative transition (Craford 2008). That being the case, it is important to note that the materials that have been used for the LED will always have a direct band gap such that they have energies that correspond to visible, near infrared, or near ultraviolet lights.

With advances in material science, it has been possible to have other devices with shorter wavelengths and as a result being able to emit different colours of light. Such lights are therefore applied uniquely based on the intended purpose (Thomas 2007). The LEDs are built mainly on the N-type substrate such that the electrode has been attached to the P-type that is deposited as a layer on the surface. The majority of LEDs used for commercial purposes are known to use different substrates such as sapphire. As discussed above, it is worth noting that the materials used and the junction determine the light-optical characteristics and therefore applying them accordingly is important in order for the LED to meet the characteristics required for the intended purpose.

Currently there is on-going research conducted on materials science to come up with different substrates that will be used depending on the intended purpose of the LEDs. This will also be done to improve the efficiency, durability and the applicability of the LEDs. At present, most of the materials used in the production of LEDs tend to have a high refractive index. The higher the refractive index of a material, the more light will be reflected backwards and absorbed by the material at the interface. Hence light extraction in LEDs is very important (USDOE 2009d). The ability to extract light from LEDs is necessary in their functioning. This is why the area is being advanced and researched towards future development of the devices. In the future, LEDs are expected to be even more energy efficient with better light producing properties and, thus, even more applicable for use in buildings and many other functions where a source of light is needed.

3.4 White Light LEDs

White light from LEDs can be produced in three ways. One method of producing white light is to combine the light of red, green and blue LEDs together, but this method can create problems in determining white light for people with colour deficiencies. Another, less common way is to combine an ultra-violet LED with red, green and blue phosphors. The most popular method though, is the addition of a photo luminescent phosphor combined with an InGaN LED, which creates a blue-white coloured light (Rea 2000).

There has been a widespread application of such LEDs mostly for decorative purposes or signage applications, but now with the development of 'warmer' colour LEDs, their use in general lighting applications is increasing. Some of the advantages and disadvantages of Phosphor conversion and RGB white LEDs are presented in the table below, where it becomes clear that even though RGB white LEDs are more flexible, phosphor converted white LEDs hold the key to wider adoption due to their lower cost and higher efficacies, which are expected to further improve as technology evolves. These advantages also provide the reasons why phosphor converted white LEDs will be the focus of this thesis from this point forward.

Table 3.1 Some advantages and disadvantages of Phosphor conversion and RGB white (USDOE 2012c)

	Advantages	**Disadvantages**
Phosphor conversion	Most mature technology High-volume manufacturing processes Relatively high luminous flux Relatively high efficacy Comparatively lower cost	High CCT (cool/blue appearance) Warmer CCT may be less available or more expensive May have colour variability in beam
RGB	Colour flexibility, both in multi-colour displays and different shades of white	Individual coloured LEDs respond differently to drive current, operating temperature, dimming, and operating time Controls needed for colour consistency add expense Often have low CRI score, in spite of good colour rendering

3.5 Electrical Characteristics and Quality Control

LEDs are very small devices that typically operate at currents less than 1 Amp and low voltages, of 1.5 - 4.0V. As they are such small semiconductor devices, variation in performance due to manufacture is to be expected. Hence all LEDs are tested and grouped based on their performance. The process is called binning. This allows for LEDs to be purchased based on specific performance criteria, with the ones most valued exhibiting the least variation. In the future, with the use of better manufacturing techniques, it is expected that these differences in performance between LEDs will diminish (Forster 2005).

3.6 Lumen Depreciation

Over time the light output from a light source decreases, and that is also the case for LEDs. The main cause for lumen depreciation in LEDs is a rise in temperature in the P-N junction. Inadequate removal of heat by the heat sink, combined with potential rises in ambient temperature, can lead to lower light outputs in the short term, and permanent reductions if the heat is not removed. In either case though, LEDs rarely fail catastrophically and continue to operate, but with much lower light outputs.

For many high powered LEDs, light emission of 90% is still possible after 9-10,000 hours, but this is not the case for all LEDs, as shown in Figure 3.4.

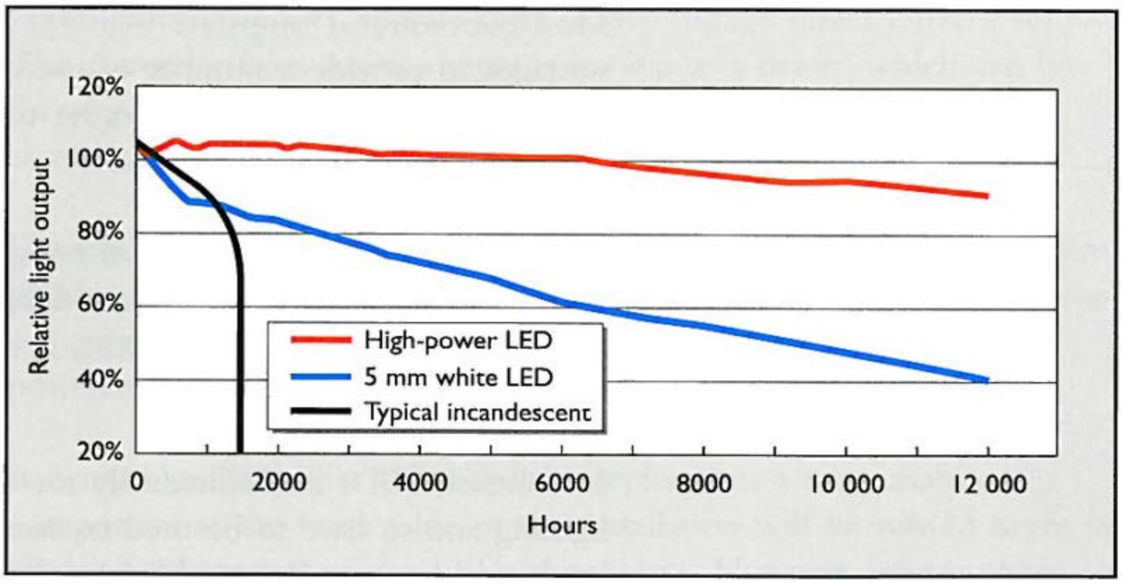

Figure 3.4 How light output decreases with burning hours (Forster 2005)

43.7 Lamp Life

As it would take years to test the real life of LEDs, and by then such products would be surpassed by other LEDs, estimations on LED life are made through laboratory testing. A companion method (IES LM-21) to the IES LM-80 testing procedure has been developed by IESNA that allows for the testing of LED life as IES LM-80 was developed for other light sources.

Due to the long expected life of LEDs and their lumen depreciation, the concept of ‘Useful LED Life’ has been proposed by the Alliance for Solid State Illumination System and Technologies (ASSIST), a group led by the Lighting Research Centre (LRC), of Ranssellaer University, New York. This is the point at which light output has reduced to a specific percentage of the original. For decorative applications, this would be L_{50} (i.e. time taken until lumens have reduced to 50% of the original). For the case of general lighting, that is more relevant to this thesis, L_{70} is proposed as research has shown that most occupants in an office environment would not perceive a gradual reduction over time of 30% in general illumination (Rea 2000).

Most manufacturers are quoting lifetime figures of 50,000 hours, or even 100,000 hours for L_{70}, but these figures are yet to be measured in the field, hence it is important at this early stage of LED technology to be more cautions on such figures. In any case though, LEDs appear to offer longer lifetimes than existing light sources.

Table 3.2 Lifetime data, quoted by manufacturers (USDOE 2009b)

Light Source	**Range of Typical Rated Life (hours) *** *[Source: lamp manufacturer data]* (varies by specific lamp type)	**Estimated Useful Life (L_{70})**
Incandescent	750 - 2,000	
Halogen incandescent	3,000 - 4,000	
Compact fluorescent (CFL)	8,000 - 10,000	
Metal halide	7,500 - 20,000	
Linear fluorescent	20,000 - 30,000	
High-Power White LED		35,000 - 50,000 *(or higher by some manufacturers)*

3.8 Operation and Maintenance

Owing to their long life and small size, it is unlikely that they will be replaced at an individual LED device level throughout their service life. More likely, a whole luminaire will be replaced. However, there are instances where individual LEDs might fail within a luminaire and in such cases it is important that some spare LEDs are available. The electronic drivers on the other hand, that powers the LEDs, depending on the specific design each case, might fail sooner than the LEDs. This reduced maintenance can provide savings over the life time of LEDs, in comparison to other light sources that need to be replaced sooner (Nadarajah Narendran and Y Gu 2007), (Longer 2011). In fact, savings on maintenance is currently one of the primary drivers of market adoption of LEDs in several markets (Navigant Consulting 2011)

3.9 Optical Characteristics

Optics is an important field in physics used to study the behaviour of light, including how different materials interact to produce different forms of light. This section will deal with the optical characteristics of LEDs, as this knowledge is important in order to understand what distinguishes LEDs from other forms of lighting. More specifically, it will deal with the light output of LEDs in terms of quantity of light, distribution of light and colour characteristics. Other aspects such as dim-ability and control will also be considered.

3.9.1 Luminous Efficacy

Efficacy of a light source is a measure of how much light is emitted from the source in relation to the input power to the light source. As in the case of other light sources, luminous efficacy is the luminous flux (in lumens) divided by the input power (in Watts), providing a unit of Lumens-per-Watt (lm/W). It is important to note that luminous efficacy is tailored for human vision (i.e. 400 - 700nm of wavelengths), thus any UV or infra-red radiation emitted from a light source is not accounted for. Also, losses due to the efficiency of the LED driver are not taken into consideration. Hence this is very commonly used for rating stand-alone lamps and in this case single, or small packages of LEDs.

For other light sources, standard test procedures are used to rate luminous flux. However, there is currently no industry standard test procedure for rating the performance of LED devices. Typically, manufacturers take measurements both for purposes of luminous flux and colour, which also addresses the binning of LEDs into groups of equal performance, by testing LEDs in a controlled environment of 25 ^{o}C and providing a short pulse of power of less than 1 second. This short time is necessary as they are tested without the use of a heat sink, in which case they would immediately fail at longer operating times.

Even though currently there are no standards in place for LEDs, it is expected that in the near future the issue of standardisation of the test procedures will be resolved, with the use of test procedures such as: LM-79-08, developed by joint IESNA-ANSI committee ("IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products," designated LM-79-08, was developed by a joint IESNA-ANSI committee on SSL and published in 2008).

Luminous efficacy values for LED devices provided by manufacturers under the above process can range from 50-120 lm/W, or even higher in some cases. The efficacy of LEDs has been improving every year, meeting targets that had been set and in many cases surpassing them. Figure 3.5, shows the progress of LED efficacy over the years and predictions for the future.

Figure 3.5, shows that the efficacy of LEDs has seen a dramatic increase in the past few years and the predictions for the future are suggesting a sustained improvement every year. Efficacies achieved in the laboratories are always higher than the efficacies available commercially.

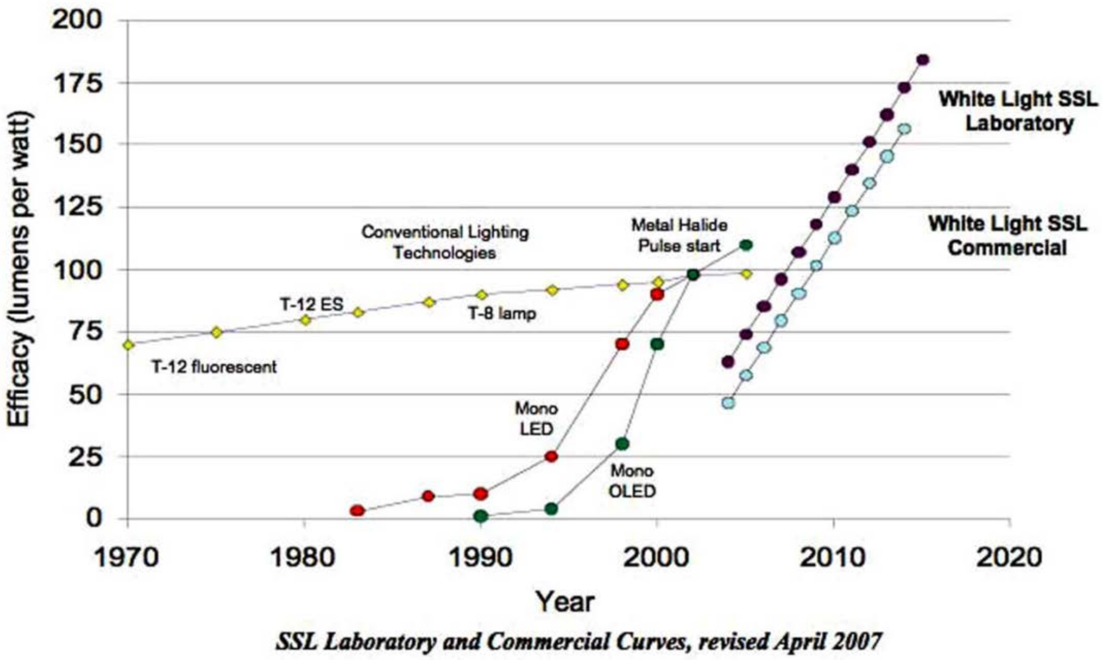

Figure 3.5 US DOE forecast of LED efficacy improvements, relative to current conventional lighting technologies and monochromatic red LEDs and green OLEDs (USDOE 2012c)

3.9.2 Light Distribution

Light emitted from most existing light sources has a wide output angle, whereas light emitted from an LED is usually a more focused beam of light. This means that, in the case of a small room, one incandescent or compact florescent lamp would be able to illuminate the whole room whereas, in the case of LEDs, only a small portion of the room would be lit - that to which the LED beam was pointing. In order to illuminate a whole room, multiple LEDs would need to be used, each pointing in different directions.

Figure 3.6, shows an example of a typical polar distribution from a commercially available LED, where the directionality of the light source is evident.

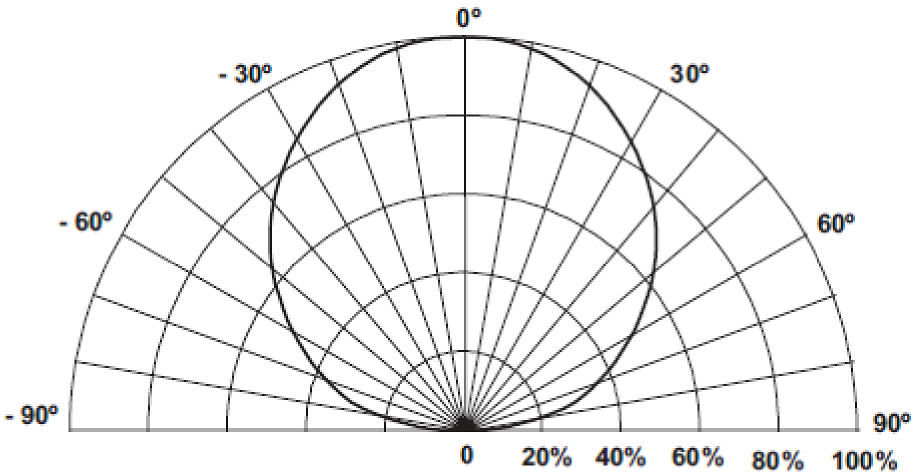

Figure 3.6 Typical light distribution from a white LED (source: Philips Lumileds)

This directionality can also lead to confusion when comparing light sources based on their luminous efficacy. The lumens used to account for the amount of light emitted have no regard to directionality of the light source. Hence when comparing the luminous efficacy of LEDs to other light sources, what is actually being compared is the amount of light directed to the front of each light source.

Taking the example above of a room it is possible to have the same luminous efficacy for all of the light sources, but only some of them managing to illuminate the whole room. Therefore, distribution of the light emitted is an important parameter on optical performance and for LEDs it should be taken into account in conjunction with luminous efficacy.

3.9.3 Colour Characteristics

LEDs come in a range of sizes and shapes. The colour of the plastic lens is often an indication of the colour of light emitted. The spectral properties of LEDs is something that distinguishes them from other types and sources of light. The radiant power is usually more monochromatic in comparison with other types of lighting, which is also the case with lasers as they emit in a narrow wavelength band (Craford 2008). This means that LEDs lack a broadband emission spectrum, but their narrow band can lie anywhere within the visible spectrum.

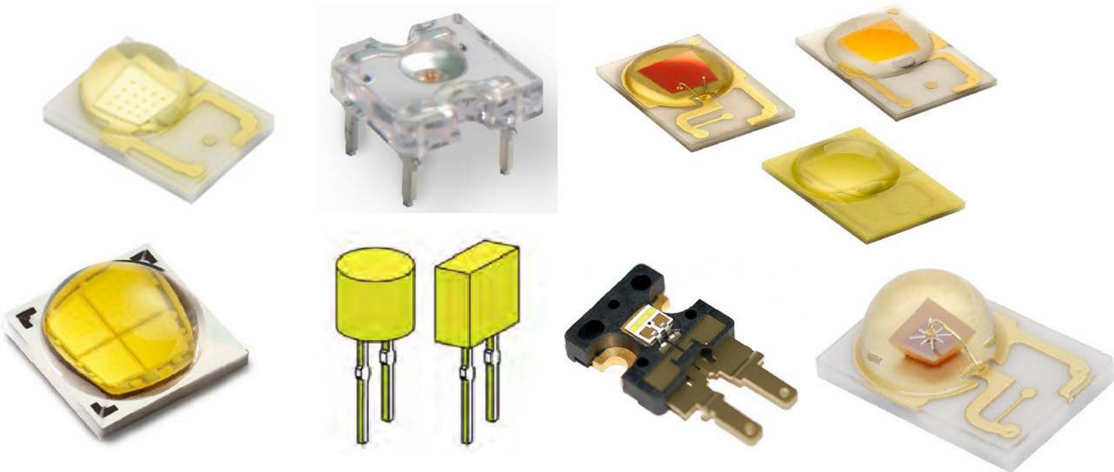

Figure 3.7 Variety of shapes and sizes of LEDs in production (source: Philips Lumileds)

One of the unique characteristics of LEDs is a pronounced peak wavelength (λ_p), which is determined by the semiconductor material used during the manufacturing process. As shown in Figure 3.8, the spectral parameters that quantify this characteristic of LEDs are centre wavelength ($\lambda_{0.5m}$), centroid wavelength (λ_c), and dominant wavelength.

As discussed in Section 3.4 (White Light LEDs), there are a number of methods to produce white light, with the most common one using a phosphor on a blue, or near ultraviolet emitting die (LED). The colour characteristics of the light emitted are usually specified as colour temperature and colour rendering.

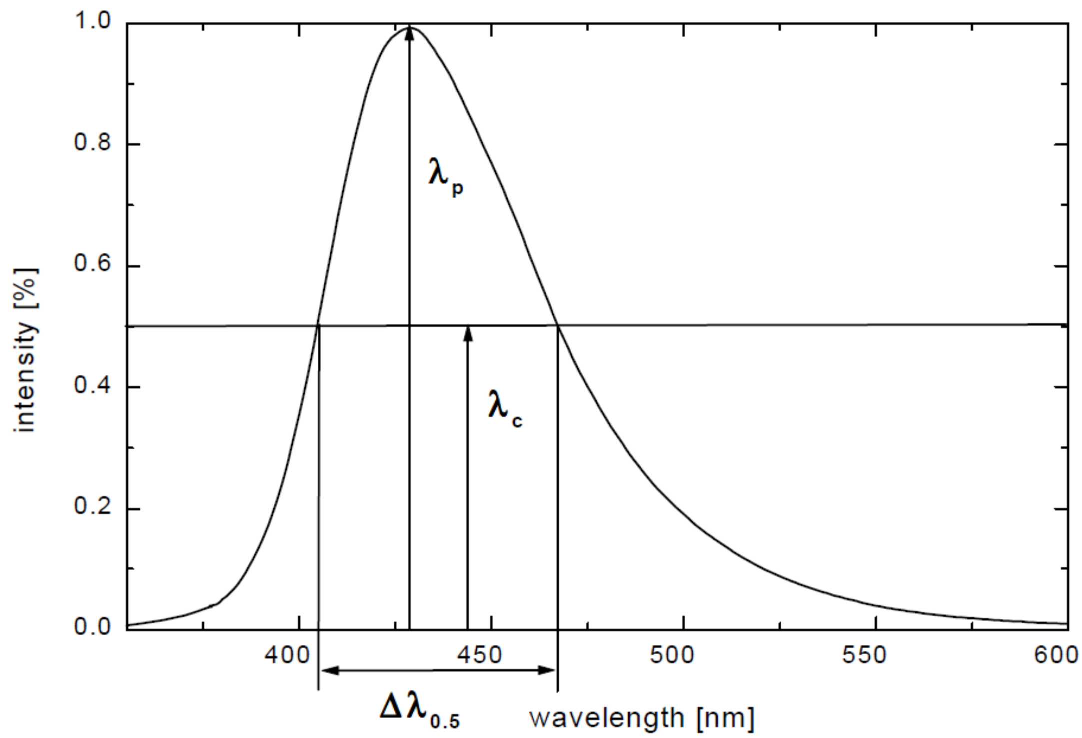

Figure 3.8 Spectral parameters of a typical blue LED (Instrument Systems 2010)

3.9.3.1 Colour Temperature

The colour temperature of a light source is an indication of colour appearance and is typically characterised as ‘cool’, or ‘cold’ (indicating a bluish colour), or ‘warm’ (indicating a yellowish colour). The metric used in this case is Correlated Colour Temperature (CCT), which relates the appearance of a light source to the appearance of a theoretical black body when heated. When a black body is heated, it progressively turns from red to orange to yellow to white and then to blue. CCT (in Kelvin) is the temperature needed for the black body to match its colour to the colour of the light source. CCT is not linked to the colour of the illuminated objects.

LEDs producing a ‘cold’ light (often above 5000 K) are the ones with the highest luminous efficacies, although ‘warmer’ LEDs (2600-3500 K) are increasing improving their luminous efficacy too (USDOE 2009a). In office lighting, cooler colour temperatures are acceptable, in contrast to homes, where warmer colours are desired.

The use of CCT can, in some cases, lead to confusion as two light sources with the same CCT can be perceived slightly differently. Hence, the American National Standards Institute (ANSI) has developed a metric called Duv that addresses this issue by quantifying the distance between the chromaticity of a given light source and the black body radiator of equal CCT (ANSI C78.377-2008).

3.9.3.2 Colour Rendering

Colour rendering relates to how accurately colours are rendered on surfaces by a light source. The most commonly used metric for light sources is the Colour Rendering Index (CRI), which measures how ‘true’ a light source is compared to a reference source. The index number can range from 1-100, with 100 being highest number that can be obtained and indicating that the light source renders colours in an identical way to the reference light source.

CRI was developed for light sources other than LEDs, with different spectral power distributions, and has been in wide use for many years. For LEDs, CRI can only really serve as a rough guideline for performance. The CRI of LEDs is improving and currently warm white LEDs are available with a CRI of 80 and above (USDOE 2009a).

The inadequacies of this method to fully characterise the performance of LEDs is becoming more apparent though, as CRI is based on how well 8 colours that do not span the full range of object colours are rendered. This can lead to situations where some white LEDs that actually make object colours appear more vivid score a low CRI, and some LEDs that render red object colours very poorly to score high a high CRI.

The International Commission on Illumination (CIE) in their Technical Report 177:2007 has recognised this and does not recommend the use of CRI for LEDs. The CIE's TC-1-69 technical committee was commissioned to develop and recommend a new metric, but no agreement has been reached yet (Bodrogi et al. 2009).

The first proposal to be published and formalised clearly was the Colour Quality Scale (CQS) by the National Institute of Standard and Technology (NIST) and is under consideration by the CIE. It uses the same fundamental method as CRI, but rather than assess colour fidelity as CRI, it assesses overall colour quality of light sources, by using 15 colours instead of 8 (Davis and Ohno 2005) (Ohno and Davis 2010). Based on psychophysical experiments, some improvements to the CQS have been suggested by Pousset et al (2010) to further improve CQS.

3.9.4 Dimming

Dimming is a feature that can be very useful in lighting, as it allows for reduced illumination levels and thus reduced energy consumption, when daylight can provide a lot of the light. Dimming equipment for existing light sources is very commonly found in buildings, but this is not necessarily compatible with LEDs.

The electronics of LEDs are often incompatible with the dimmers that were designed for incandescent lighting that are so commonly used, especially in residential buildings. An LED driver, in this case, may be damaged by current spikes or not receive enough power to operate at lower dimming levels. In the case of dimming controls designed for fluorescent lighting though, there is more potential there for LEDs to be used as well, making them more suitable for retrofitting applications.

LEDs can be dimmed by reducing the drive current. The most common LED drivers use pulse width modulation (PWM) to control input power to the LEDs, by turning LEDs on and off at high frequency, varying the total on time to achieve perceived dimming. At frequencies above 120 Hertz, this would not typically be perceived by the human eye. If a dimmer is specifically designed for LEDs, or the existing dimmer has been appropriately matched with the LED driver, dimming is possible down to 5%, or even less (Gu et al. 2006).

For phosphor converted white LEDs a study conducted by Dyble et al. (2005), showed very little chromaticity shift when the light output was reduced from 100% to 3%. In contrast, an RGB white LED showed very large chromaticity shifts, over the same range. The technology continues to evolve in this area, but phosphor converted white LEDs which are the focus of this thesis, are already performing well in this area, even when dimmed to a very low level.

3.10 Thermal and Energy Characteristics

Of the total energy in an LED, approximately 80% of the energy supplied is usually dissipated as pure heat while only 20 per cent of the energy ends up being converted to light that is visible to the eyes. That being the case, thermal management of LEDs is something that needs to be considered towards a reliable performance of the devices as conventional sources for lighting (N. Narendran and Y. Gu 2005). In contrast, in an incandescent bulb, approximately 8% of the energy supplied to the bulb is directly converted into visible light. The remaining is dissipated as heat to the surrounding air (19%) and infrared radiation (73%), which is then also converted into heat upon reaching surfaces. That means most of the electrical energy supplied to the lamp is converted into heat making it a very inefficient source (Narendran 2011).

This section looks at the various aspects affecting the thermal and energy performance of LEDs.

3.10.1 Thermal Effects

A very important aspect of LED performance is the junction temperature. In the junction, due to its small area, high power densities are developed and hence there are difficulties in dissipating the heat. As a consequence, the temperature tends to rise with use, also known as the LED die temperature, and this is a critical characteristic determining the performance of an LED. Any increase in the LED junction temperature will result in adverse effects on the output of the light as well as the LED forward voltage, which are inversely proportional to the junction temperature (Jayawardena et al. 2011), (Dong and Narendran 2009). Narendran and Gu (2005) confirmed by experiments that the lifetime of LEDs declines exponentially with the rise in junction temperature. Moreover, another effect of rise in junction temperature is a chromatic shift in the light emitted (Figure 3.9). It is also worth noting though, that there can be significant differences between LEDs as different manufacturers use different standards in their manufacturing process.

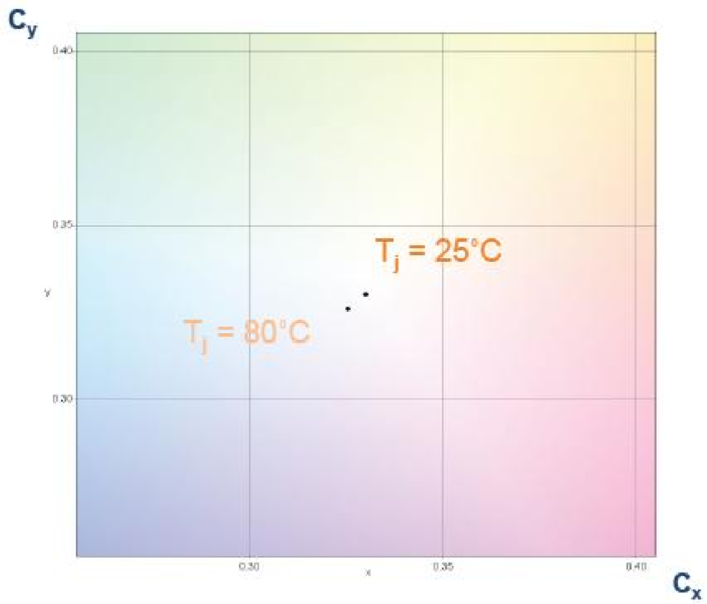

Figure 3.9 Shift in chromatic coordinates with rising temperature of LED junction (Swamy 2010)

LEDs will emit different amounts of energy depending on the polarity, voltage supplied and the operating environment. Depending on the construction and the physics of the semiconductors, the performance and heating capacity of the LEDs will vary significantly. It is also worth noting that heat is dissipated by the LEDs themselves as well as their electric transformer. The values cited by manufacturers in terms of luminous flux, or in efficacy, are usually based on a junction temperature of 25 ^{o}C and short operation (20-25 millisecond pulse). In a real room and in the context of a luminaire, the actual temperatures developed would be much higher, meaning that there would be a drop in performance due to this.

Studies have shown that even if LEDs with heat sinks are positioned in a well designed luminaire, there will be a drop in luminous flux of 10-15%, compared to the rated value (USDOE 2009a). This is important, as it is a factor often neglected when predicting the performance of LEDs. In this thesis, custom LED luminaires were designed, so that measured performance data can be obtained that would account for such effects.

The heat that is generated in the P-N junction must be carried to the environment. The energy that gets converted into light carries minimal heat with it and most of it gets transferred to the back of the LED with the use of a heat sink and through conduction. Some models predicting the P-N temperature can be found in Domke and Wandachowicz (2008) and Jayawardena et al. (2011)

A careful thermal management design is therefore necessary for an LED failure-free operation, as in any other case there would be adverse effects on photometric and electric characteristics. The use of a heat sink is therefore necessary in most occasions, so that heat can be extracted. A lot of research is being conducted in the field of heat management and some novel methods have been proposed for heat extraction. One example can be found in Liu et al. (2006). As this area progresses, improvements are expected so that LEDs in the future will have the heat generated by them removed faster and more efficiently. It is important to note though, that heat dissipated by LEDs is also a function of efficacy (lm/W) as the higher the efficacy the less heat generated, so improvements on this part of the technology have an impact on heat management as well

When rises in temperature occur, as illustrated in Figure 3.10, reduced light outputs and voltage shifts can be expected, which can also lead to permanent damage of the LED if the expose is prolonged.

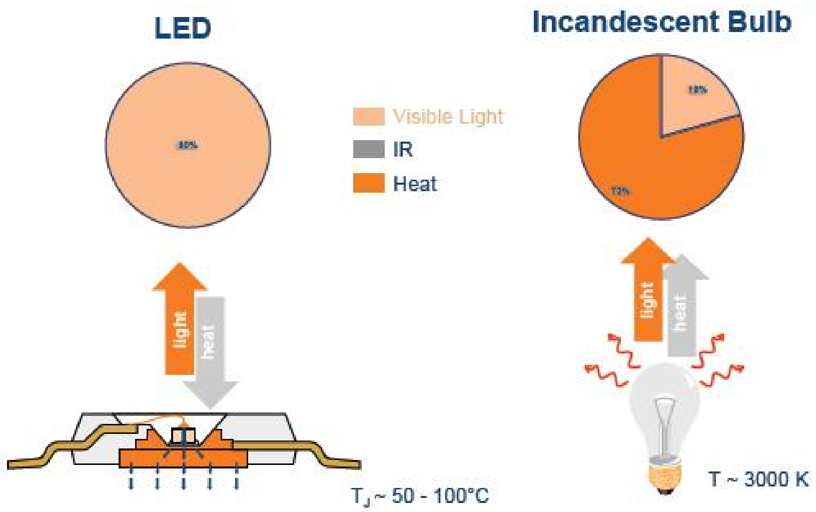

Figure 3.10 Contrasting energy conversion between and LED and an incandescent bulb (Swamy 2010)

The office luminaire type that is investigated in this thesis (ceiling tile recessed type), is the one that has high potential to accommodate such effects, as there is a significant area (600mm x 600mm) of space where the LEDs can be placed. This avoids having to place LEDs very closely together and thus making heat extraction simpler. Furthermore, because heat is extracted by heat sinks at the back of the luminaire, it can be dissipated into the ceiling void above passively. Examples of other recessed luminaires, where the LEDs and their heat sinks are all within a metal can, would not allow for the same potential. The thermal performance of such luminaires has been studied by Dong and Narendran (2009).

3.10.2 Driver Losses

LEDs function under DC voltage and hence a power supply is needed to convert unregulated AC voltage to constant DC current. For LEDs, this power supply is called a driver and for high brightness LEDs appropriate for general illumination, voltages would be between 2-4 volts DC, with a current of 200-1000 mA. The equivalent to a driver for LEDs, is the ballast, for fluorescent and high-intensity discharge (HID) light sources (USDOE 2009a).

Drivers incur losses in this conversion and thus typically there is a 85% efficiency in the conversion process. This should also be accounted for in the case of LEDs, as quoted luminous efficacies by manufacturers do not usually take this into account. For this thesis, in order to get reliable data on the LED luminaires and take into account of this effect, custom LED luminaires were constructed and measured in use.

Even though LED life is long, the life of the driver that is always needed to power them is typically less, thus necessitating the need for a replacement driver before the end of the useful life of the LEDs and making them the weakest link in the context of an LED luminaire. Han and Narendran (2009) have studied this among others and developed an accelerated life test method for LED drivers. Predictions can vary significantly, but two examples reported are in the range of 11-14,000 hours, which is significantly less than LED life spans. Research in this area is also on-going and improvements are expected in terms of reliability and lifespan, rather than efficiency.

3.10.3 Efficacy and Efficiency

In Section 3.9.1, luminous efficacy was introduced, which takes into account the sensitivity of the human eye to light and discounts UV and IR radiation. Even though this unit includes Watts, it is not sufficient to describe all the processes taking place in an LED luminaire. Efficacy of a light source, takes into account UV and IR radiation, but since there is almost no UV and IR radiation emitted from LEDs, this makes both virtually the same.

As discussed in previous sections, losses in the driver of the LEDs and well as the heat sinks should be taken into account. Due to the nature of the measurement of luminous flux, these effects are not accounted for in luminous efficacy. Considering that these are typically the values reported by manufacturers, a lot of confusion exists in the literature regarding the efficacy of LEDs, as they are treated the same as existing light sources. An example of this, would be studies quoting efficacies of LEDs in the range of 120+ lm/W (as quoted by manufacturers), whereas in the context of heat gains and thermal performance of a building, this is incorrect, as the figure of 120 lm/W does not take into account loses incurred due to driver and heat sink, or even light loses in the luminaire itself. This, leads to an over-estimation of the actual efficacy achieved by LED luminaires.

In the context of an LED luminaire, where a driver and heat sinks are present, the term that accounts for all these effects is luminaire efficacy, which is the total lumens out of the luminaire, divided by the input watts. In this case, all effects taking place are taken into account. Because the design of a luminaire (whether LED or not), will redirect and shield some of the light emitted, to account for this and indicate the actual lumens emitted by a fixture, the term ‘fixture efficiency’ is used which is defined as the lumens out of the luminaire divided by the rated lumens, and is given as a percentage.

```
Luminaire Efficacy = Lumens out of luminaire / Input Watts

Fixture Efficiency = Lumens out of a luminaire / Rated Lumens
```

Due to the different nature in which light is produced by LEDs compared to other light sources and the fact that heat sinks and drivers need to be used, existing terms widely used to compare other light sources are not always appropriate to be used for comparing them with LEDs. The performance of individual LEDs can be very different when put together into the housing of a luminaire. Even in the same luminaire, differences in performance will be observed depending on the spacing between LEDs, the heat sinks and drivers used. Therefore, it makes more sense if LEDs are compared to other sources, in the context of a specific LED luminaire each time. Examples of typical luminous efficacy for various light sources are given in Table 3.3.

Table 3.3 Typical luminous efficacies for various light sources (USDOE 2009a)

Light Source	**Typical Luminous Efficacy Range in lm/W** *(varies depending on wattage and lamp type)*
Incandescent (no ballast)	10-18
Halogen (no ballast)	15-20
Compact fluorescent (CFL) (incl. ballast)	35-60
Linear fluorescent (incl. ballast)	50-100
Metal halide (incl. ballast)	50-90
Cool white LED >4000K (incl. driver)	60-62
Warm white LED <4000K (incl. driver)	27-54

This information was critical to this thesis, as the intended purpose was to investigate the effect of LED luminaires on heating and cooling load demands. Hence an in depth understanding of how heat flows in an LED luminaire and how electricity is converted to heat was necessary.

3.10.4 Electrical Energy and Overall Building Energy Demand

Most of the research currently being conducted is looking at ways of improving the efficacy and light output of LEDs by developing better heat management methods and using better materials. In addition, ways of characterising their performance in terms of light output and quality of light are also being researched.

In the context of buildings where LED luminaires are used the focus is on potential reductions in electrical load demands. This though, discounts the effects that lighting has on the thermal environment and hence on space conditioning loads. All electrical energy required to operate them will eventually be converted into heat and in the case of LEDs as described in Sections 3.10.1-3, most of that heat will be emitted to the back of the LED. This heat will affect the thermal environment of the spaces they are in. Therefore, the effect of LEDs on overall building energy demand, which includes electrical energy demand as well as space conditioning load demands, has not been thoroughly studied, to the knowledge of the author. This thesis is focusing on the effects of LED luminaires on heating and cooling load demands in offices and complements studies on the effects of using LEDs on electrical load demands.

3.11 Other Properties and Characteristics

Beyond the above mentioned aspects of performance, LEDs exhibit a range of other characteristics. Most notably that they are resistant to mechanical failure as there are no moving parts. There is no need for a warm-up period like other light sources, hence they can be turned on instantly. They also do not contain mercury, which is an important environmental and health consideration.

3.12 Configurations of LEDs

There is great flexibility in the way in which LEDs can be put together to produce light, especially in the context of a luminaire. They can be stand alone, as single LEDs producing light; they can be put together as a series of single LEDs in a luminaire, or put together as a group of LEDs, with each group acting as a unit.

In terms of layout in a luminaire, LEDs can be put together both in series and in parallel. This is because they can function in the same manner and control their polarities. The connection also improves their performance and reduces their breakdown especially when expected to function for long. Therefore, LEDs exhibit great flexibility in terms how they can be put together in the context of a luminaire.

3.13 Limitations

One of the main problems concerning the use of LEDs for general illumination is the management of heat generated by LEDs. Especially when LEDs are put closely together, this increases the amount of heat generated in a small area and thus makes it very difficult for that heat to be dissipated as the surface area involved is very small. This, as described earlier, can have adverse effects on the junction temperature and thus their optical performance and lifetime (US DOE 2012).

Even though LED efficacies are improving every year, LED luminaire efficacies are the important ones and these are still not significantly better than existing light sources (USDOE 2008), (Narendran 2011). Another limitation of LEDs that are commercially available is the colour temperature of the white light that they produce, which is considered as cool white in most cases. This inhibits their wider adoption especially for domestic applications where warm white light is typically preferred. Advancements in technology in this area are expected to improve the colour temperature of light produced by LEDs, bringing them closer to the warmer and more familiar light produced by incandescent lights (Brodrick 2007). Warmer white LEDs already exist, but they are much more expensive than cool white.

The high cost of LEDs is another barrier towards wider adoption. A number of case studies do exist that demonstrate that, even though the capital investment in LED lighting is higher than other sources, the investment is paid back over a few years, as in the case of a supermarket in Kansas USA, where LED lights were fitted, resulting in 12% total cost savings due to reduced energy and maintenance costs over 10 years (PNNL 2011). LED efficacies from that period have improved, hence savings are expected to be even greater now. Unfortunately, in the majority of cases the capital cost is what is typically considered by home owners, as well as businesses, although some signs of change are appearing in commercial applications where the benefits in the long run have become apparent.

Finally, there are specification and testing issues regarding LEDs. Other light sources have been widely used and studied for many years and thus tests and specification procedures have been tailored to their performance. LEDs require new methods for assessing their performance and comparing them to existing light sources. A significant amount of research is being conducted in this area, but there are still no international standards regarding the specification and testing of LEDs, which leads to a lot of confusion regarding their performance.

3.14 Opportunities

Research and development is on-going to improve the performance of LEDs and to make sure the devices are more reliable, long lasting and capable of solving the needs of different users (Navigant Consulting 2010). A range of materials are being produced to improve the performance of such LEDs and ensure they can be used in a range of applications, including alarm systems, signage, TVs and in the automotive and aerospace industries among others (Steigerwald et al. 2002). Other developments are concerned with reducing the chances of failure and resistance, as well as their size, thus making LEDs more applicable for lighting in applications where security and reliability is of utmost importance.

Another area, where LEDs can help is with reducing mercury disposal to the environment. Currently, fluorescent lighting is the dominant light source in offices and compact fluorescents are increasing their share in the residential sector. A lot of these light sources, when replaced, will end up in land field sites and thus pollute the environment with mercury (Humphreys 2008). As LEDs contain no mercury, there can be an additional environmental benefit associated with their increased use.

For general illumination purposes, there has been a recent increase in the adoption of LED lighting for commercial applications and it is expected that, with improvements in technology, a wider adoption will be achieved (Brodrick 2007). Economies of scale will also help to reduce the cost of LEDs and thus remove one of the main barriers to wider adoption (USDOE 2012d). It has been suggested that by 2035, LEDs should provide the majority of light sources (Richards and Carter 2009).

The recent track record of performance improvements suggests that LEDs will continue to improve on their efficacy, which will make them a viable solution for new buildings with the potential to reduce energy consumption and help meet carbon reductions. Their flexibility also suggests that they are suitable for retrofitting the existing building stock, which represent the majority of buildings and where a lot of savings can be made. In that respect, LEDs present an easy and fast route towards major reductions in energy and emissions.

The most important aspect though, regarding the performance of LEDs, is their continuous improvement every year, which promises that many of the issues currently faced with LEDs will be alleviated in the near future (Krames et al. 2007).

Finally, due to their flexibility, it would be reasonable to expect a small revolution in terms of lighting design with the use of LEDs. Currently, lighting designers account for the lighting performance and size of various light sources and then design, based on those limitations, therefore significantly restricting their design options. With LEDs, it will be possible to first specify any desired lighting environment for a given space and then design the LED lighting system that fulfils that purpose. In this respect, it is also not unreasonable to assume that custom LED luminaires, providing the desired performance either for new, or for retrofitting an existing building, will be common in the near future. For example, in the case of an office building where fluorescent lighting has already been designed and luminaires are in place, to order LED replacement luminaires, that provide the same (or a better) lighting environment by simply replacing the existing luminaires with new ones at the same positions, without requiring a new lighting layout and thus additional costs. This is an area that is explored in this thesis, as in the author's opinion, it represents a significant amount of buildings, where performance improvements need to be made, within a limited budget.

3.15 Summary

This chapter has reviewed the optical and thermal characteristics of LEDs and found that their technology is rapidly improving and is expected to surpass other lighting technologies in terms of efficacy in the near future. Moreover, the way in which light is produced significantly differs from other light sources. The main difference in their optical characteristics is that the light that LEDs produce is directional and that many LEDs are needed in a luminaire to produce enough light for general illumination.

For LEDs to operate in a luminaire a driver is needed as well as heat sinks in order to dissipate the heat that the LEDs produce. Both, introduce losses in luminaire efficiency and therefore a careful thermal design and management is necessary, as otherwise, increases in the P-N junction temperature of LEDs, will affect efficacy, lamp life and the colour of light.

The way in which heat is emitted from LEDs differs from other light sources, as most of the heat produced is emitted to the back of the LEDs from the heat sink that is attached to them. This presents an opportunity for using LEDs in recessed suspended ceiling tile luminaires, as this way the majority of the heat produced by lighting could be emitted to the ceiling void above a room. This thesis investigates this potential in offices, where heat gains from occupancy, equipment and solar gains can be high and thus reductions in heat gains from lighting could result in savings on space conditioning loads.

Chapter 4. Towards Low Energy Lighting Retrofitting in Offices

4.1 Comparing LEDs with Fluorescent Lighting Technology

From the previous two chapters, it became obvious that LEDs appear to have the potential to be used for general illumination purposes and with the expected improvements in performance, even surpass fluorescent lighting. There are a range of benefits that LEDs offer, compared to other light sources.

LEDs can emit light at any targeted colour temperature without the use of reflectors or filters, as required by other light sources. They have a very fast response time to lighting up, especially compared to fluorescent lighting where there is typically a warm up time required until they reach their maximum light output. Also, there is no detectable flicker with LEDs, whereas with fluorescent this can often be the case. This is especially noticeable as fluorescent light source age over time (Bullough, Hickcox, et al. 2011), (Bullough, Sweater Hickcox, et al. 2011).

They have very high shock resistance and cannot be destroyed by small vibrations, as they have no moving parts (Schubert 2006). Their life span, which is in the order of 40,000+ hours is significantly greater than incandescent which is in the order of 1,000 hours, or even fluorescent, which is in the order of 20,000 hours. LEDs do not contain any mercury or harmful gases like some other sources do, thus making them more environmentally friendly.

As discussed on the previous chapter, the potential for improvement, as demonstrated over the past few years is another major advantage of LEDs compared to other light sources. In the case of fluorescents, some improvements in performance are expected there too, but the technology used does not show the same promise as LEDs.

As far as light distribution, fluorescent lighting provides a wider angle coverage, compared to LED lighting. In Figure 4.1, the differences between LED and fluorescent lamps is apparent, with the incandescent used as a reference. A single incandescent and compact fluorescent can illuminate a whole room, whereas a single LED can only provide a beam of light. It would require a series of LEDs put together in a number of different orientations, to illuminate a whole room.

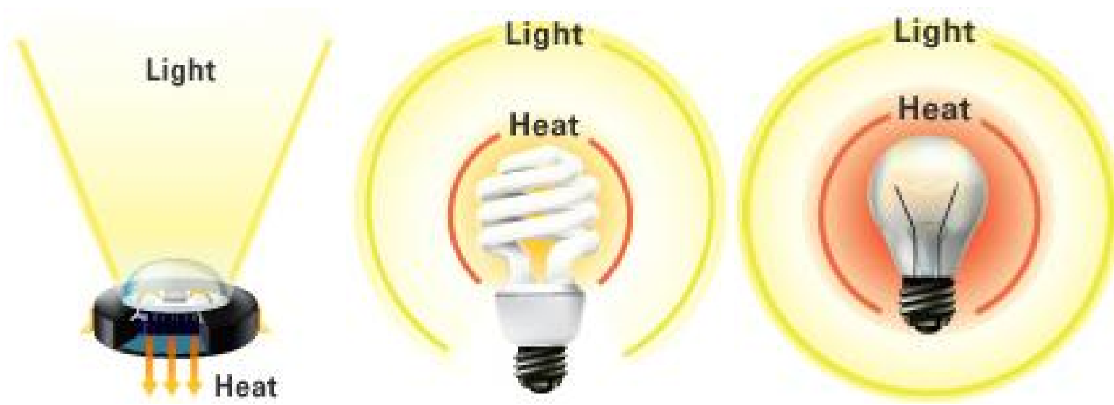

Figure 4.1 Visual comparison of light distribution between three different light sources (LED, compact fluorescent, incandescent) (source: Energy Star)

For offices, that are the focus of this thesis, fluorescent tubes are very commonly used where, again, illumination is provided uniformly all around the tube. In the context of ceiling tile luminaires, reflectors and concentrators are typically used to redirect the light from the fluorescent tubes down to the floor of an office. With LEDs there is the potential advantage that little re-direction is actually necessary as most of the light could be directly pointed to the intended target floor area, thus increasing the fixture efficacy.

In terms of colour quality, LEDs are currently on a similar performance level to fluorescents but, due to their rate of improvements in performance, it is expected that they will surpass fluorescent lighting in this respect.

4.2 The Case for Retrofitting Using LEDs

Most of the current research on LEDs is focusing on new buildings and ways of implementing and taking advantage of LED lighting in that context. However, 75% of the UK's existing building stock has been constructed before 1980 (Pout et al. 2002). Thus the greatest potential impact towards reducing energy demand and carbon emissions, and thus meeting energy conservation targets set by governments, would be by improving the performance of the lighting available in these existing buildings. Replacing lighting systems in existing buildings offers one of the fastest and easiest ways of getting closer to those targets.

The technology used in existing offices typically employs a suspended ceiling system with fluorescent luminaires installed within the ceiling tile grid. Typically T12 and T8 fluorescent tubes are used, which are surpassed now by the much improved and more efficient T5 tubes (Dubois and Blomsterberg 2011). Therefore it would seem logical that all older fluorescent tubes should be replaced by new fluorescent tubes. However, with the benefits that LEDs bring, it is worth investigating the potential impact of using LEDs as replacements luminaires instead of fluorescents, but within the same lighting and luminaire infrastructure.

This thesis therefore explores the potential of using LEDs as direct replacements for existing fluorescent ceiling tile technology.

4.3 LED Replacements for Fluorescent Tubes

Retro-fitting LED tubes as replacements for fluorescent tubes has already been attempted and is an area that manufacturers are still exploring (USDOE 2010). This approach appears to directly address the case for retro-fitting with LEDs. The Department of Energy in the USA, through the CALiPER program (USDOE 2009c), has already tested a range of such commercially available products and the results showed that, in all cases, the light output and intensity of the original fluorescent tubes (either as stand-alone or in a luminaire), were not matched by the LED replacements.

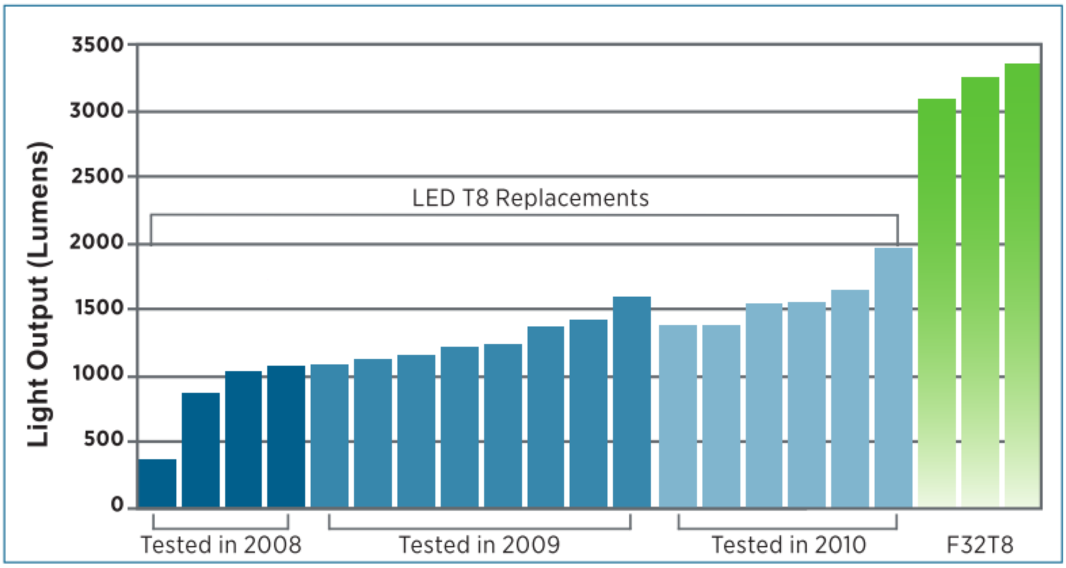

Figure 4.2 Measured light output (lumens) for four-foot LED and fluorescent lamps tested by CALiPER (USDOE 2011)

As shown in Figure 4.2, LED replacement tubes produced outputs ranging from 48% to 58% of the original fluorescent. There are two main reasons for this. First, when LEDs are used in such a confined environment, the heat management required is very difficult to achieve, which leads to the selection of lower output LEDs that can be thermally managed within the confines on a small tube. Second, the LEDs can only be placed in a line, therefore providing a very narrow angle of light, as illustrated by Figure 4.3.

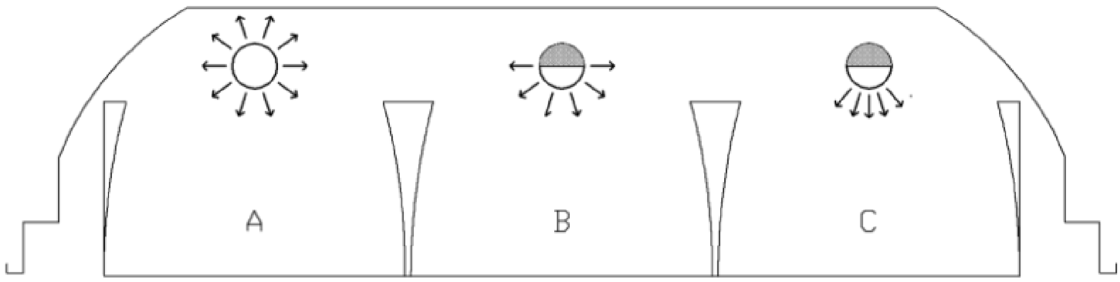

Figure 4.3 Cross section of three-lamp fixture showing light distribution of a linear fluorescent (A) vs LED replacement lamps (B and C) (USDOE 2011)

Therefore, in order to provide LED replacement luminaires that actually provide the same environment that existed before, matching light quantity and distribution, custom LED luminaires would need to be designed. This forms part of what this thesis investigated, so that predictions on energy load demands could be made.

4.4 Research Questions

The majority of research conducted in the field of LEDs is concerned with improving their performance or devising test procedures to more accurately describe their performance. In the context of buildings, most published work looks at the effect of using LEDs on the electrical lighting energy demand of a building. All of this energy will eventually be converted to heat. In the case of fluorescents, a significant portion of it will be radiated into the room whereas the rest of the energy will be given as conducted and convected heat. In the case of LEDs, there will be minimal radiative heat into the room as most of it will be conducted to the back of the luminaire and convected into the air within the ceiling void. This heat emitted into the space will contribute to the internal heat gains of that space, and thus influence the heating and cooling loads of the building. This area has not been studied in the context of LEDs.

Jenkins and Newborough (2007) and D. Jenkins et al. (2008) have looked into the effects of using LEDs with different efficacies on the heating and cooling loads of buildings. In these cases, the LED lighting design was devised from the beginning and the purposes of such simulations were made for first order estimates. Based on the literature review in Chapter 3, it is not always possible to accurately predict the performance of an LED luminaire and, in this work, it is not clear how the performance of LED luminaires was obtained. For this thesis, custom LED luminaires were constructed and their performance was measured. Also, the focus of this thesis is on custom LED replacement luminaires that are capable of being placed at the same position as an original fluorescent luminaire and producing the same light output. This was not the focus of the quoted work. Finally, for purposes of rigour, in this thesis two validated thermal simulation software were used to predict heating and cooling loads, which again differentiates this work.

The research questions that the thesis aims to answer are the following:

- Can custom LED luminaires be modelled in lighting simulation software and their lighting output accurately predicted?
- Can custom LED luminaires be designed to provide an equivalent work plane illumination to fluorescent ceiling tile luminaires?
- Can LED luminaires be used as a retrofitting solution to existing ceiling tile fluorescent luminaires, while providing the same work plane light distribution?
- Can the thermal effects of ceiling tile LED luminaires in the room below and the ceiling void above, be accurately predicted by thermal software?
- Can LED luminaires provide an improvement in space conditioning loads over existing fluorescent ceiling tile luminaires in office buildings?

Chapter 5. Research Design

In order to answer the research questions posed in Section 4.4, a series of objectives were set in the introduction chapter of this thesis. Some of these objectives have already been met, namely those that were relevant to the literature review already presented. As the focus of this work was the use of LEDs as replacements for existing fluorescent ceiling tile type luminaires, there was a need for a method to be developed whereby custom LED luminaires can be designed that replicate room lighting distribution from fluorescent lighting at the working plane. In order to arrive at this method, a series of steps were necessary.

First, to identify suitable lighting simulation software that can accurately predict room illumination from artificial lighting. This was necessary so that the light distribution from luminaires in case study buildings can be accurately predicted. The first part of Chapter 6 is devoted to this, where a range of software are reviewed and selection criteria are put in place. A experiment is then setup in a room so that comparisons between measured and simulated data can be made, which leads to a selection of an appropriate software.

As an LED luminaire is made of multiple LEDs, it was necessary to determine a suitable way for simulating lighting under these conditions. First, LEDs are simulated as individual light sources and then as a whole luminaire composed of multiple light sources. To test the accuracy of this method, a test was devised and measurement data were then compared to simulated data.

To design custom LED luminaires that replicate the working plane illumination of a fluorescent luminaire, another method was developed where, through the use of an iterative algorithm, the positioning of LEDs within the luminaire was determined and a similar working plane illumination achieved. This method is tested against simulated data from two fluorescent luminaires in Chapter 6.

For purposes of rigour and accuracy, there was a need for a real case study where custom LED luminaires could be designed, built and placed within the test office room. This process would allow for testing how accurate the lighting prediction methods developed were and also how the custom LED luminaires compared to existing fluorescent luminaires when their lighting distribution is measured in each case. The process of design, testing and measurements performed, and the methodologies used, are described in more detail in Chapter 7.

Another focus of this work was to test whether LED lighting in this context would be any different in terms of human perception and task-based performance, compared to the existing fluorescent lighting conditions. To find this out, a series of tests were performed with subjects of different age groups where their perception of LED and fluorescent lighting conditions was tested by making them perform a series of visual performance tasks. Details of the methodologies used and the design experimentation setup, and results, can be found at the end of Chapter 7.

In order to predict the potential energy impact of using LEDs as replacements to existing fluorescent lighting in offices, the use of appropriate thermal simulation software was necessary. The process of identifying the simulation requirements for this work, setting up criteria and reviewing appropriate software is described in more detail in Chapter 8, along with the testing that took place in the test office room previously setup to validate the models used with measured data.

To assess the impact on heating and cooling load demands of using LEDs as replacements for existing fluorescent lighting a series of case study buildings were used. Four of them were real buildings that were about to be built, or recently built in the UK at the time the study was conducted. Even though the work in this thesis is about retrofitting existing fluorescent lighting with LED lighting, and the basis of comparison could have been older buildings and older lighting systems, it was found necessary to use recently built buildings as those would employ more up-to-date fluorescent lighting systems. This would mean that their performance would be better than older buildings that employ older fluorescent lighting technology. Therefore, the basis of comparison would be the fluorescent luminaires that would otherwise be used to replace older fluorescent luminaires in an older building.

In each of the case studies presented in Chapter 9, the existing lighting layout designed by lighting engineers was used as the base case for comparison, and then LED replacement luminaires were designed that would replicate the intended lighting design. Each case was then simulated for heating and cooling demand loads so that, later, comparisons on annual demand loads can be made between lighting systems.

An additional case study was devised as a ‘notional’ building designed to UK regulations, of typical office proportions and size, in order to widen the applicability of the results obtained as variations of this design can be found more often throughout the UK. The depth of this building was set at 15 metres and was defined by assuming a 6-7 metre setback from windows either side of the building, which allows for good day-lighting conditions in a building and the remaining space in-between as corridor and circulation space. The layout was rectangular, as this is the most common form found in buildings (Steadman 2006).

Details of the methodology used for each one of the case studies, along with a discussion on the results obtained, can be found in Chapter 9.

Chapter 6. Simulating Artificial Lighting and Designing Custom LED Luminaires

6.1 Introduction

In order to investigate the light that is emitted from a light source, manual calculations are possible as well as lab measurements and computer based simulations. Both manual calculations and lab measurements are very labour-intensive and time consuming, with lab measurements having significant added costs. Computer simulation software, on the other hand, allows for more flexibility and faster calculation of results. This is especially true when custom luminaires are used in rooms of variable sizes and shapes. For this reason, the core of the work in this thesis has been conducted using lighting simulation software in order to predict resulting room illuminations from artificial lighting.

This chapter looks into the process of simulating artificial lighting in a room using suitable software and, more specifically, how fluorescent ceiling tile and custom LED luminaires can be simulated. A comparison between a range of suitable software is presented, as well as testing against measured data. From this, software is selected to be used for lighting simulations in this thesis. A method is then devised for the design of custom LED luminaires that can replicate working plane illumination from fluorescent lighting. The chapter concludes with the development of another method for devising IES profiles for custom LED luminaires.

6.2 Simulating Artificial Lighting in Rooms

In order to predict the lighting distribution in a room, the geometry of the room needs to be specified, as well as the properties of all surfaces present in that room, to account for light reflection. Specification of the artificial light sources are also necessary so that the amount of light sources present in a space, as well as their properties, is fully considered. Properties for artificial light sources are commonly provided by manufacturers and they typically exist in two levels:

- The light output specifications for the artificial light source itself as a standalone illuminating object (i.e. an incandescent lamp, a single fluorescent tube, an individual LED, etc), and
- The light output specifications for a luminaire as a whole, where one or more light sources could be present inside the housing of a luminaire.

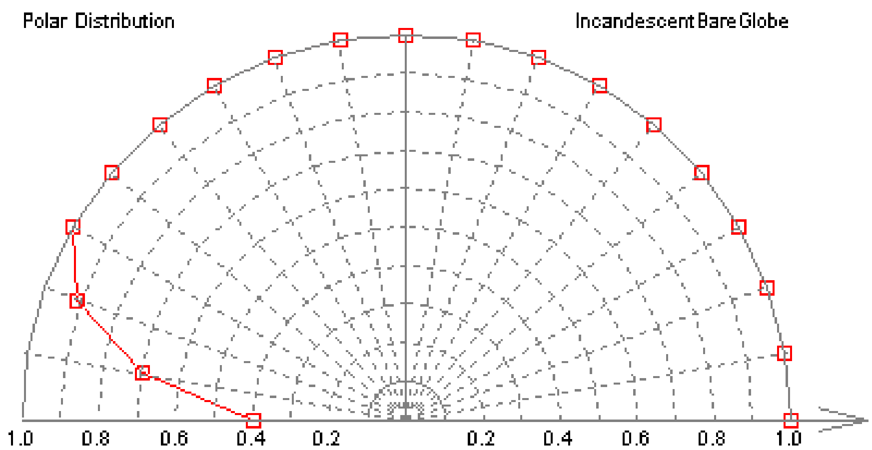

Figure 6.1 Extract from a photometric data sheet for a single light source (source: Philips Lighting)

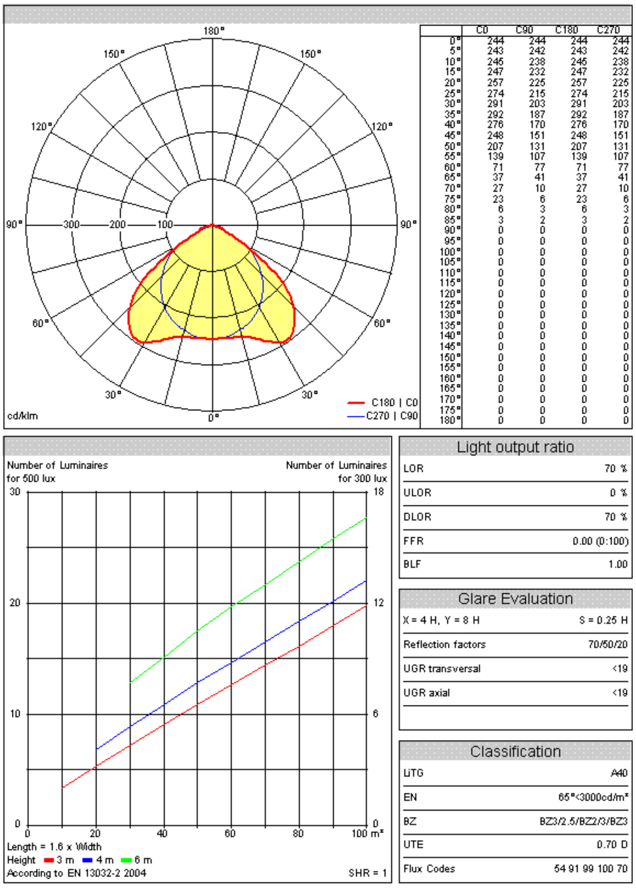

Figure 6.2 Extract from a specification sheet for a luminaire (source: Thorn Lighting)

Figures 6.1 and 6.2 provide example light output specifications from a manufacturer for each one of the above cases respectively. It is worth noting that, in the case of a whole luminaire (Figure 6.2), the specification provided accounts for the combined effects of each light source inside the luminaire, as well as the effect of the luminaire housing which could include reflective and light diffusing surfaces.

For more accurate photometric specification, IES (Illuminating Engineering Society) profiles are used. These come in the form of a data file that can be used by the majority of light simulation software. The use of such files significantly speeds up the process of transferring photometric information from manufacturers to lighting engineers and is considered as an industry standard. It contains detailed three-dimensional photometric information for a whole luminaire and may also include geometric information for the luminaire itself. An example of the data contained in an IES file can be found in Table 6.1 where the same light source as in Figure 6.2 is used.

Table 6.1 Extract from an example IES data file for a luminaire (source: Thorn Lighting)

```
IESNA:LM-63-2002
[TEST]      TLG_SP_0039531
[TESTLAB]
[ISSUEDATE] 29.11.2011 / Kerry Steve
[MANUFAC]   Thorn
[LUMCAT]    96548491 (STD - Standard)
[LUMINAIRE] INDI FAST 1x55W TC-L HF LV L840
[LAMPCAT]
[LAMP]      TC-L  55W
[_CONVERT]  LDT Eulumdat (eCat/PDB)
TILT=NONE
1 4800 1.0 73 19 1 2 0.575 0.575 0.000
1.0 1.0 57.0
0.00 2.50 5.00 7.50 10.00 12.50 15.00 17.50 20.00 22.50 25.00 27.50
30.00 32.50 35.00 37.50 40.00 42.50 45.00 47.50 50.00 52.50 55.00
57.50 60.00 62.50 65.00 67.50 70.00 72.50 75.00 77.50 80.00 82.50
85.00 87.50 90.00 92.50 95.00 97.50 100.00 102.50
105.00 107.50 110.00 112.50 115.00 117.50 120.00 122.50 125.00
127.50 130.00 132.50 135.00 137.50 140.00 142.50 145.00 147.50
150.00 152.50 155.00 157.50 160.00 162.50 165.00 167.50 170.00
172.50 175.00 177.50 180.00
….
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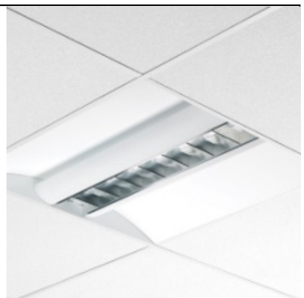


Photometric data of light sources, both in terms of light output specification sheets or IES data files, are typically obtained through laboratory measurements with the use of an integrating sphere (also known as Ulbricht sphere, see Figure 6.3) to obtain the luminous flux of the light source and light distribution photometers to obtain luminous intensity distribution on various planes and angles. With this information, IES data files can be compiled. Luminaire manufacturers, or independent laboratories, provide such files for use in lighting simulation software so that the output of each luminaire in a room can be accounted for. The following section reviews some of this software and makes a software selection for the work required in this thesis.

Figure 6.3 Integrating (or Ulbricht) sphere, used for measuring luminous flux of light sources (source: Lighting Research Group)

6.3 Software Selection

6.3.1 Criteria

A wide range of lighting simulation software exist on the market. A lot of them only deal with daylight whilst others deal only with artificial lighting, and there are some that deal with both. For this thesis, a range of criteria were put in place to test and select appropriate lighting simulation software, as detailed below:

- Accuracy of results in predicting room illumination from artificial light sources,
- Ability to model a physical environment ranging in geometry, from the scale of a whole building, to a room,
- Ability to define fluorescent and LED luminaire lighting specifications from existing luminaires in the market and predict lighting performance in a space,
- Ability to provide rendered images of results, and
- Software that are already available to the Welsh school of architecture, Cardiff University, or can be made available within a reasonable cost budget.

6.3.2 Software Overview

A range of thoroughly researched and validated lighting software already exist in the market and a number of them were already available to the Welsh School of Architecture, namely ECOTECT, Radiance and DIALux, that would comply with the criteria set in the previous section. Therefore, these were the starting point of the search for appropriate and suitable software to undertake this work. A wider search of the market supplemented this list with two additional software, namely AGI32 and

Relux, that would also comply with the criteria set in the previous section and thus a final list was devised that was tested and compared to find the most suitable software for the purposes of the experiments that follow.

The following provides a list of these software, together with a short description for each one and a review of their performance.

RADIANCE

Radiance is a freely available radiosity-based lighting simulation program that uses a backward ray-tracing process for simulation. It was developed by Lawrence Berkeley Laboratory (Ward 1994) and its accuracy in lighting simulation is well established as it has been validated. Radiance requires the 3D geometric information of a model to be provided as a text file, usually derived from other software. Radiance is capable of handling complex geometries and there are no limits imposed by the software on what can be modelled.

In this work, the geometric setup of the software was provided by ECOTECT (Marsh 1996) which is a building simulation software originally developed by Square One and Dr. A. J. Marsh, and is now part of the Autodesk suite of products (http://usa.autodesk.com/ecotect-analysis/). This software provides a comprehensive exporter for RADIANCE and also allows the importing of RADIANCE results back into ECOTECT for visualisation. Furthermore, it allows for the specification of custom grid points for calculating lux levels in a room and it is not bounded by any geometrical limits.

DIALux

Developed by DIAL GmbH (http://www.dial.de/DIAL/en/dialux.html), this is a freely available and widely used package in lighting design. This program specialises in interior lighting and uses the POV Ray rendering engine to produce photorealistic images and provides outputs in PDF format. DIALux imposes some limits on the ype of geometry and can be created on imported, thus limiting the usability of the software for more complex geometries.

Relux

Relux Professional is developed by Informatik AG (http://www.relux.biz/) and can be used for both interior and exterior lighting simulations. This software uses RADIANCE as the calculation engine and can produce a photorealistic image output through it's sister product, Relux Vision. It has the ability to generate geometry through its own object library, or import geometry from other software.

AGI32

AGI32 is a lighting simulation tool by Lighting Analyst (www.agi32.com) that can perform daylight and artificial lighting simulations. This lighting simulation software has integrated ray-trace and radiosity-based calculation engines to produce light data output and photorealistic images. It has the ability to generate complex geometries, or import 3D geometries from other software.

6.3.3 Experimental Setup

In order to compare the lighting software, it was decided that software predictions should be compared with measured data in a real room and hence a real office room was selected for this experiment. Light measurements were taken and then compared to the software simulation results. This section describes in detail the experimental setup used.

An office space was needed that would allow for easy access for a range measurements throughout the experimental period and also included a suspended ceiling with fluorescent ceiling tile type luminaires. An office room with these specifications was provided by the School of Optometry and Vision Sciences at Cardiff University.

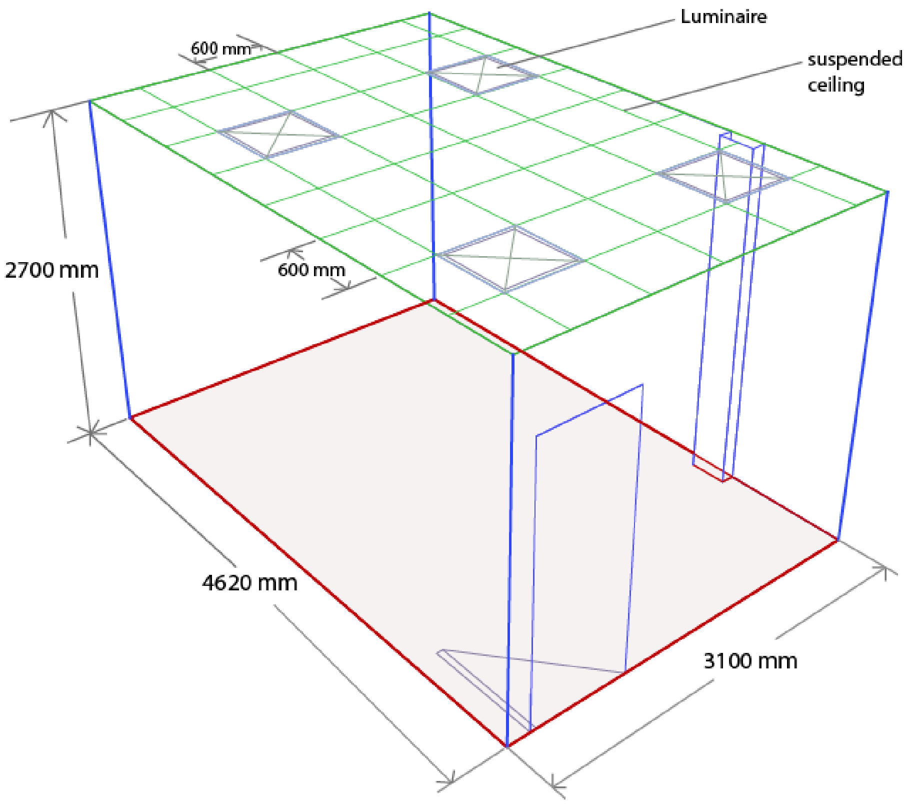


Figure 6.4 Test room model

Figure 6.5 Luminance meter used for determining reflectance of surfaces

The geometry of this room was replicated in all lighting simulation software under investigation (as shown in Figure 6.4). In order to perform lighting simulations, the reflectance of each surface had to be determined in order to be used as input in the software.

Reflectances for all surfaces in the room (walls, floor, ceiling) were obtained using the Konica Minolta LS-110 luminance meter (Figure 6.5), which was provided by the environmental lab of the Welsh School of Architecture, which was responsible for the maintenance and calibration of the device, in order to ensure accuracy of the measurements. This spot luminance meter with and angle of view of 9^o has been categorized in the highest range of DIN quality class B, which is considered one of the highest in the market, and is capable of measuring dark surfaces with a beginning range of 0.001 cd/m^2 and has the ability for user calibration (http://konicaminolta.asia/products/ls-110-luminance-meter).

In order to measure the surface reflectance of each of the room surfaces, the procedure described in the SSL Lighting Guide 11: Surface Reflectance and Colour (2001) was followed, whereby a range of measurements were taken using the Konika Minolta device, which was held perpendicular and at the same distance to each surface in the room. There are two main ways of measuring the diffuse reflectance of a surface, either by using a luminance and an illuminance meter and then using the equation: $\rho = L \times \pi / E$, where ρ is the reflectance, E is incident illuminance and L is emitted luminance. The other way is by using reflectance sample cards provided in the guide to match the surface in question.

Such measurements were taken over a grid of sample points for each surface under artificial lighting and then the average value was used, so that potential reflection variations can be accounted for. It was found that wall surfaces were uniform in their reflectance. In order to account for the non-uniformity of the material used in the acoustic tiles and thus potential reflectance variation, a regular grid of points was used over a typical acoustic ceiling and then the simple average was used as the reflectance value for each ceiling tile. Table 6.2, shows the reflectance values obtained for each for the surfaces in the test room.

Table 6.2 Measured reflectances on site for the test room

Surface	Surface Reflectance
Walls	0.90
Floor	0.30
Ceiling	0.76

The exact model of the fluorescent ceiling tile luminaire was also necessary so that photometric data from the manufacturer could be obtained for use in the software for simulations. A site survey revealed the following to be the luminaire used:

Manufacturer: Thorn

Fitting: Quattro C Body-lin 3 x 18w T26 HFD

Diffuser: Quattro EFL diffuser 600x600 mm

In order to compare software with measured data, a series of points forming a grid of 300mm x 300mm were specified at a height of 800mm, which represents a typical desk height. This was setup as 15 rows and 9 columns, represented by numbers 1-15 and letters A-I accordingly in Figure 6.6. Lux measurements were then obtained using a lux meter device (model: TES 1332, Digital Lux Meter, Model No: 980706290), as seen in Figure 6.7. This device was provided by the Welsh School of Architecture, which was responsible for the calibration of the device, according to BS 667:2005 and its regular maintenance, so that accurate measurements can be obtained.

Two of these devices were positioned on a custom made stand, provided by the environmental lab of the Welsh School of Architecture, which held the meters at the specified height of 800mm from the floor throughout the measurements. This provided a stable position for measurements to be taken. Any movement of the meter, if held by hand, could potentially alter the angle at which measurements were taken and hence influence the results. Care was taken during measurements, so that no obstructions that could shade the meter would be present above 800mm, which meant that the person taking the measurements had to lie on the floor. A series of pre-marked positions were set in the room, so that the whole stand can move to precise locations within the room and thus obtain measurements at the pre-defined grid.

	A	B	C	D	E	F	G	H	I
1	383.00	410.00	417.00	424.00	424.00	416.00	410.00	400.00	386.00
2	430.00	446.00	461.00	473.00	478.00	478.00	467.00	454.00	435.00
3	482.00	506.00	526.00	538.00	543.00	537.00	522.00	505.00	475.00
4	526.00	552.00	566.00	580.00	584.00	576.00	565.00	548.00	516.00
5	542.00	573.00	589.00	596.00	599.00	595.00	582.00	568.00	535.00
6	537.00	564.00	580.00	580.00	595.00	585.00	575.00	560.00	528.00
7	514.00	541.00	557.00	569.00	573.00	569.00	557.00	537.00	513.00
8	497.00	522.00	536.00	548.00	553.00	548.00	537.00	520.00	496.00
9	491.00	514.00	532.00	545.00	550.00	544.00	530.00	512.00	487.00
10	499.00	522.00	540.00	554.00	560.00	554.00	540.00	519.00	494.00
11	514.00	541.00	561.00	575.00	582.00	577.00	564.00	541.00	513.00
12	537.00	565.00	586.00	598.00	607.00	603.00	595.00	577.00	541.00
13	539.00	572.00	592.00	608.00	617.00	617.00	611.00	597.00	567.00
14	515.00	544.00	569.00	590.00	604.00	604.00	598.00	583.00	553.00
15	468.00	489.00	509.00	547.00	564.00	566.00	558.00	546.00	521.00

Figure 6.6 Measured illuminances over a series of points

Figure 6.7 Working plane (800mm) measurement setup

In all lighting simulation software, the same room geometry was replicated and a grid of points of the same dimensions as the one used for site measurements was specified so that lux levels could be predicted for comparison. In all software, appropriate settings of high accuracy were used, so that comparisons could be made between them and the measured data. A list of settings used for each software can be found in Table 6.3. The following section presents and discusses the results of this study.

Table 6.3 Lighting software settings used for simulations

Software	Software setting used in the simulations
RADIANCE	Indirect Reflections: 5 Model detail, Variability, Image Quality: High rtrace -I -h -dp 2048 -ar 32 -ms 0.063 -ds .2 -dt .05 -dc .75 -dr 3 -sj 1 -st .01 -ab 8 -aa .1 -ad 512 -as 256 -av 0.01 0.01 0.01 -lr 12 -lw .0005 -af
DIALUX	Calculation options: very accurate Calculation method: standard
RELUX	Precision: High indirect fraction Raster: 0.7 Active Dynamic Raster: on, fine Maintenance factor: 0.85
AGI32	Calculation mode: full Radiosity Convergence: Maximum Steps: 1000 Stopping Criterion (Convergence): 0.01 Display Interval: 10 Maximum Subdivision Level: 5 Minimum Element Area: 0.0465 m^2 Element Luminance Threshold: 1.5

6.3.4 Results

Figures 6.8, 6.9 and 6.10, show a comparison of results for measured and four simulated sets of data. Three graphs are presented, each one showing data points for three positions in the room. Positions A(1-15) for a series of data points on one side of the room close to the wall, positions E(1-15) for a series of data points at the centre line of the room and positions I (1-15), for a series of data points along the other side of the room, close to the opposite wall.

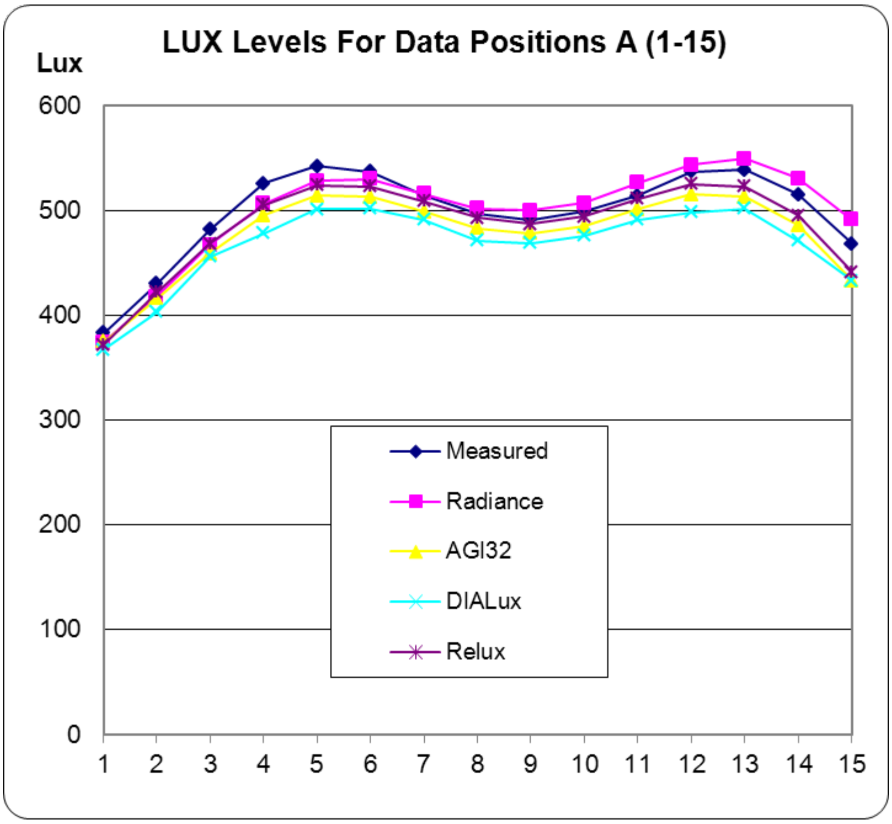


Figure 6.8 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series A

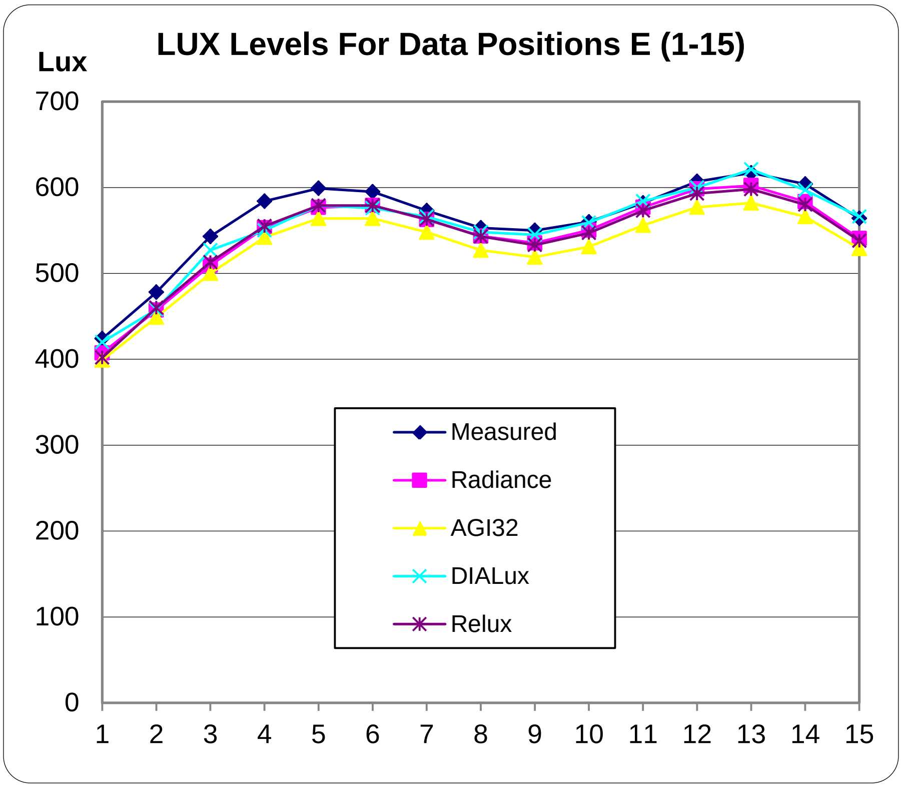


Figure 6.9 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series E

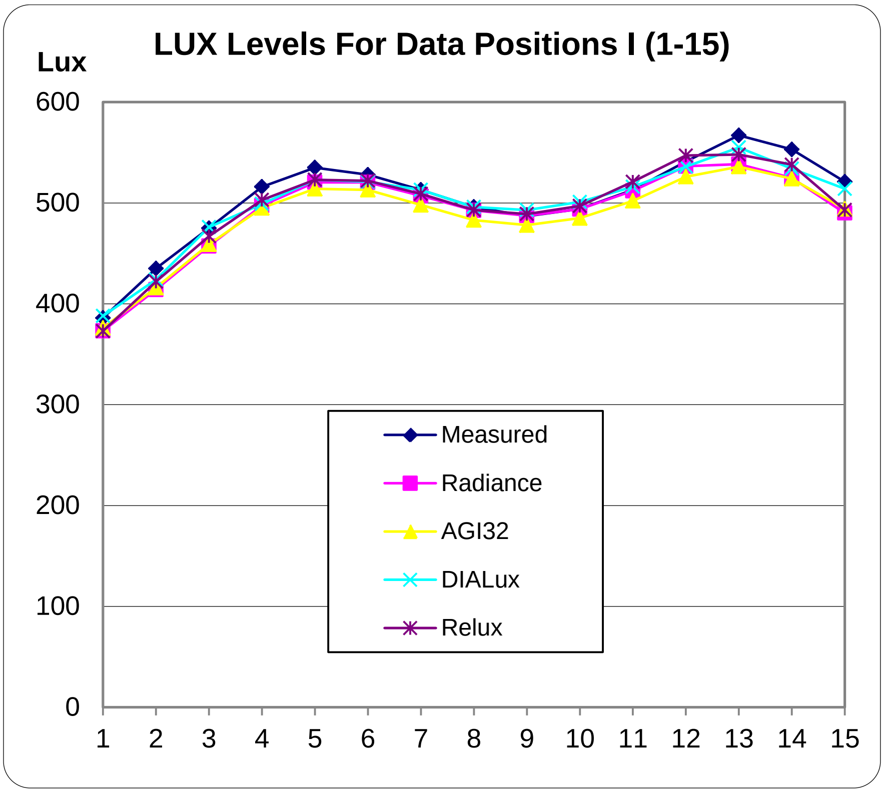


Figure 6.10 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series I

Results show that, in all of the above occasions, all software remain very close to measured lux values. Differences in results range between 1% and 6%. A closer examination of all data points throughout the grid revealed that the average difference between measured and simulated data was 2.7% for RADIANCE, 2.7% for Relux, 5.5% for DIALux and 4.8% for AGI32. As Relux uses the same calculation code as RADIANCE, it was expected that the two software would provide similar results.

In building regulations and guidance, the average light levels in a room are typically considered. Thus the average lux levels obtained in all occasions were also compared, together with the maximum and minimum lux levels, as shown in Figure 6.11. Results agree with observations made on individual lux level sample points, where RADIANCE and Relux are closer to measured values than DIALux and AGI32.

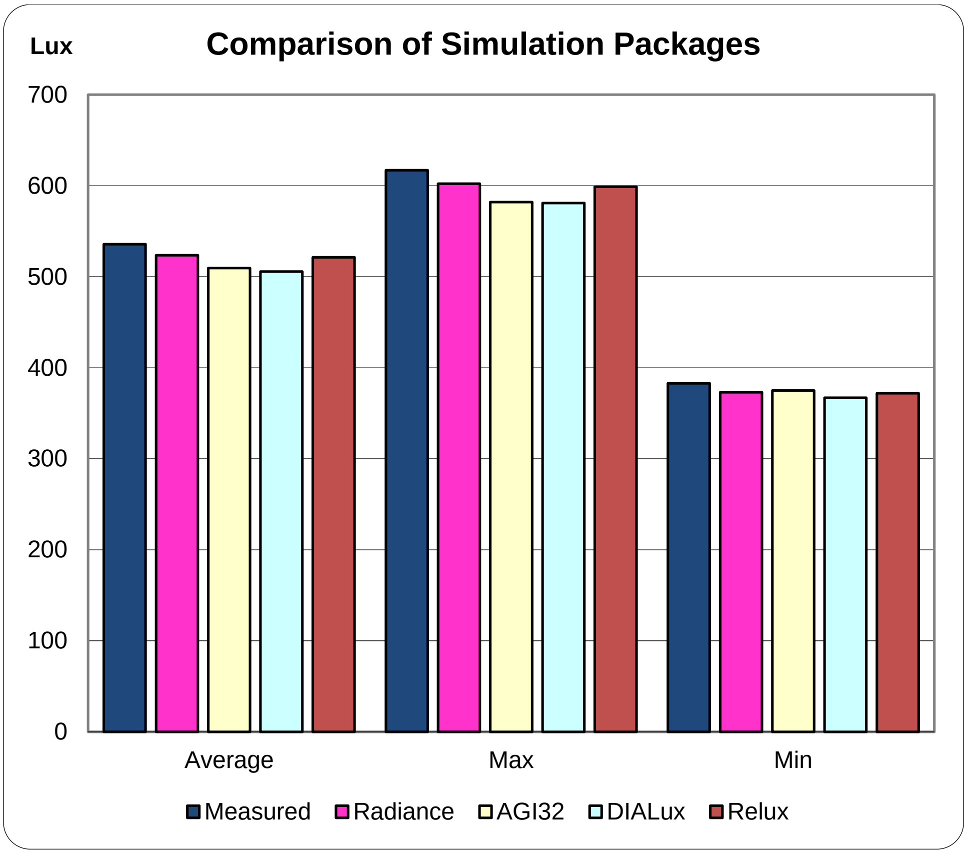


Figure 6.11 Comparison of measured and simulated in terms of overall average, maximum data value and minimum data value

The results obtained show close agreement between all simulation software and measured data. This was to be expected as all software are extensively used in industry and academia for their accuracy, and also because accurate photometric data existed for the fluorescent luminaire from the manufacturer.

6.3.5 Lighting Software Selection

This study showed that all four lighting simulation software were in close agreement to measured data, hence all could be considered for the lighting simulation tests within this thesis. Radiance and Relux showed the smallest deviation from measured data and, hence, appeared to be the most accurate and suitable for the work required in this thesis.

Therefore, the basis for selecting between these two would not be accuracy, but rather one of the other criteria specified within the aims and objectives section of this chapter. As a result, RADIANCE was chosen as the software to conduct the lighting simulations for the remaining of this thesis as it showed more flexibility in terms of modelling a wider range of geometries, compared to other software, as well as greater possibilities for the customisation of data output when used together with ECOTECT. The additional benefit of using RADIANCE was the intuitive link to the ECOTECT software, which was also used to create thermal models for the case study buildings used in Chapter 9. This allowed for the same ECOTECT model to be used for lighting analysis in RADIANCE as well as thermal and energy analysis in other software, thus maintaining consistency and accuracy in the setup and geometrical description of models.

6.4 Simulating Lighting from LEDs

6.4.1 Individual LEDs

LEDs are light sources that emit light just as other light sources do. Thus, there is no difference in the way that they are considered by light simulation software. Once photometric specifications are provided, their light output in a room can be predicted just as with any other light sources.

Photometric specifications are typically provided as photometric data sheets from manufacturers, as shown in Figure 6.12. In some cases, IES data files are provided too, but because their light output is usually symmetrical, it is relatively easy to compile an IES file within software like ECOTECT (Figure 6.13) or other similar software.

Therefore, simulating the light output of an individual LED is not different than simulating the light output in a room from a whole luminaire when photometric specifications are available.

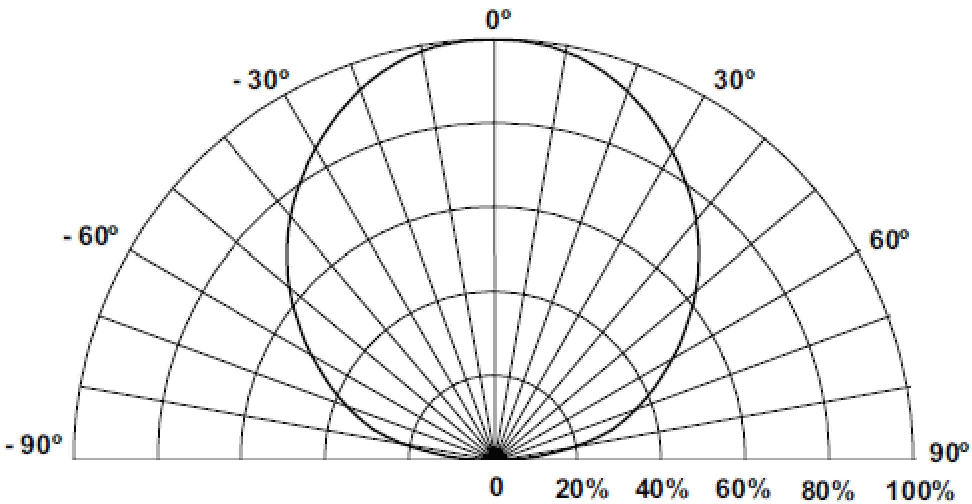


Figure 6.12 Typical polar radiation pattern for an LED (Source: Philips Lumileds)

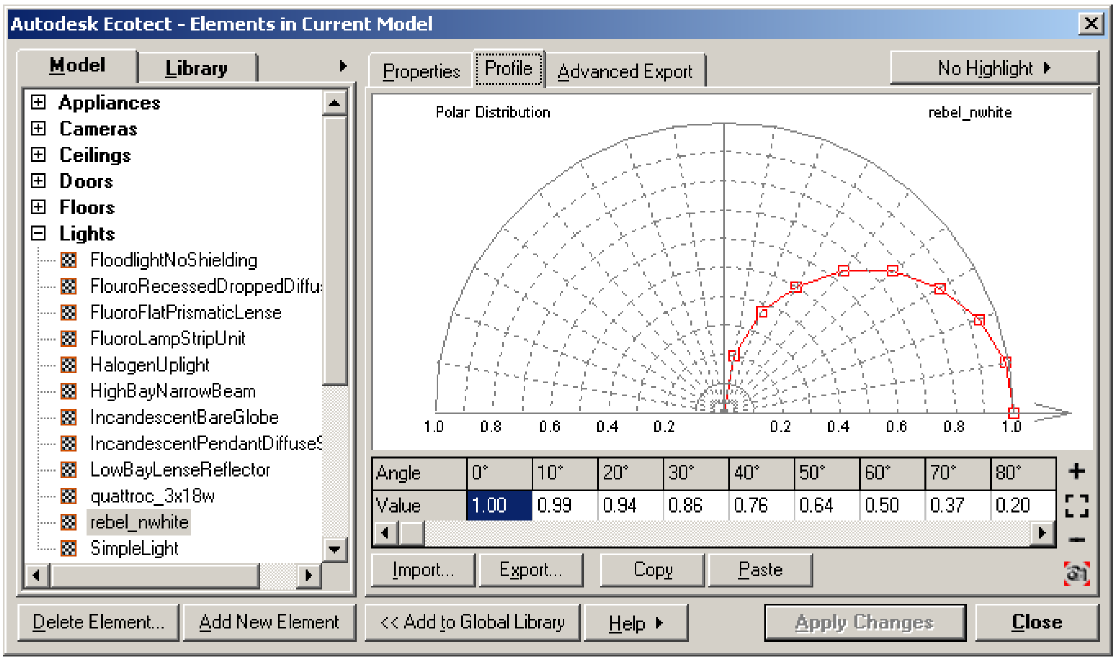


Figure 6.13 Photometric specification of light output profile in ECOTECT

6.4.2 LED Luminaires

One of the main differences between LEDs and other light sources, as explained in Sections 3.6 and 3.9 of Chapter 3, is that the light emitted by a single LED is very directional (along the centre axis of the LED), with little light emitted sideways, and is not enough to illuminate even a small room. This is very different from the case of an incandescent bulb or a fluorescent tube. Therefore, many LEDs are needed to provide enough illumination from an LED luminaire to be comparable with other luminaires with different light sources.

As in the case of other light sources, photometric specifications are needed in order to simulate the light distribution in a room from an LED luminaire that houses many LEDs. Again, this is provided by manufacturers or laboratories in the form of a specification sheet or, most commonly, as an IES data file.

The design of an LED luminaire though, containing many LEDs, entails quite a different process compared to other light sources. More specifically, in the case of fluorescent ceiling tile luminaires where two to four fluorescent tubes are typically used, it can be a process of placing the light sources in the luminaire housing and then moving them around manually until the desired light output is achieved by taking regular measurements throughout the process.

With LEDs, this is not possible as every single LED needs to be already designed as part of a module (containing one or more LEDs) with an appropriate heat sink so that heat is quickly and efficiently removed before the LEDs start to fail. This poses significant limitations in terms of adopting a manual method for constructing an LED luminaire and then measuring the light output to devise the IES data file. Hence, simulations are very commonly used by manufacturers when designing LED luminaires.

Specialised luminaire design software exist, that allow for the specification of multiple LEDs positioned in a custom layout within the housing of a custom luminaire. The most well known commercial software in this area is ZeMax, by Radiant Zemax LLC (http://www.radiantzemax.com/en/zemax/), which is used in the industry.

Due to the commercial nature of the software, it was not possible to obtain access to the code used for calculations and thus get a better understanding of how it operates. Furthermore, there were no independent published studies known to the author, demonstrating its accuracy or performance comparison to other known software. Finally, due to the limited accessibility of this software, it would not be possible for other researchers to replicate the calculations and results obtained in this thesis using the same software.

Therefore, an alternative method was explored for predicting light output from custom designed LED luminaires. More specifically, the possibility of using the four lighting simulation software reviewed in Section 6.3 was investigated.

6.5 Designing LED Luminaires Using RADIANCE

Out of the four software reviewed in Section 6.3 for simulating room illumination, Dialux, ReLux and RADIANCE allowed for the specification of LED individual light sources. However, RADIANCE was the only one that allowed the most flexibility in terms of the positioning of each LED and the design of any custom luminaire housing. This was an important consideration for this thesis as the design of custom luminaires was necessary. Furthermore, the ease of use of using RADIANCE together with ECOTECT allowed for complete freedom in geometric model creation and many options on data visualisation and manipulation.

The use of RADIANCE to design luminaires has been explored by Wandachowitz (2004), where results were found to be in good agreement with manual calculations and measured data. This work though, was dealing with other light sources (incandescent and fluorescent) using a single light source. As in an LED luminaire, many LEDs are needed, so a similar process was adopted whereby each LED used in the custom LED luminaire was specified as an individual light source with its own photometric data. This method was tested for its accuracy by comparing the results obtained against measured data.

A custom LED ceiling tile luminaire (Figure 6.14) that was used as a demonstrator for testing and was obtained from the LEDLED project (for which the author of this thesis was the Principal Investigator and project manager) and measured for its light output. The luminaire was placed in a dark room and, with the use of a light meter (Figure 6.15), light illumination levels on a virtual grid of points on a plane at a distance of 1.75 meters away from the luminaire were taken. The results from this can be found in Figure 6.16.

Figure 6.14 Custom LED ceiling tile type luminaire demonstrator used for measurements

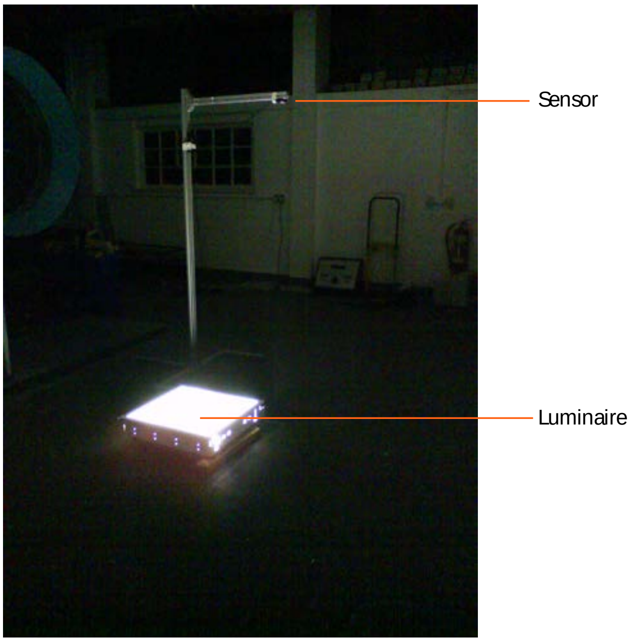


Figure 6.15 Illuminance measurements for a custom LED luminaire in a dark room

A geometric model of that luminaire was created in ECOTECT, together with the exact location of each LED inside it. Photometric data for each of the 90 Philips Lumileds Luxeon LEDs used in the luminaire were then obtained from the Philips Lumileds website (http://www.philipslumileds.com/support/documentation/) and inputted into the model. The results obtained from the simulations were then compared to the measured results (Figure 6.17).

The grid of data points used to compare the data consisted of 20 points, spaced at 1mx1m, and labelled as A, B, C, D, E and 1, 2, 3, 4 to indicate data positioning in rows and columns of the grid accordingly. Differences between measured and simulated data ranged from 3 to 16 lux, with the average difference of all points being 8.5 lux.

The results obtained from simulations were in close agreement to measured data, thus confirming that the methodology employing Radiance for light simulation is capable of accurately predicting the light output from a custom LED luminaire housing multiple LEDs.

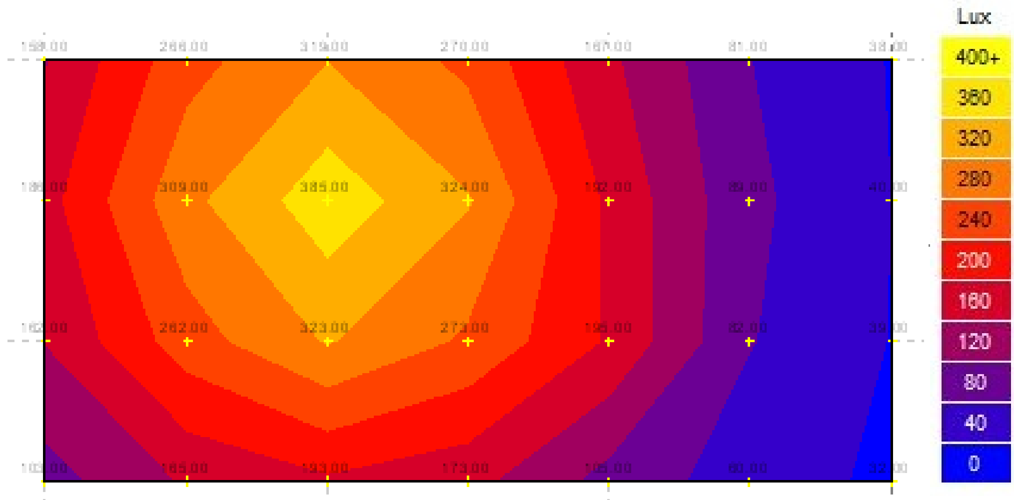


Figure 6.16 Measured illuminance data for a custom LED luminaire

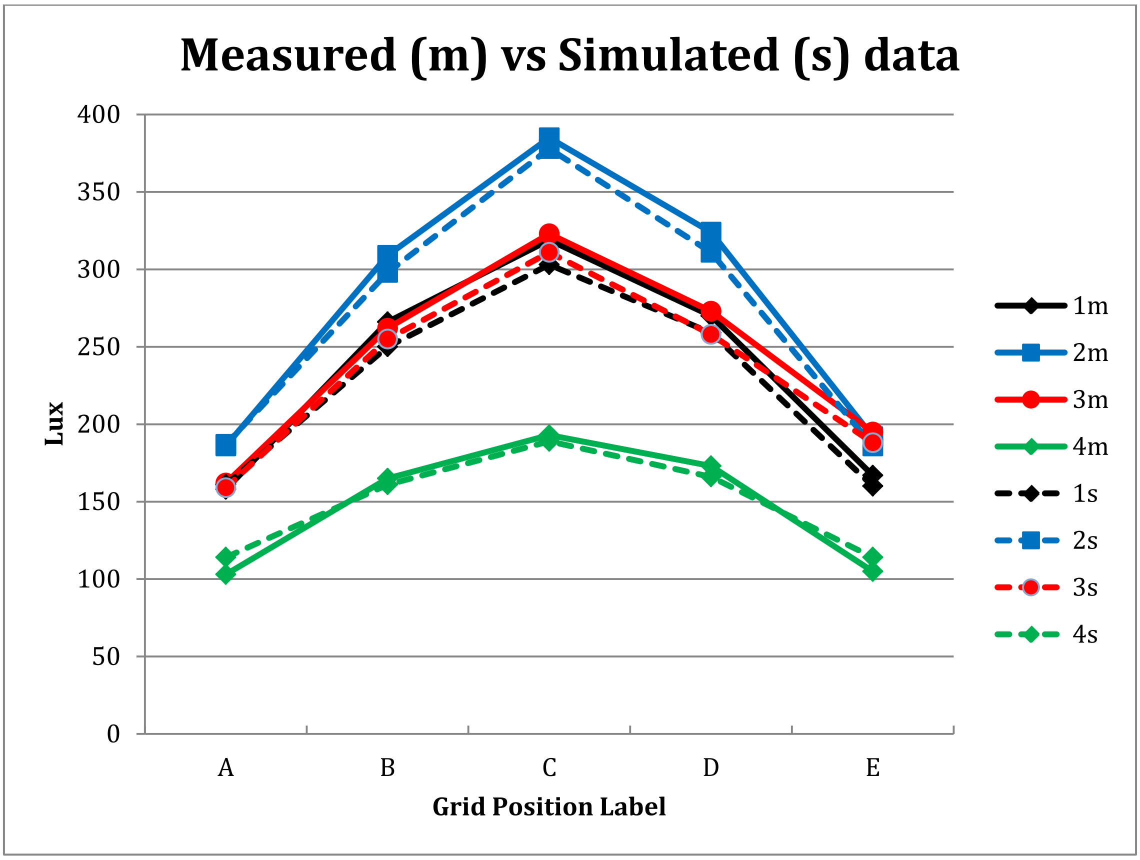


Figure 6.17 Measured vs simulated data for a custom LED luminaire. Measured data represented as solid lines and simulated and dashed lines

6.6 Replicating Fluorescent Lighting with LED Lighting

The method proposed with the use of RADIANCE showed that it is possible to predict light output from custom LED luminaires with some accuracy. As the purpose of this thesis is to study the effect of LEDs as replacements for existing ceiling tile fluorescent technology, it is necessary to design custom LED luminaires that replicate the light obtained from existing fluorescent light sources. The aim of replication was set as the replication of light quantity and distribution at a working plane height of 0.8m.

Since LED lighting consists of multiple individual LEDs housed within a luminaire, a method was devised for laying out LEDs within a luminaire housing so that the desired light intensity and distribution can be achieved. The method used was an adaptation of the methods proposed by Stravoravdis and Marsh (2011). In this paper, a dynamic daylight linking control system was proposed for LED lighting, where LED coefficients at control points (i.e. at a working plane grid) were calculated using RADIANCE to establish the contribution of each LED ceiling tile luminaire at each point. Based on the contribution of daylight at a point for each hour of the day, the LED coefficient would be used to determine the required supplementary light contribution of an LED luminaire and thus dimming the output accordingly.

The same concept was used here, where LED lighting coefficients determined the contribution of each LED within a luminaire at each grid point and hence, through the use of an iterative optimisation algorithm, determine the optimal position of each LED to achieve the desired output. Table 6.4 provides an outline of the steps involved in this method.

Table 6.4 Outline of the methodology used to specify LED luminaires that would replicated fluorescent luminaires

Step No	Description of step
1	Establish boundary conditions
2	Define initial LED positional layout
3	Define target (and acceptable deviation) lux levels at working plane grid points
4	Simulate lux levels on grid points for defined LED layout
5	Determine contribution of each LED to each of the grid points
6	Determine lux level deficit at each point, from set target
---	(if target levels are not within acceptable deviation range, then)
7	Re-arrange LED positioning and repeat from step 4

The first step deals with the boundary conditions, which would include the allowable area where LEDs can be placed as well as the size of each LED or the size of each LED module (if 2 or more LEDs are grouped together in a module). This is mostly to do with geometrical restrictions, which will be derived from the geometry of the luminaire and the exact area at which LEDs can be placed within it. Once those are known, then restrictions can be put in place in the script that can define boundary conditions. These boundary conditions, might dictate for example minimum allowable distances between LEDs or modules, as the distance between LEDs will influence their thermal management (the closer LEDs are together, the more heat is generated).

The next step requires the definition of starting positions for LEDs, as well as the total number of LEDs. This is necessary as otherwise the possible combinations would be too many to go through. The initial layout could be the positioning of LEDs at equal distances, thus forming a virtual grid. A starting position is important, as it can help speed up significantly the design process. A starting layout might be defined for example with most LEDs being placed towards the edges of the luminaire if the desired light output is for a more spread out light distribution. This initial layout would allow the script to converge much more quickly to a more optimised solution, compared to placing all LEDs in the centre of the luminaire.

Defining lux levels for each working plane point allows for targets to be set which could match the exact output of an existing fluorescent luminaire. As this might not be practically possible, if simulations show that the desired level cannot be reached, an acceptable range of deviation is also defined. Then, light simulations (using ECOTECT and RADIANCE) are performed on a grid of points, at a working plane height of 0.8m, to establish lux levels at each point.

To determine the contribution of each individual LED on the light levels of each grid point, the ‘rtcontrib’ program from RADIANCE is then used, which allows for the calculation of the contribution of different light sources to the light received by a sample point in a room. In this case, it is used to determine the contribution of each individual LED within a luminaire, to the lux levels received by each point. These values are then stored on a on a file as comma separated values for later use.

Finally, the difference between the simulated lux levels at each point and the target lux levels is calculated. If the differences fall within the acceptable range already defined, then the LED layout within the luminaire is finalised. Otherwise, the data already stored on the relative contribution of each LED is then used to make a decision on how many of the LEDs and in which direction they should move, so that a new LED layout is defined. For example all LEDs are given X, Y and Z coordinates, so that their spatial positions are known. If the target lux levels on the working plane have been reached directly underneath the centre of the luminaire but not on the sides, then all LEDs are moved apart from the centre of the luminaire by 1cm towards the edges of the luminaire (depending on the orientation of the grid). Based on the new results obtained on the working plane, a decision is then made on which direction each LED should be moved again and by how much.

This the process is repeated from step 4 onwards and as many times as necessary, in an iterative way, until either a satisfactory solution is found or that the number and model of LEDs initially specified are not enough to provide the desired output. In this case, the whole process is repeated with either more LEDs in the luminaire or the same number of LEDs, each with improved light output.

This process was devised within the ECOTECT scripting tool facility that made use of the ECOTECT and RADIANCE software and included the generation of a software code (as a script) and an iterative optimisation algorithm which controlled the positioning of LEDs within the luminaire, a sample of which can be found in Appendix A.

In order to test the accuracy of this method in replicating working place illumination from fluorescent ceiling tile luminaires, a test was devised. The light output from two different commercially available fluorescent luminaires were simulated in a dark test model room (so that surface reflectance does not interfere with the results), as seen in

Figure 6.18, and then compared against the LED replacement designed luminaires. The two fluorescent luminaires chosen were Hacel IMod Solo PLL040 (by Hacel Lighting) and QuattroC 3x18w T26 HFD (by Thorn Lighting).

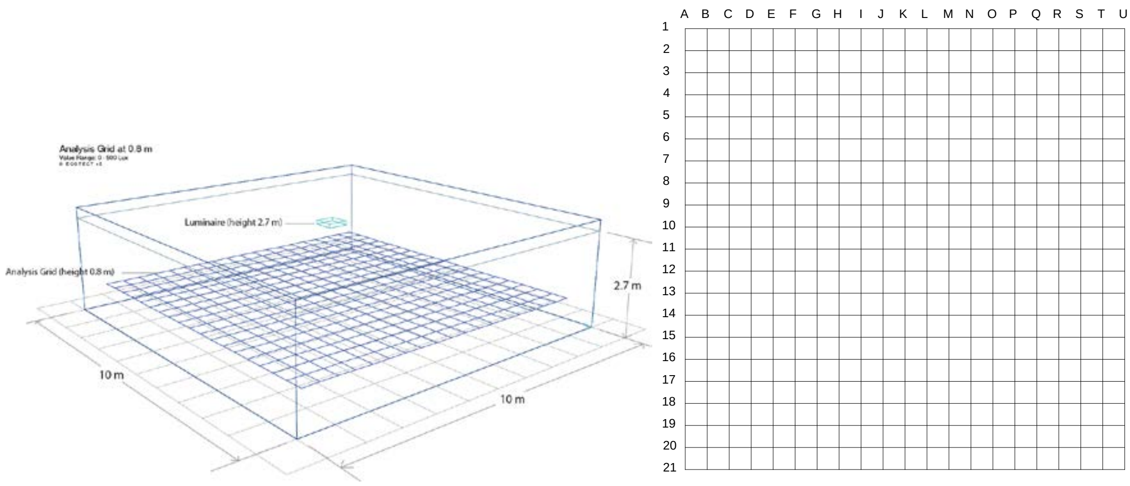


Figure 6.18 Model space used for testing (10m x 10m x 2.7m); grid cell spacing of 0.5m with labels for all positions in the grid

By using the IES data profiles of each luminaire provided by the manufacturers, their effect on light distribution at desk level was simulated using ECOTECT and RADIANCE, with the results obtained presented in Figure 6.19. From the specification obtained through the algorithm method devised, two custom LED luminaires were developed that would replicate the light output of the fluorescent luminaires on a desk level. These resulted into two luminaires using 90 and 72 LEDs respectively.

From the light simulations conducted, a graph was plotted for the lux levels along the centre of the room (row 11 in Figure 6.18) for both the original fluorescent and the replacement LED luminaire. The results for each luminaire can be found in Figures 6.20 and 6.21.

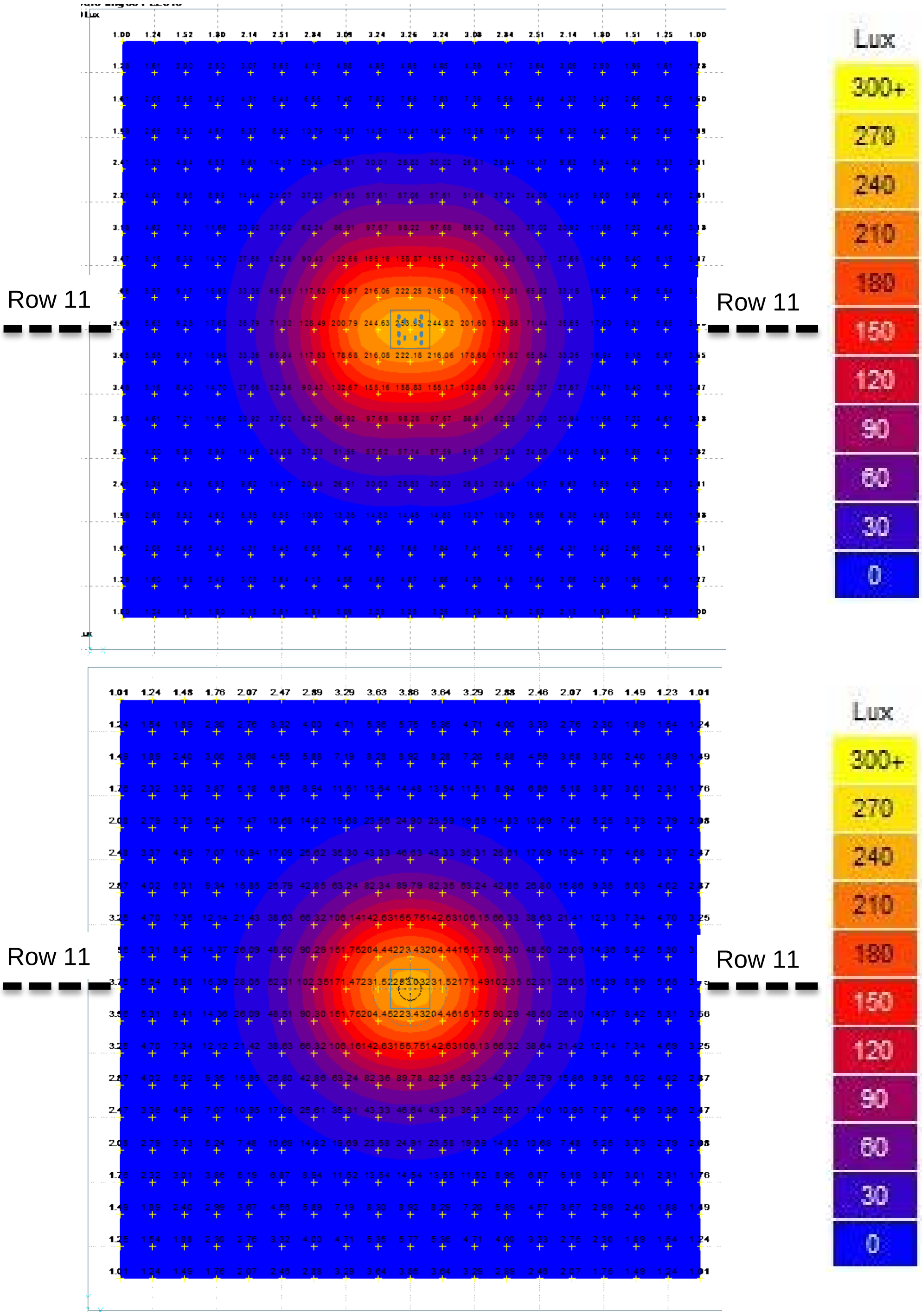


Figure 6.19 Light distribution pattern on working plane, from the Hacel IMod Solo PLL040 (above) and the QuattroC 3x18w T26 HFD fluorescent ceiling tile luminaire (below)

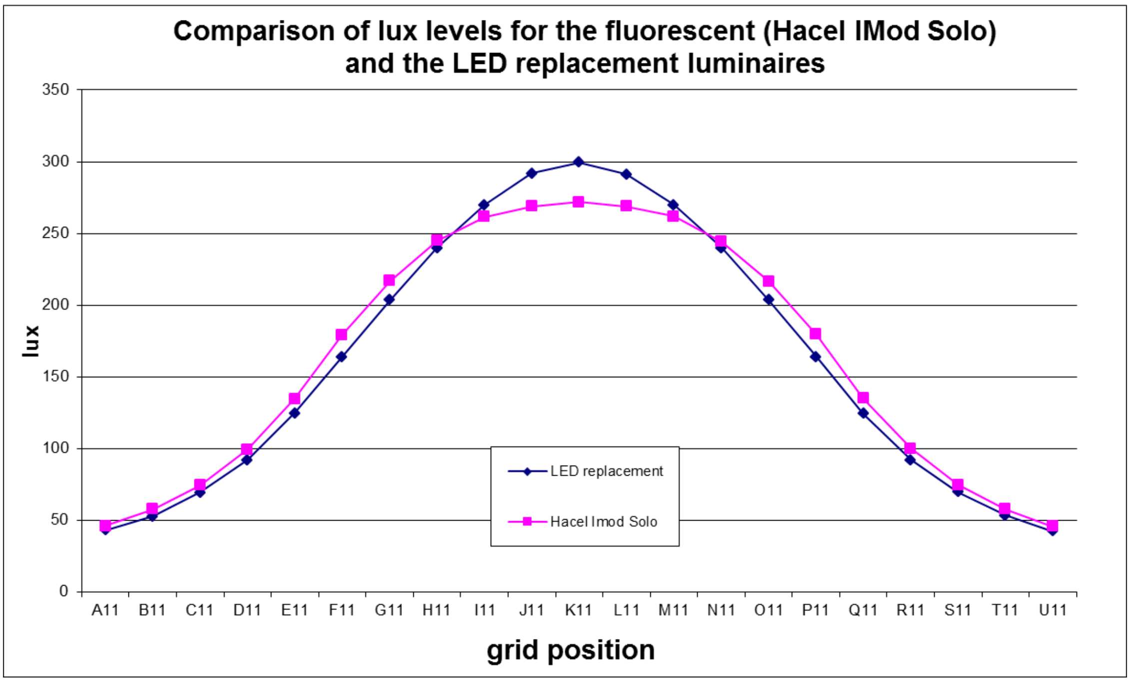


Figure 6.20 Lux level comparison between the Hacel IMod Solo and the LED replacement luminaire, along the row 11 data points

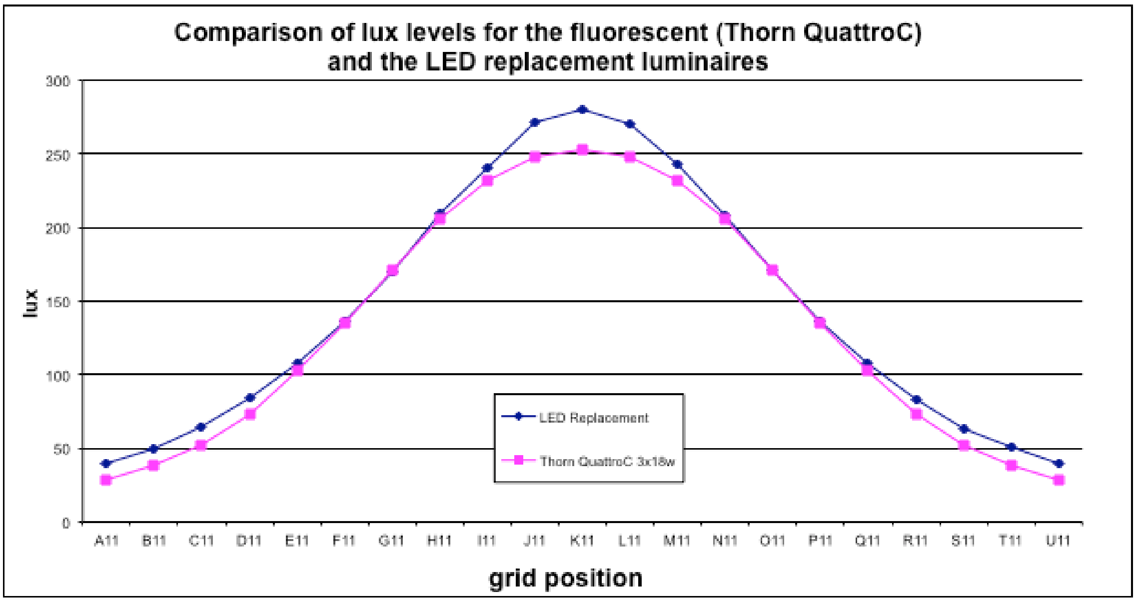


Figure 6.21 Lux level comparison between the QuattroC and the LED replacement luminaire, along the row 11 data points

For the centre line row of values displayed, the maximum surplus of light that the LED replacement luminaire (of the Hacel IMod Solo) provided was 25 lux at the centre and the maximum deficit from the existing luminaire was 15 lux. For the Quattro C luminaire, the maximum surplus that the LED replacement luminaire provided was 26 lux at the centre and the maximum deficit was 2 lux.

The results indicate that there is a close agreement between the existing and the LED replacement luminaires, and that there is a potential for even closer agreement with more adjustments to the LED layout. The fluorescent luminaires provide a slightly more spread-out distribution of light, compared to the LED replacements that provide more light in the centre beneath the luminaire. This was to be expected, as individual LEDs provide much more focused light, as opposed to fluorescent light tubes that provide a much more spread out light. Differences of about 20 lux, when a room will be illuminated with at least 500 lux, are considered negligible.

Therefore, it has been found that it is possible to replicate lighting from fluorescent luminaires by using custom LED lighting. This method will also be used to develop a real LED luminaire to be used in a test room for experiments, as well as custom LED luminaires to be used in the various case studies presented in Chapter 9.

6.7 Developing an IES Profile for LED Luminaires Using RADIANCE

The previous sections showed that it is possible to model a custom LED luminaire using RADIANCE to accurately predict the light output on a working plane and replicate the light from a fluorescent light source. This, in terms of lighting simulation, entailed the modelling of each LED as an individual light source and, in the case of the two LED luminaires developed, these were 72 and 90 LEDs. For a room that contains only a few such luminaires, it is still possible to model the overall light output. But, in the context of an open plan office where many such luminaires would be needed, this would be very inefficient and time consuming. The use of an IES profile would be preferred for greater modelling efficiency, instead of modelling each LED in every luminaire. It would also allow for more lighting simulation software to use this data for lighting simulations. For custom LED luminaires though, IES data files are not readily available.

Commercial software like ZeMax, that was reviewed in Section 6.4, are capable of producing an IES data file from a custom designed LED luminaire. But, for the same reasons as stated earlier, it was not possible to make use of this software. Therefore, an alternative method was adopted whereby RADIANCE was used to devise an IES profile from a custom designed LED luminaire.

The method used is adapted from the method proposed by Wandachowicz (2003; 2004), where RADIANCE was used to simulate various fluorescent luminaires and then compared to measured data. The results showed good agreement, thus confirming the accuracy of the method used. The difference in this case is that multiple LEDs (i.e. multiple light sources) are used instead of a single light source.

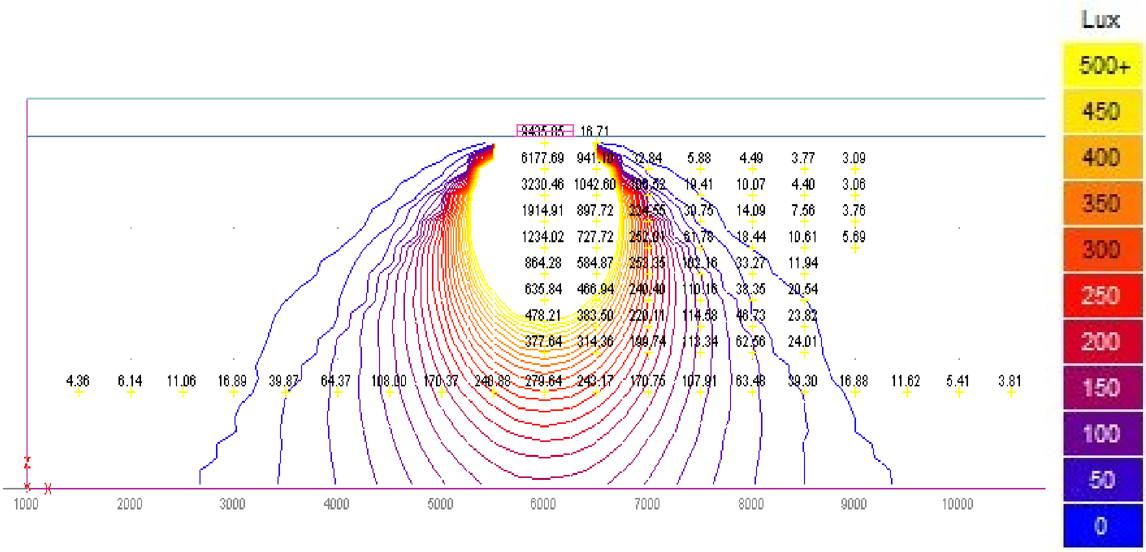
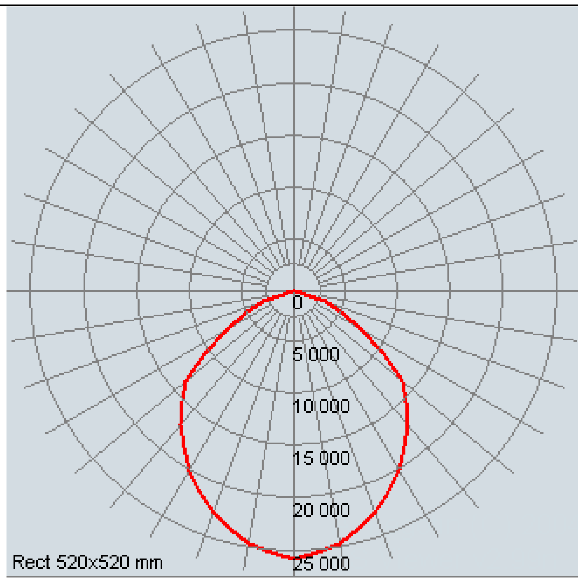


Figure 6.22 Light distribution at a vertical grid, for a custom LED luminaire

Through the use of a script in ECOTECT, a series of radial points were defined around the custom LED luminaire that match the radial output of an IES profile (Figure 6.22). The model was then automatically exported to RADIANCE for lighting calculations and the results imported back into ECOTECT for visualisation and analysis. The illuminance data obtained on the various radial points were then converted into the required format and style so that an IES data file could be created. The process used to convert simulation data into an IES file was adapted from the method proposed in Ward and Shakespeare (2004), where a detailed description exists on how to convert lighting manufacturer specification data sheets into an IES data file. The difference in this case was that the data were not provided by a manufacturer (as the luminaire was custom designed), but were generated through simulations. An example IES data file output can be found in Table 6.5.

Table 6.5 Example of generated IES data file and profile output, for a custom LED luminaire

<table>
<tr>
<td>IESNA:LM-63-1995
[TEST] TLL01872.ITF
[MANUFAC] ----
[LUMCAT]
[LUMINAIRE] CUSTOMLED_1
[LAMPCAT]
[LAMP] 51W
[DATE] 07OCT88
[_CONVERT] LDT Eulumdat
TILT=NONE
72 45 1.0 37 1 1 2 0.520 0.520 0.000
1.0 1.0 51.0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
80 85
90 95 100 105 110 115 120 125 130 135 140 145 150 155
160 165 170 175
180
0
1158.22 1132.97 1107.71 1061.68 1015.66
954.99 894.32 824.39
754.47 679.60 604.73 465.36 325.99 233.53
141.06 73.16
5.26 2.63 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0</td>
<td>
</td>
</tr>
</table>

To test whether the IES data file produced matched the room light output predicted by simulating each LED individually, a comparison was made between the room illumination predicted through individual LED simulations for 2 custom LED luminaires and through using IES profiles that were developed for these same luminaires. The same custom LED luminaires used in Section 6.6 (72 LED and 92 LED luminaires) were used here as well. To show differences between the two methods, maps comparing the two methods were created, whereby the data obtained from the individual LED lighting simulation method were subtracted from the data obtained from the IES method, thus showing the lux level differences between the two methods, as shown in Figures 6.23 and 6.24.

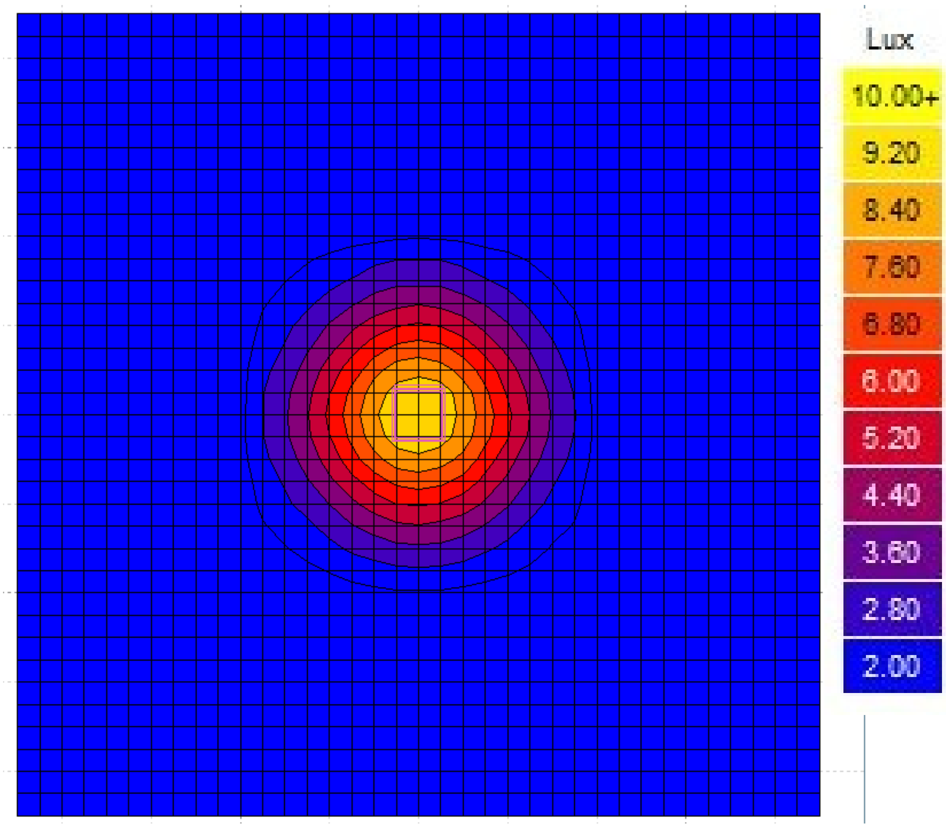


Figure 6.23 Map showing the differences, at each grid point, between two lighting simulation methods for a 72 LED custom luminaire, when data obtained with the individual LED simulation method are subtracted from the IES method. (Blue indicates a surplus of 2 Lux and yellow indicates a surplus of 10 Lux compared to the individual LED method)

The results show that there are minor differences between the two methods. In one case (Figure 6.23) the method employing a luminaire IES profile is providing overall higher illumination compared to the method where all LEDs are modelled as individual light sources. Differences range from 1-9 lux, with the biggest difference observed directly underneath the luminaire. For the other luminaire (Figure 6.24), there are also differences that range from -2 lux to +3.5 lux, compared to the individual LED method.

The differences in data range from 0.33 to 3%, showing a good agreement between the two sets of data. The benefits of using whole luminaire IES profiles for whole building daylight simulations also include faster and more efficient simulations as well as the ability for these profiles to be used by other software.

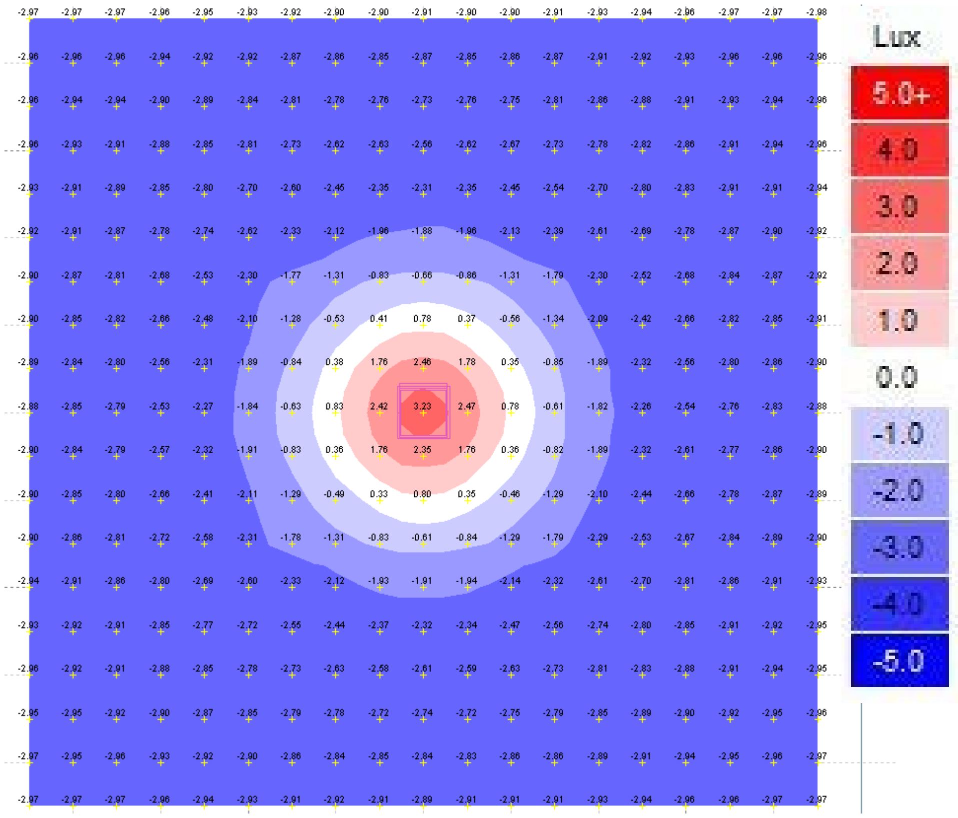


Figure 6.24 Map showing the differences, at each grid point, between two lighting simulation methods for a 90 LED custom luminaire, when data obtained with the individual LED simulation method are subtracted from the IES method. (Blue indicates a deficit of 5 Lux, white indicates no difference and red indicates a surplus of 5 Lux compared to the individual LED method)

6.8 Conclusions

In this chapter, a selection was made for suitable software for room illumination studies from artificial lighting when IES data profiles are available. RADIANCE was selected as the software of choice due to its accuracy, flexibility and collaboration with ECOTECT. It was also shown that it is possible to accurately simulate custom LED luminaires using RADIANCE, by simulating each LED as a separate light source and that it is also possible to replicate the light distribution on a working plane in a room, from of a fluorescent ceiling tile luminaire, using a custom designed LED luminaire. Finally, it was shown that an IES profile of custom LED luminaires can be generated with the use of RADIANCE.

The above work, and the methodologies derived are important for this thesis as they allow for the study of LEDs as replacements for fluorescent lighting. This is critical for the following chapters, as LED luminaires need to be designed that can be used as replacements for existing fluorescent lighting in a range of case study buildings and rooms.

Chapter 7. Test Room Experiments

7.1 Introduction

In this chapter, the methodologies developed in Chapter 6 will be tested in the context of a real room and their accuracy compared. Measurements of the light output from the existing fluorescent lighting in this room have already been used in Section 6.3 to compare lighting software. In this chapter, the same room is retrofitted with other luminaires to conduct additional tests and take more measurements. The first part of this chapter deals with the setup of the test room, so that experiments can be conducted, and presents the results of these findings. The second part presents the findings of a study conducted to test task-based performance under fluorescent and LED lighting, as well as peoples' subjective perception of each light source.

7.2 Test Room Setup for Light Studies

The physical office space used for these experiments was the same room as the one used in Section 6.3, in order to compare lighting simulation software against measured data. Therefore, the same computer model of the room was used here.

The setup of this room for these experiments had to address the following objectives:

- The comparison of measured and simulated data between fluorescent and custom LED replacement luminaires, and

- An appropriate setup for conducting an experiment where subjects would be used to test their task based performance and visual perception under both lighting conditions

In order to address the first objective, custom LED luminaires had to be designed and constructed that would replicate the working plane illumination of the existing fluorescent lighting. The methodology for designing them was devised in Chapter 6 and was employed here for this purpose. Once the LED luminaires were built, they would have to be put in place of the existing fluorescent and then measurements would be need to be taken in the room for comparison.

To address the second objective, the above methodology of designing luminaires would not be appropriate as subjects would have to come in to the room to conduct a range of performance tests under fluorescent lighting, then go out and then come back in the room within a short period of time and perform the same test under LED lighting. A solution to this could be provided by placing the LED ceiling tile luminaires next to the existing fluorescent luminaires. This idea was, again, not appropriate as the light distribution in the room would not be the same due to the different luminaire positions on the ceiling and that could affect results obtained from the tests. The most appropriate solution was found by designing a combined LED luminaire where both the fluorescent and LED lighting existed within the same luminaire, which could very quickly switch between the two.

The existing fluorescent lighting luminaires were taken off the ceiling and LEDs were fitted inside the same housing. The existing luminaire was a Quattro C Body 3 x 18w T26 HFD fluorescent ceiling tile luminaire by Thorn Lighting and incorporated 3 fluorescent tubes. In the space provided between the tubes and fitted to the back metal plate of the luminaire is where LEDs would be placed. Figure 7.1 shows the finished product placed on the floor and facing upwards, where the presence of both fluorescent tubes and LED is visible. The positioning of the LEDs within the housing of the luminaire was restricted due to the presence of the three fluorescent tubes. By adopting the methodology devised in Section 6.6, and using RADIANCE for light simulations, it was determined that the optimal location of LEDs, taking into account the constraints posed, was to provide three strips of 24 LEDs parallel to the fluorescent tubes. A partner to the LEDLED project (Swansea School of Engineering) was commissioned to build four such luminaires to be placed within the test room.

Figure 7.1 Combined fluorescent and LED luminaire. The LEDs are placed on three blue coloured modules (left image). LED lighting turned on and in use (right image). (Note: for demonstration purposes the light diffusing panel in front of the luminaire was removed)

To test whether the light output produced by the LEDs in the room matched the simulated output and the measured output by fluorescent lighting, lux measurements were taken in the test room with the LED lights turned on and then with the fluorescent lights turned on, and compared to the simulated values. The room lux level measurements were taken on a series of points (a grid of 300mm x 300mm) at desk level height (800mm).

7.3 Results and Discussion

Figure 7.2 shows the differences between the simulated and the measured values under LED lighting. The values obtained from measurements at each point were subtracted from the simulated lux levels obtained from RADIANCE in order to get this differential illuminance map.

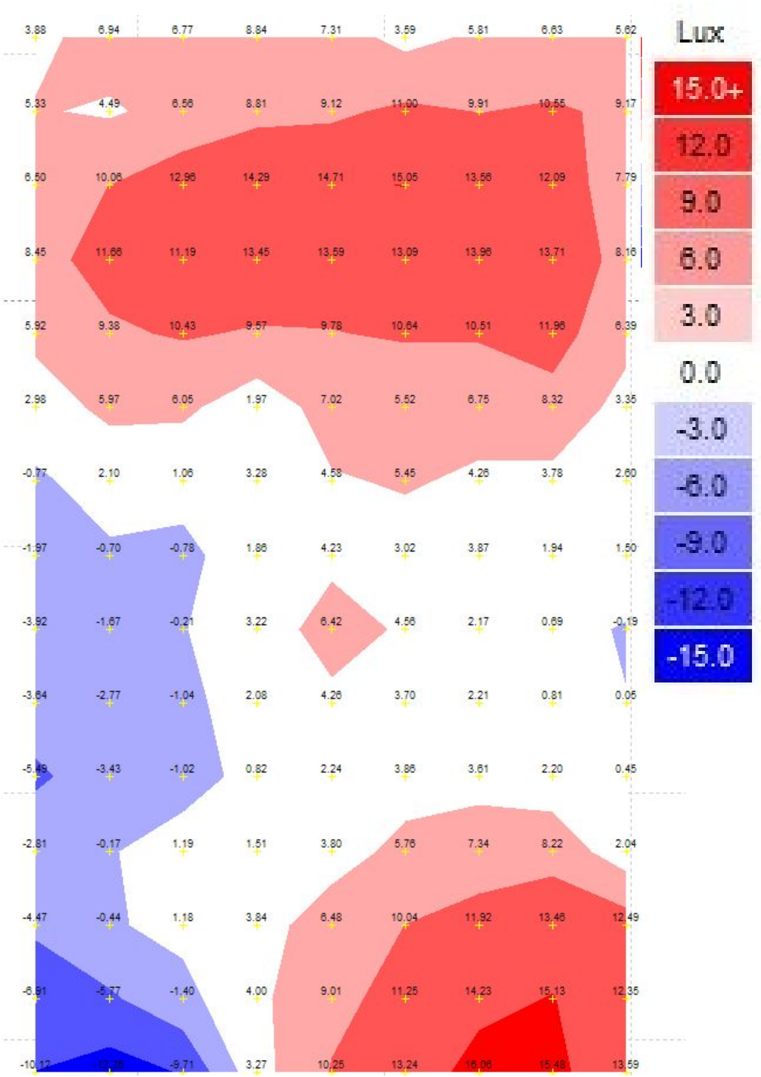


Figure 7.2 Illuminance differential map, when measured lux levels are subtracted from simulated lux levels. Red colours indicate higher lux levels than measured and blue colour indicate lower lux levels than measured. White, indicates almost the same lux levels.

The minimum difference between results is less than 1 lux and the maximum difference is 16 lux. The maximum deficit between simulated and measured values is −12 lux and the maximum surplus is +16 lux. The results indicate that, for the majority of points, the predicted values were either the same (white colour on the graph), or slightly higher than measured (red colours on the graph). Throughout the room though, the difference between predicted and measured is considered very small, especially when taking into account that the lux levels in the room are in the order of 600+ lux, therefore confirming the accuracy of the methodologies developed in Chapter 5.

Furthermore, the measured LED light output in the room was also compared to the measured light output under fluorescent lighting to determine whether the custom LED lighting design could successfully replicate the existing lighting output.

The three images on Figure 7.3 show measured lux levels under fluorescent lighting (left image), then the image next to it shows measured lux levels under LED lighting, and the image next to them (image on the far right) shows a map highlighting the differences between them, where LED lux levels are subtracted from fluorescent lux levels at each point.

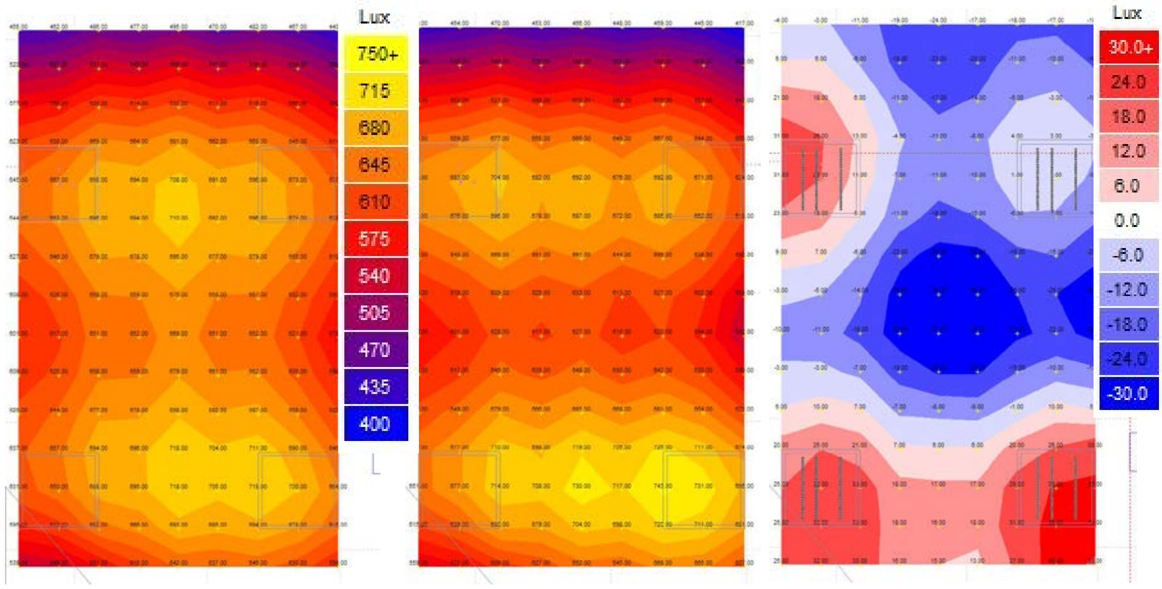


Figure 7.3 Measured lux levels under fluorescent lighting (left); under LED lighting (middle) and differences between them (LED measured - fluorescent measured) (right). Blue colours for the image on the right, indicate deficit in lux levels compared to fluorescent and red colours indicate surplus. White colour indicates that there is no difference in lux levels. The scale used in the left and middle images is the same.

The light distribution on the working plane is very similar in both cases. Results show some differences on specific points up to 41 Lux between the two lighting systems. The maximum deficit in lux levels compared to fluorescent is −35 lux and the maximum surplus is +41 lux. For lux levels in the room ranging from 500-700 lux, this would be a minimum difference 5 % and a maximum difference of 8.2%. This difference in illumination, under such overall light levels, is not considered significant, as differences of up to 100 lux in illumination in a working environment when done gradually are not noticeable by workers in offices (P. Boyce et al. 2006). In this case, there is no gradual change of lux levels between fluorescent and LED lighting, as the purpose of this work is to replace a fluorescent lighting system with an LED one. Therefore, one would expect that once in a building, the LED lighting system would be installed and the next day workers in an office would find a new lighting environment. In this test room case, the change between fluorescent and LED lighting is sudden (at the flick of a switch) and hence the importance of the visual performance study in Section 7.4, where it is shown that the subjects do not notice the slight variation in lux levels.

Considering that, in this combined luminaire, both light sources had to be fitted, thus restricting the available space where LEDs could be placed, it can be assumed that, had LEDs been laid out in three strips at exactly the same position as the existing fluorescent tubes, lux levels differences would be even smaller. The right image in Figure 6.3 shows the exact positioning of each LED strip, and it can be seen that the distance between them is not regular (as it is with the fluorescent tubes).

Moreover, the fact that LEDs are positioned to the back metal plate of the luminaire and the fluorescent tubes are placed in front of them, it can be assumed that the tubes themselves would reflect and prevent some of the light from the LEDs from coming out of the luminaire.

The study conducted indicated that light levels and distribution in a room lit by fluorescent lights can be successfully replicated by LEDs through the use of lighting simulations.

7.4 Visual Performance Study

The typical office worker spends one third of their waking time at work (CIBSE 1993), so it is important for them to have a pleasant and comfortable environment to help provide good working conditions, minimise fatigue and consequently improve performance and productivity. Lighting has been shown to influence all of these aspects (Boyce 2007) and hence any change in an existing lighting environment, such as the replacement of fluorescent lighting with LED lighting in offices as proposed in this thesis, can potentially have an impact in performance in such settings, so is worth investigating.

Thus, the aim of this study was to ascertain the difference in visual performance in short term exposure under fluorescent lighting and LED lighting by carrying out simple visual performance tests under each.

7.4.1 Experimental Setup

One of the most common tasks performed in office environments is reading from printed media and VDU units. Lighting conditions can significantly influence performance in such tasks. As one of the most commonly used light sources in the office environment are fluorescent tubes, with LED becoming increasingly more common, an experiment was devised to find out whether users performed differently under the two different light sources.

It is important to note that, due to time and budget constraints, it was not possible to examine long term effects on performance when exposed to these two different light sources, hence the experiments devised had a focus on tests that could be conducted over a short period of time.

A test room was set up, as described in Chapters 6 and 7, where combined luminaires were fitted into the test room incorporating both fluorescent lighting and LED lighting (Figure 7.1) with each light producing an very similar illumination at the working plane of that room (see Figure 7.3). The lighting was setup in such a way, that the light distribution between the two light sources in the test room was as much as possible the same, so that both lighting conditions are the same and hence did not influence the test.

These luminaires were also setup in this way to allow for rapid changing of the lighting conditions from fluorescent to LED lighting, at the flick of a custom designed switch. This was necessary so that subjects can take tests under one light source and then shortly after repeat these tests under lighting from the other light source.

The luminaires included a plastic diffuser surface, which diffused the light under both lighting conditions. Furthermore, the light switches were labelled as A and B, in order not to provide any clues regarding which light source was on to subjects taking the tests. A close examination of the luminaires, by looking directly at them, could clues to a trained eye as to which lighting condition was active, hence subjects were discouraged from looking directly at the light sources and encouraged to focus on the tasks provided at the office table.

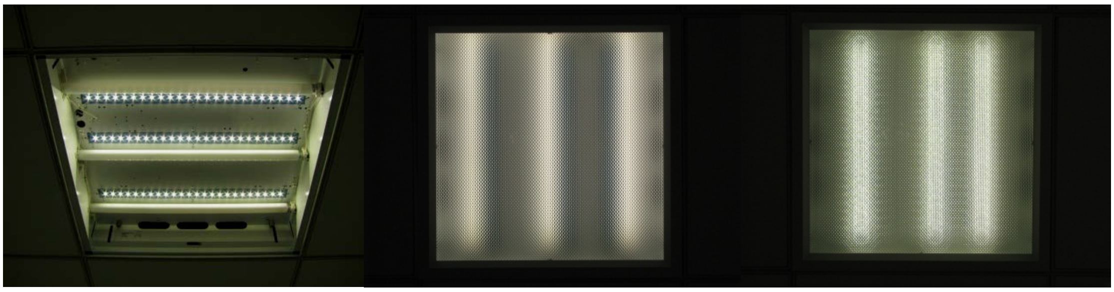


Figure 7.4 Layout of LED and Fluorescent light sources in each luminaire (left) and the appearance of the luminaires when the Fluorescent (centre) and LED (Right) lamps are illuminated.

The LEDs that were fitted into the existing fluorescent luminaire housing produced a desk level lighting distribution that was similar to the one produced under fluorescent, with differences between the two light sources up to 41 Lux at specific points in the room, as described in Section 7.3 and shown in Figure 7.3.

The test was setup at the centre of the room, where a desk was placed and a chair for subjects to sit while conducting various tests.

One of the most widely used methods of investigating the effects of lighting upon visual performance is the Landolt ring test (Boyce 1981) developed by Weston (Weston 1945) and hence it was used to compare the visual performance under fluorescent and LED lighting conditions.

Subjects aged between 20 to 70 years were presented with sheets containing 1,024 Landolt rings with line thickness and gap width of one fifth of the total character size (Figure 7.5). Line thickness and gap width of the Landolt rings was calibrated to subtend 1.5’ arc at the eye when viewed from 40cm.

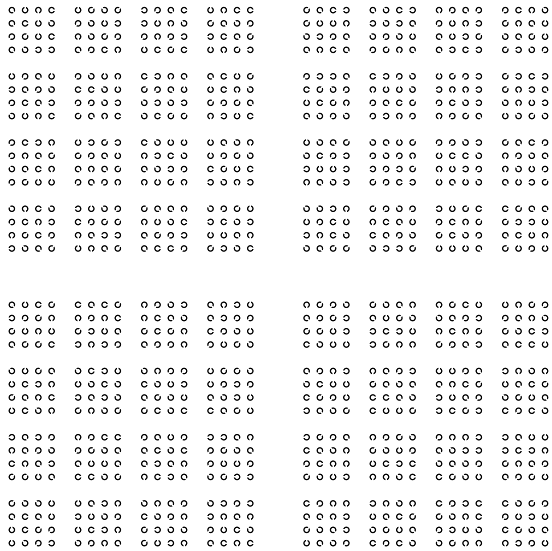


Figure 7.5 Arrangement of Landolt rings presented to subjects

The subject was positioned, using a head rest, at 40cm from the target and instructed to cancel out/mark, with a pen, all the rings with the gaps facing in a diagonal up and to the right (‘north-easterly’) direction. Subjects were instructed to do this as quickly and accurately as possible and to avoid re-checking the grid. Each subject carried out the task four times, with rings at 100% contrast (black on white) and 20% contrast (grey on white) under the two different light sources. Rings were printed at high resolution, on high-quality, matt white card. The time taken to complete this task was recorded and a score of performance calculated using the following formula.

$$\left[\left(\frac{\text{Time}}{\text{Rings cancelled}}\right) \times \left(\frac{\text{Total rings to be cancelled}}{\text{Rings cancelled}}\right) - \text{Correction factor}\right]^{-1}$$

(Weston 1945; Boyce 1981)

A correction factor was calculated for the time taken to physically cancel/mark a Landolt ring on the page. This was assessed by using 32 easy-to-see rings and timing how long it took to cancel each of these. From this, time per ring was calculated.

Prior to the above task, subjects were given a practice run using oversized (easily visible) rings to ensure familiarity with the task.

A task was also designed to assess reading performance from a VDU. In order to do this, the Wilkins rate of reading test (Wilkins, Jeanes et al. 1996) was adapted for presentation on a computer screen.

The same subjects were positioned at 40cm from an LCD VDU screen and instructed to read passages of around 150 unrelated words (Figure 7.6), out loud, as quickly as possible from the screen. These passages were presented at 3 different sizes; 12pt, 8pt and 7pt at 100% contrast (black on white). The time taken for the subject to read each passage was recorded, as was the number of errors. This was also carried out under both lighting conditions described above.

dog is my up the for to and you to not cat for look is my
and up come play you see the dog my play see for you is
the look up cat not dog come and look to for my come play
the dog see you not cat up and is up come look for the not
dog cat you see is and my play is you dog for not cat my
look come and up play see come see the play look up is

Figure 7.6 The arrangement of words used in on the VDU reading test. This arrangement was varied for each size of text (Wilkins, Jeanes et al. 1996).

For both procedures described above, the order of lighting conditions used was randomised.

7.4.2 Results

24 subjects aged between 20 and 70 years carried out a Landolt ring-based visual performance test as described above. Their performances under each type of illuminance and at both levels of contrast (20% and 100%) is shown in Figure 7.7. The difference is not statistically significant at the 5% level (p> 0.5), meaning that the null hypothesis (lack of difference) was accepted at the 5% significance level. Therefore, no significant differences were found in performance under both types of lighting in each of the two contrasts. The scores were significantly lower at 20% contrast compared to 100% contrast, which can be attributed to the difficulty in distinguishing the rings are a reduced contrast.

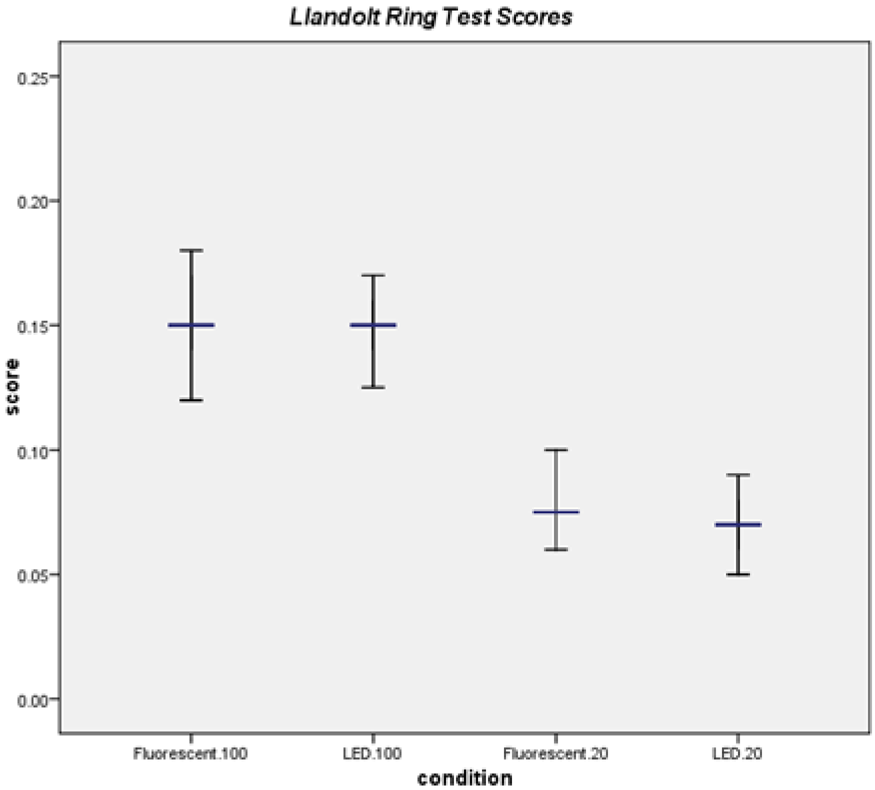
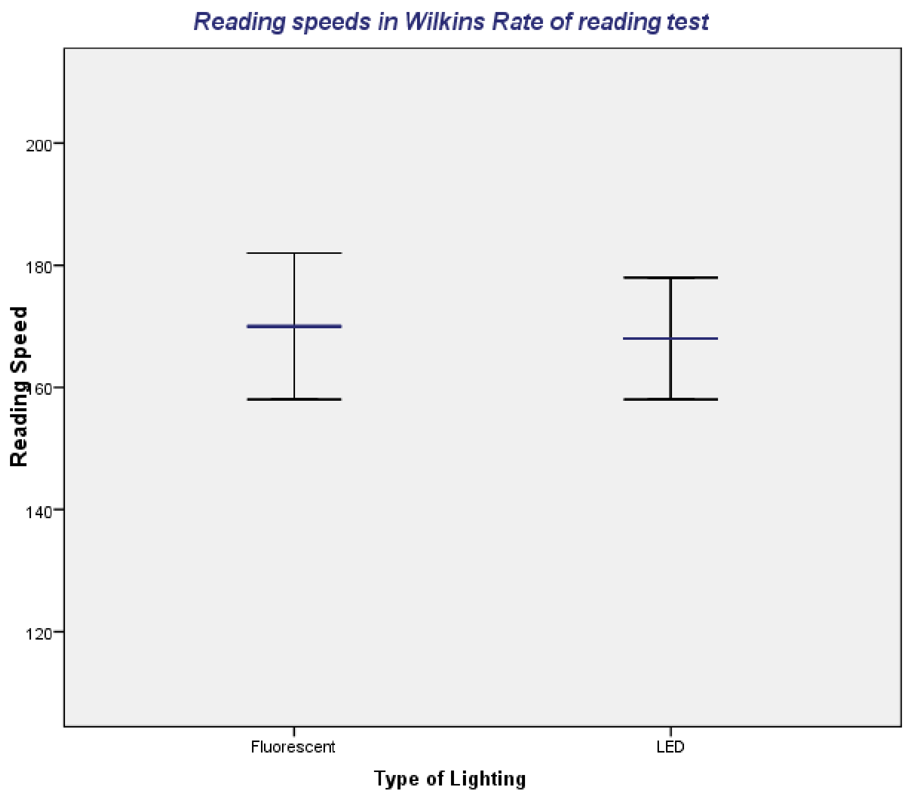
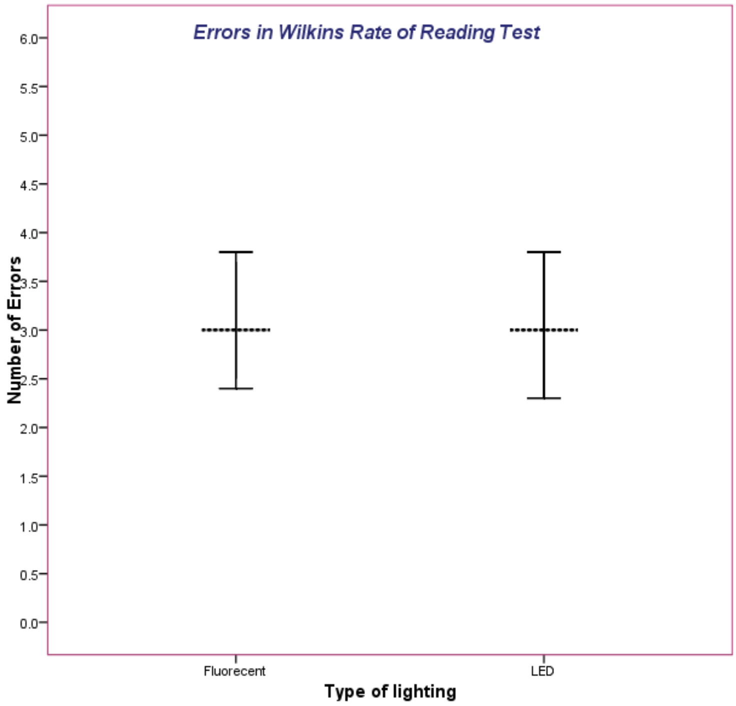


Figure 7.7 Scores in the Landolt ring test for 100% (black on white) and 20% (grey on white) ring contrast, under Fluorescent and LED lighting, showing that performance was unaffected (p=0.98) by the type of lighting at 100% contract. Similarly performance was also unaffected (p=1.00) by the type of lighting at 20% contrast.

The same subjects carried out the Wilkins rate of reading test, viewed on a VDU screen and their overall performances are shown in Figures 7.8 and 7.9. Again, the difference is not statistically significant at the 5% level (p> 0.5), meaning that the null hypothesis (lack of difference) was accepted at the 5% significance level. Therefore, no significant differences were shown in either of these tests under fluorescent or LED lighting.



Fiture 7.8 Reading speeds under fluorescent and LED lighting, showing no significant differences (p=0.14) between them.



Fiture 7.9 Errors made per 150 words in the Wilkins rate of reading test under fluorescent and LED lighting, showing no significant difference between them (p=0.74).

Subjects were also questioned on their subjective opinion of the lighting. Out of the 24 subjects, 14 subjects had no understanding of which light source was on in each of the experiments and out of those subjects, 7 said they had no preference between the two lighting types. 4 subjects preferred the fluorescent strip lighting (i.e. Lighting A in the tests) and the remaining 3 preferred the LED illumination (Lighting B). The main reason given for preference toward the fluorescent illumination was that it was a softer, less glaring light than the LEDs and those who preferred the LEDs said that they gave a cleaner, whiter light with increased contrast. One subject preferred the LEDs because of the reduced flicker and another preferred the fluorescent lights and gave exactly the same reason.

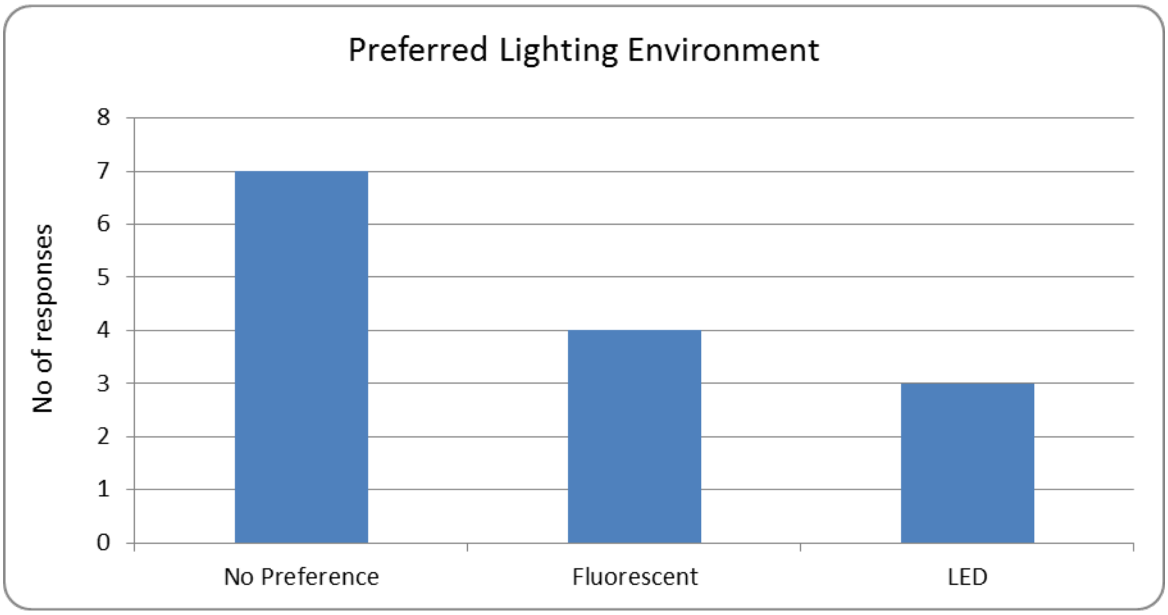


Figure 7.10 Number of responses received, regarding subjective preference to a light source in the test room, showing no clear preference between fluorescent or LED lighting

In summary, this study suggests that there is no significant difference in short term visual performance for paper based visual search tasks and reading tasks from VDU screens with the two lighting conditions. Also subjectively, subjects showed no clear preference for one particular light source.

7.5 Conclusions

The studies in this chapter showed that the methodologies developed in Chapter 5, to model and design custom LED luminaires and predict their light output, are in close agreement to measured data. It also showed that it is possible to design a custom LED luminaires that replicate the light output and distribution at a desk level in an office lit by fluorescent ceiling tile luminaires. Finally, the last study conducted showed that there is no difference in task-based performance, nor in the perception of people, between fluorescent and LED lighting, confirming that it is possible to successfully replicate lighting conditions in a room using LEDs without affecting visual performance.

Chapter 8. Modelling of the Thermal Environment

8.1 Introduction

In order to assess the potential energy implications of using LED replacement luminaires in offices, thermal and energy simulations were performed. Even though building examples exist employing LED lighting technology, it would require energy measurement data for the existing fluorescent ceiling tile lighting, as well as measurement data for the replacement LED lighting. Such information has not been published, to the knowledge of the author and therefore is not available. Hence, simulations were used as an alternative for this assessment.

This chapter reviews suitable simulation software and presents the findings of a study that compared simulated data, against measured thermal and energy data.

8.2 Criteria

For the thermal and energy simulations required in this thesis, a range of criteria were put in place to assess the suitability of software to conduct this work. The criteria were are follows:

- Ability to model a physical environment ranging in geometry from the scale of a room to a whole building,
- Ability to define heat gains from luminaires, in the context of a suspended ceiling system, and specify the split down of that heat into the main space below and the ceiling void above, as needed per luminaire,
- Accuracy of results in predicting room temperatures and energy demand, and
- Software that were already available to the Welsh School of Architecture, or could be made available within a reasonable cost budget.

8.3 Software Overview

A range of thermal and energy software were already available to the Welsh School of Architecture and, from those, two were selected to review, based on familiarity, ease of use and accuracy. These were the EnergyPlus and the HTB2 thermal and energy simulation software.

EnergyPlus is an energy simulation software developed by the Department of Energy in the U.S.A. (USDOE 2012b). Version 7 was used in this thesis, which was the latest available at the time of writing this thesis. EnergyPlus is used extensively in academia and practice globally as it has been extensively tested and validated, and it still continues to be developed and improved with updates on the code every six months or so. Comparative and analytical tests conducted include HVAC tests based on ASHRAE research project 1052, ASHRAE Standard 140-2007 and IEA HVAC BESTTEST E100-E200 series (Neymark and Judkoff 2002).

HTB2 is an energy simulation software developed in the Welsh School of Architecture at Cardiff University (Lewis and Alexander 1990) and is used in academic studies, but less so in practice, as it is only available to academia for now. It has been tested extensively and continues to be developed (Alexander and Hassan 1997), (Alexander et al. 2005). The version used in this thesis was HTB210.

Both software require the use of a weather file that contains hourly weather data of temperatures, humidity and solar radiation, among others. Such files were obtained from the EnergyPlus website, where they are freely available for a range of locations around the world. This is where weather data was obtained for the various case study building locations that were selected.

HTB2 and EnergyPlus are energy simulation software that also require detailed information on the geometry, layers and thermal properties of a building, among others, in order to perform calculations. It is possible to provide 3D building information by exporting from a range of software, but there is only one software that exports to both, and that is ECOTECT. Therefore ECOTECT was used as the tool where 3D geometry was constructed and model details imported, so that they were then exported to each software separately. ECOTECT was also the software used to export to RADIANCE for lighting analysis, therefore maintaining consistency throughout all models and reducing modelling time for the range of models and versions that were needed for this thesis.

Both software allowed for a detailed description of how heat is emitted in spaces by luminaires. This allowed the specification of heat emitted by luminaires as radiative, convective and conductive, as well as the allocation of part of that heat to one space and part of that heat to another space (i.e. main room space and ceiling void). This, would account for the different ways in which heat is emitted by fluorescent and LED lights, as described in Chapter 3, and also addresses the last point of the criteria setup for software selection.

For purposes of rigour and accuracy, it was necessary to ensure that both thermal models contained the same settings and model information. It is very often the case that simulation software are used without an in-depth investigation of how properties and settings get transferred from model to model. Therefore, extensive tests were performed on the accuracy of the transfer of settings and parameters from ECOTECT to HTB2 and EnergyPlus, as well as appropriate ways of modelling luminaires in a test room. From this work, it was possible to identify areas where additional editing of the output files was necessary to maintain full consistency. A sample of the tests performed to ensure an accurate transferring of information and appropriate modelling techniques can be found in Appendix B.

To examine the accuracy of both software in terms of modelling the thermal environment of a room that employs ceiling tile luminaires, a test was devised in the same test room that was used for lighting tests, as described in Chapters 6 and 7.

8.4 Test Room Setup for Thermal Studies

After the LED replacement luminaires (as described in Chapter 6 and 7) were installed into the test room, a series of temperature measurements were taken, including room temperature and ceiling void temperature with the use of temperature probes and equipment, as seen in Figure 8.1. The Eltek Squirrel Special 1000 series data logger was used for logging room temperatures, which were taken using Eltek Thermistors (Sensor: Pt100, code: P4), which were then logged into a computer on site. All of the equipment was provided by the environmental lab of the Welsh School of Architecture, which was responsible for the maintenance and calibration of the devices to ensure accuracy. Whenever it was not possible to calibrate the devices themselves, then information was provided by the environmental lab to the author of this thesis, so that the measured data from a particular device can be calibrated on an excel sheet. All the measured data presented in this chapter have been calibrated to ensure accuracy of the measured data.

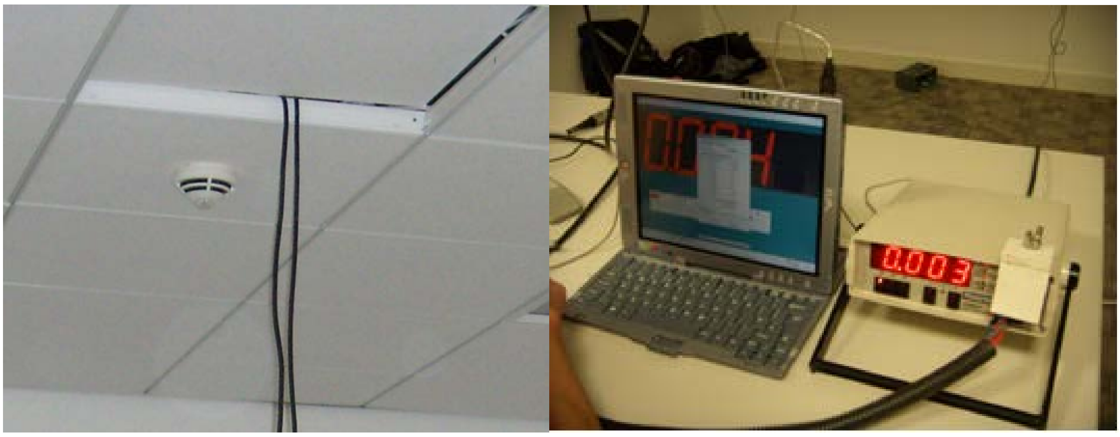


Figure 8.1 Part of the equipment used for recording room and ceiling void temperatures

The measurements took place over a period of 3 days in summer, with the LED lights being on over all of this period so that the effect of heat emitted by LEDs in the room and the ceiling could be measured. In order to compare the measured data with the simulated predictions, weather data for the exact same period were obtained from the weather station situated at the roof of the BUTE building, which houses the Welsh School of Architecture in Cardiff and is within 500m of the building where the test room was located.

From a survey conducted on the building where the test room was located, and information obtained from the services engineer and architect, a thermal model of the room was setup in ECOTECT containing construction information. The room was mostly unoccupied during the three day measurement period and it was mechanically serviced (along with the rest of the building) from 7am until 6pm and, for the summer period that measurements took place, this meant that cool air was cooling the room whenever necessary. The settings used in the models to simulate the effect of heat from lighting can be found in Table 8.1.

Table 8.1 Settings used in the thermal models for simulating the heat emitted from luminaires (ASHRAE 2009), (Chantrasrisalai and Fisher 2007), (Rea 2000)

Luminaire	Measured Power*	Heat emitted to the room below	Heat emitted to ceiling void above
Fluorescent (Quattro C Body-lin 3 x 18w T26 HFD)	58 W	47%	53%
LED replacement luminaire	51 W	26%	74%

** These values were obtained from measurements on site*

8.5 Results and Discussion

Figure 8.2 shows the temperature measurements for the test room for a sample 24 hour period in the summer (out of 3 measured days), when lit under LED lighting. Temperature data is presented for the room as well as for the ceiling void above. Predicted data for both spaces by EnergyPlus and HTB2 are also presented for comparison.

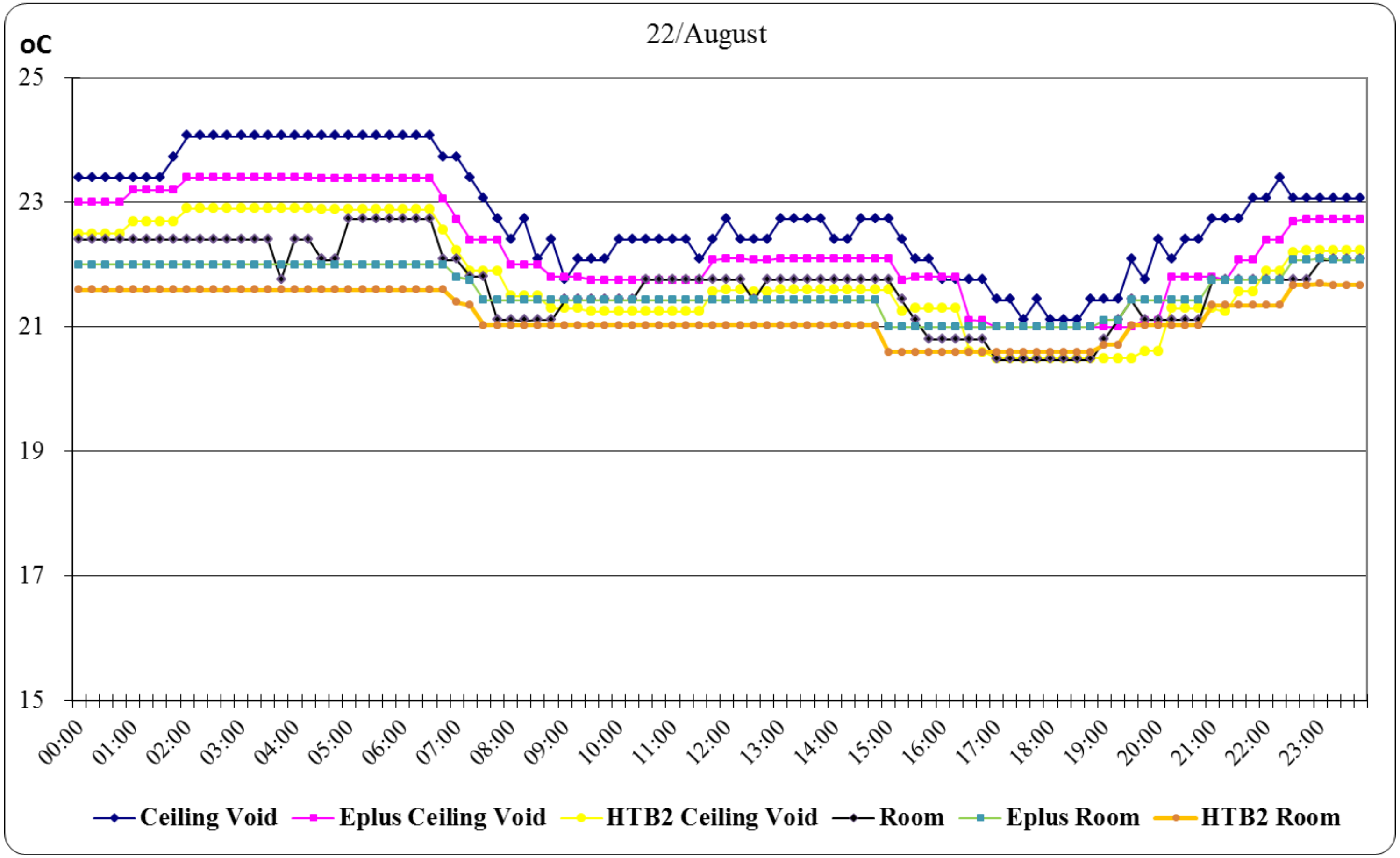


Figure 8.2 Test room and ceiling void temperatures from: Site measurements, EnergyPlus and HTB2 (Day 1)

Both EnergyPlus and HTB2 predictions are within 1 to 2^{o}C of the measured data, with EnergyPlus being slightly closer. A close examination of the data reveals that both EnergyPlus and HTB2 are consistently under-predicting the temperature in the room, although they very closely follow the trends in temperature fluctuations.

The obvious reduction in room temperatures from 7am until 6pm is due to the mechanical cooling of the room, which affects both the main space and the ceiling void. After 6pm, temperatures rise again due to the heat gains from lighting. Some temporary fluctuations in measured temperatures, that are not accounted for by EnergyPlus and HTB2, can be attributed to the temporary use of the room by staff of the building, which the author was informed of only after the experiment took place.

The same trends observed in Figure 8.2 can also be observed in Figure 8.3, where the full three days of measurements are presented.

Both software were closely matching the measured temperatures throughout the three day test period, with EnergyPlus being within 1 to 6% of the measured values most of the times, and HTB2 being with 1 to 10% of the measured values.

This confirmed that EnergyPlus and HTB2 could be used confidently to model the thermal effects of ceiling tile lighting in the context of a real room and it is therefore extrapolated that the effect of LED replacement luminaires could also be evaluated for case studies of whole buildings.

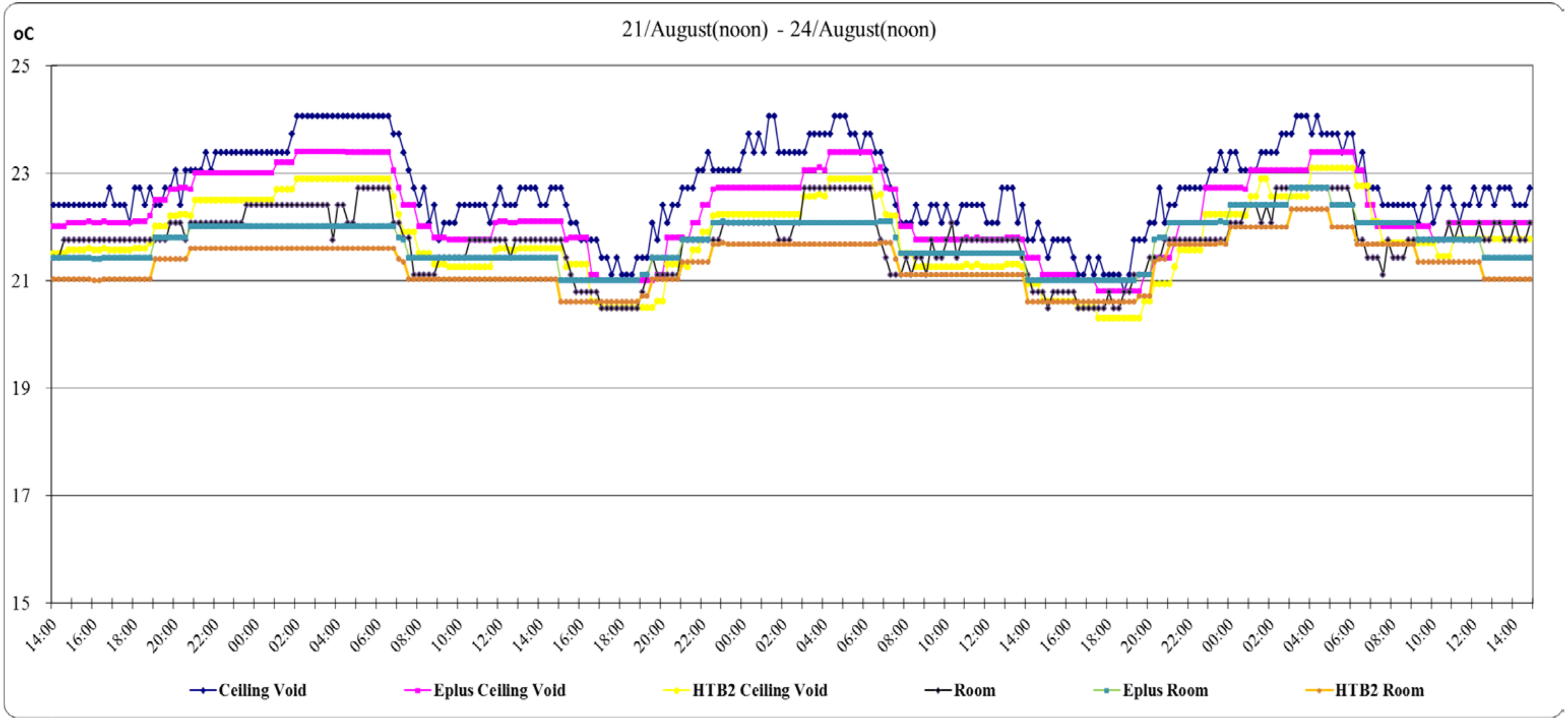


Figure 8.3 Test room and ceiling void temperatures from: Site measurements, EnergyPlus and HTB2 (Day 1-3)

Chapter 9. Office LED Replacement Case Studies

9.1 Introduction

In order to assess the energy impact of using LED luminaires as replacements to existing fluorescent ceiling tile luminaires, a range of case study buildings were selected. This, included office spaces and rooms, where ceiling tile fluorescent lighting was used by the lighting engineers as part of their design.

As a variety of fluorescent luminaires were used for the case study buildings, a range of replacement LED luminaires were designed, as described in Chapter 6. Then, their effect on the energy performance of each room was simulated and compared to the performance under fluorescent lighting.

This chapter presents the methodology used to setup each of the four case studies and the results obtained from the energy simulations conducted.

9.2 Methodology

Four case study buildings were selected from the industrial partners of the LEDLED project that this thesis is associated with. Each one of the following architectural and engineering firms provided a suitable building: Arup Consulting, CAPITA Architecture and Pentan Partnership (which actually provided two buildings). The criteria for selecting a suitable building were as follows:

- An office building, or a building incorporating rooms with ceiling tile type fluorescent luminaires

- A building where the artificial lighting design and the luminaires selected are up-to-date with current regulations and lighting systems.

- Access to the full set of constructions drawings and material specifications for the whole buildings, so that accurate thermal models in simulation software can be built, and

- Access to the full set of lighting design drawings and luminaire specifications, so that the lighting design can be replicated with LEDs.

The buildings provided were: the WJEC building in Cardiff, by CAPITA Architecture; the NewBridge building in Caerphilly, by Arup Consulting and the Warmere and Pulborough buildings, in Brighton and West Sussex by Pentan Partnership. Details of each building are provided in Sections 9.4 to 9.7, where each case study is presented separately.

All four buildings were real building examples and, as such, their design was dictated by the needs of the client and the architectural aspirations of the project designer. Also, the applicability of results obtained from these case studies could be limited to similar type buildings, in terms of size, form, construction and location. In order to widen the applicability of this research, a more commonly found size and form type case study was developed as a computer model, based in Cardiff. This was called the notional office building as it is a definition for a building used widely for comparisons between the energy performance of a design against a base case building. This notional case study consisted of a three storey open plan office, specified to current UK regulation standards and using a standard UK occupancy and usage schedule. More details on the model and the setup used for simulations can be found in Section 9.8.

Each case study model generated included the following information:

- 3D geometric model, based on drawings provided, including surrounding buildings (if they existed) to account for overshadowing, as well as correct orientation.
- The appropriate lighting design, as per case (I.e. Fluorescent and LED).
- The construction layers and their thermal properties.
- The inclusion of a weather file for the location of each building in the thermal model.
- The occupancy and usage profiles.
- The small power gains, and
- The lighting heat loads for the existing fluorescent lighting, as well as all the LED replacement luminaires (all in separate models), each with an appropriate split down of the heat emitted by each luminaire.

For all four case studies, before any thermal analysis could take place, custom LED replacement luminaires had to be designed for each one of the fluorescent luminaires employed in these buildings. These custom LED luminaires were designed based on the methodologies developed in Chapter 6. After they were designed, their lighting performance was compared against the performance of the existing fluorescent luminaires to ensure that the lighting environment was replicated. Details for each LED replacement luminaire developed are presented in the following sections.

Three cases would be simulated for all case study buildings:

1. Heating and cooling energy demand for when fluorescent lighting, as specified by the building lighting designers, is used.

2. Heating and cooling energy demand for when a custom designed LED replacement luminaire is used, that uses currently commercially available and mid-range in terms of cost, LED technology (LED(present)), and

3. Heating and cooling energy demand for when a custom designed LED replacement luminaire is used, that uses LED technology that is expected to be available in the near future (LED(future)).

The third case was used to take into account of the fact that LED technology is rapidly improving and it is only a matter time before LEDs are more efficient than what is currently available. Hence, simulating this potential effect would provide a prediction of their impact in the near future if they were used in this application.

9.3 Modelling Setup and Assumptions

As described in Chapter 8, results obtained from EnergyPlus and HTB2 were in close agreement, thus only one was necessary for simulating each case study. For purposes of rigour though, and in order to increase confidence in the results obtained, both software were used so that potential unreasonable differences in results between software could serve as a basis for further investigation and as an indicator of possible anomalous results.

All the above information was included within each of the models generated in ECOTECT and then exported to EnergyPlus and HTB2 accordingly. In some cases there was a need to edit the models within EnergyPlus and HTB2, as described in Section 8.5, in order to maintain accuracy and consistency in the transferring of model information from software to software.

To allow for more clarity in the results presented only one set of data is used, that from EnergyPlus. Results obtained from HTB2 can be found in Appendix C for reference and comparison purposes. EnergyPlus is better known and more widely used than HTB2, hence it was chosen as the software from which results will be presented in this chapter. Specific settings used for each of the models and for each case study can be found in the following sections, where each case study is presented separately along with the results of the simulations.

For all case study buildings, simulations were performed over the whole year for heating and cooling load demands. These were accumulated first on a month to month basis and then as annual total heating and total cooling demands.

For the first four real case study buildings, the use of ceiling tile fluorescent lighting ranged from extensive (compared to the total building floor area), to more limited to a few rooms. Therefore the investigation concentrated on the annual heating and cooling load demands only for those spaces that used ceiling tile lighting. For the fifth case study building, ceiling tile lighting technology was employed throughout the entire floor area.

All real case study building used an office working schedule from 8am to 7pm, which was the schedule given by all design firms as the most likely to be used in these buildings. It is expected that all occupants should be in the office by 9am and to leave by 6pm, but it is common in such offices that employees will turn up earlier at work and some also leave later, hence the extended schedule. It is also expected that around half of all employees will leave the office for lunch. A graph of this schedule and can be seen in Figure 9.1. An assumption was made for the notional office case study, that the same occupancy profile was used, in order to maintain consistency between all case studies.

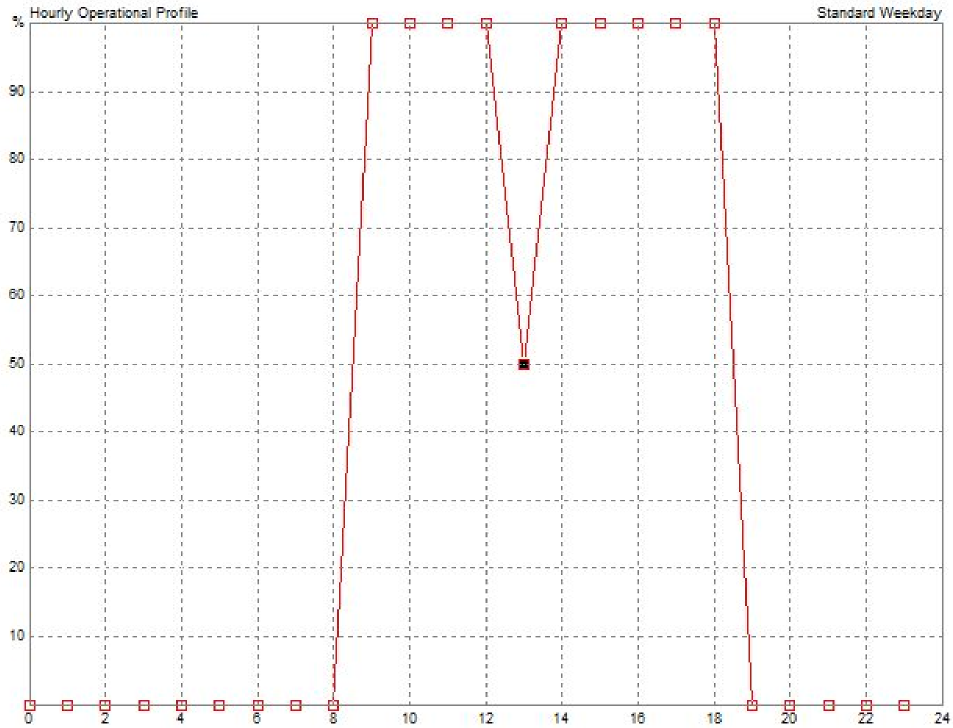


Figure 9.1 Occupancy pattern for a standard weekday, used in the thermal modelling of all case studies

Other modelling assumptions made for each case study, are presented separately in tables in each of the case studies.

9.3.1 Conversion to green-house gas emissions

All four real case study buildings were using natural gas as the fossil fuel source to generate the heating demand required in the building and electrically driven chillers to meet their cooling demand. Therefore, as the use of fuels between heating and cooling were not the same, a conversion of each simulated demand load to a suitable metric was necessary.

For the notional building case study building, an assumption was made that natural gas was used as the fossil fuel source to generate heating and electrically driven chillers for cooling. This was done, to maintain consistency throughout all case studies.

As heating and cooling used different fuel sources, this, did not allow for a direct comparison between heating and cooling demand loads, as for heating a fossil fuel is burned to generate heat, whereas in all other cases (cooling, equipment, lighting) electricity is used which is typically produced by a mix of fuels. So first, heating demand loads would need to be converted to primary energy and electrical loads used in the models, into electricity consumption.

To convert demand loads predicted through simulations to primary energy, a series of base assumptions were made on the efficiencies of the heating and cooling systems, as such information they were not available for each of the case study buildings at the time of writing of this thesis.

For heating, an overall efficiency of 90% was used, which included the distribution system efficiency and seasonal boiler efficiency taken from CIBSE (2004) and assuming a standard efficiency to the whole system.

For cooling, measured whole system efficiencies (including fans, pumps, etc) have been reported by Knight et al. (2005) in the UK and out of a range of 0.3 to 1.7, a value of 1.4 was selected as a sensible figure for the case study buildings in this thesis, as

1.7 would correspond to high end performing systems which are not always employed in buildings due to additional capital cost. Therefore, the following conversions were applied to the heating and cooling demand loads to get figures on primary heating energy and electrical consumption of the building:

Primary Heating Energy = Heating Demand Load **/** 0.9

Electrical Consumption for Cooling = Cooling Demand Load **/** 1.4

Electricity is also consumed though from equipment and lighting. It is assumed that all energy from lighting energy and equipment will eventually be converted into heat, as there is no mechanical work, which is an assumption very often made in heat-gain calculations (Mahia et al. 2005) (Stokes et al. 2004). Hence, all heat gains from small power and lighting in each room (i.e. 25 W/m^2), was factored by the total occupied days (260) and hours (11h) in the year to obtain the relevant electricity consumption for all the modelled rooms.

In order to convert the primary heating energy, as well as consumed energy into a suitable metric that would allow for comparisons between the various options tested, the figures of primary energy obtained for each, were converted into kg of green-house gas emission (kg CO2equivalent per kWh), by using conversion factors obtained from the 2012 Guidelines to DEFRA/DECC's GHG Conversion Factors for Company Report, version 1.0 (DECC 2012), which are produced by the UK Department of Energy and Climate Change and are appropriate for UK buildings. To convert primary heating energy (using natural gas) to CO2e, a conversion factor of 0.18521 was used (Annex 1, Table 1c). For electricity, a grid rolling average conversion factor of 0.52037 was used (Annex 3, Table 3c, 2010), which represents the average carbon dioxide emission from the UK national grid (plus net imports) per kWh of electricity generated. Therefore, the following conversions were applied to the primary heating energy and electrical consumption, in order to obtain kg of CO2e:

$$\text{Kg CO2e for heating (i.e. Natural GAS)} = \text{Primary Heating Energy} \times 0.18521$$

$$\text{Kg CO2e for electricity (i.e. Chillers, small power, lighting)} = \text{Electrical Energy Consumption} \times 0.52037$$

Even though small power loads were assumed to be uniform throughout all modelled rooms, the lighting loads varied sometimes from room to room. The reason for this, is because some rooms contained more luminaires than others, hence the previous equations were applied to each room of each building in turn and then added to the total figures. Due to the way in which heat is emitted from the luminaires, a portion of the heat goes into the room and a portion to the ceiling void above, hence the loads calculated only take into account of the heat and energy that goes into the room. These conversions were applied to all case study buildings that are presented in the following sections and only for the rooms that were modelled in the simulation software.

In order to allow to consistency and a better comparison between the case studies, all lighting related graphs are presented based on a scale from -40 lux to +40 lux, so that differences between fluorescent and LED replacement performance can be demonstrated. Annual heating and cooling load demand predictions, are presented on the same scale in all case studies, as is also the case for CO2e emissions graphs where the same scale has been used throughout. Furthermore, the sizes of all relevant graphs in each case study have been kept the same, to allow for an easier comparison.

9.4 Case Study 1: WJEC Building

All details for drawings, construction, lighting design and layout and other relevant information for this building were provided by CAPITA architecture. This is a multi-storey building located in Cardiff, but only in a portion of it fluorescent ceiling tile lighting was used, and that was effectively the ground floor. Therefore, the study only focused on the ground floor and all computer models were constructed using only one heated and cooled floor. The floor above the ground floor, as well as other office buildings surrounding it on the North West and North East sides were also constructed, so that any heat flow between them is also taken into account.

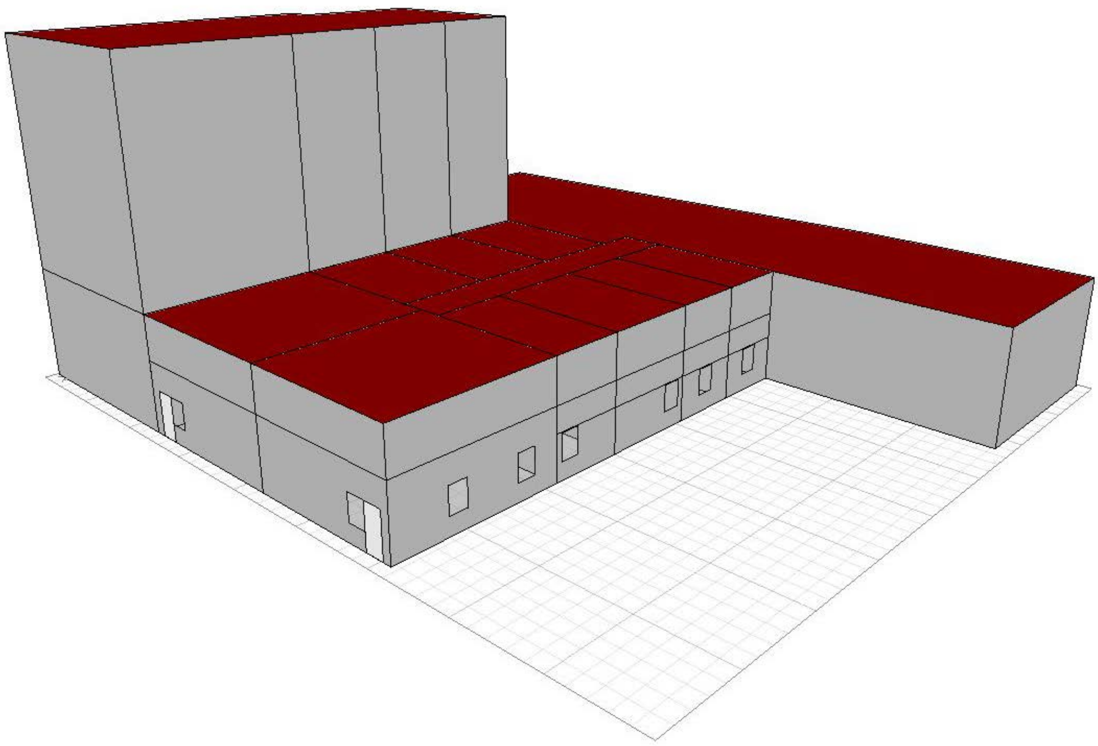


Figure 9.2 ECOTECT model used for lighting and thermal analysis

Some assumptions were made on the usage of the building, after talking to the architects and engineers of the building. A list of those assumptions together with a list of simulation settings and details of luminaires used can be found in Table 9.1.

Table 9.1 Modelling settings and assumptions

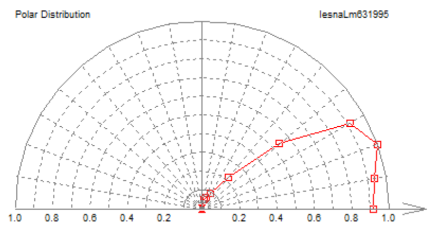
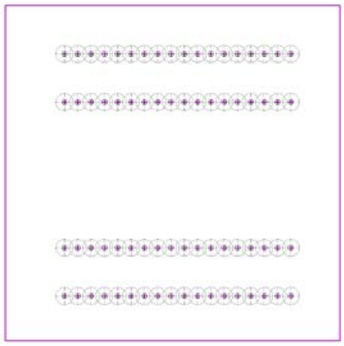
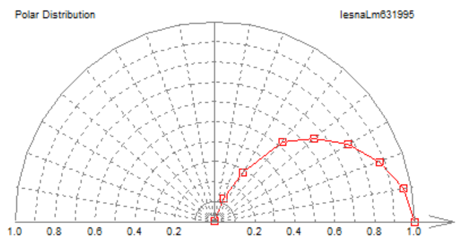
Hours of operation	8am-7pm (**same schedule used for lights)*
Temperature Band	21-24 ^{o}C
Internal Gains (excluding lighting)	25 W/m^2
Fluorescent Lighting	67 W per luminaire *[Thorn Planor]* *(Number of luminaires varies per room)*  *[Longitudinal section of IES profile]*
LED(present) Lighting	55 W per luminaire  *[72 LEDs, arranged in 4 rows]*  *[Longitudinal section of IES profile]*
LED(future) Lighting	34 W per luminaire *[same arrangement as LED(present)]*
Occupant Gains	Varies per room (4-12 people per room)
Fabric thermal properties	As specified by the architect **in line with UK Building Regulations*

Figure 9.3, presents the differences in illumination levels in various rooms, when illumination under fluorescent lighting is subtracted from illumination under LED lighting for each of the points on the working plane grid. For all locations in the room directly under each luminaire, illumination under LED lighting is higher than fluorescent by 25-32 lux, whereas closer to the walls of each room and away from the luminaires, illumination under LED lighting is in deficit of 1-14 lux. Overall, the illumination pattern is very similar under both lighting conditions with LED lighting providing higher lux levels directly under each luminaire.

Figure 9.4, presents the results obtained from the energy simulations in EnergyPlus. It shows the predicted annual heating and cooling load demand (in kWh/m^2) under fluorescent lighting; LED(present); and LED(future) lighting luminaires. Results show a reduction in cooling loads of 5% under LED(present) lighting and 23% under LED(future) lighting, compared to fluorescent. On the other hand, an increase in heating demand loads of 3% for LED(present) and 25% for LED(future) lighting.

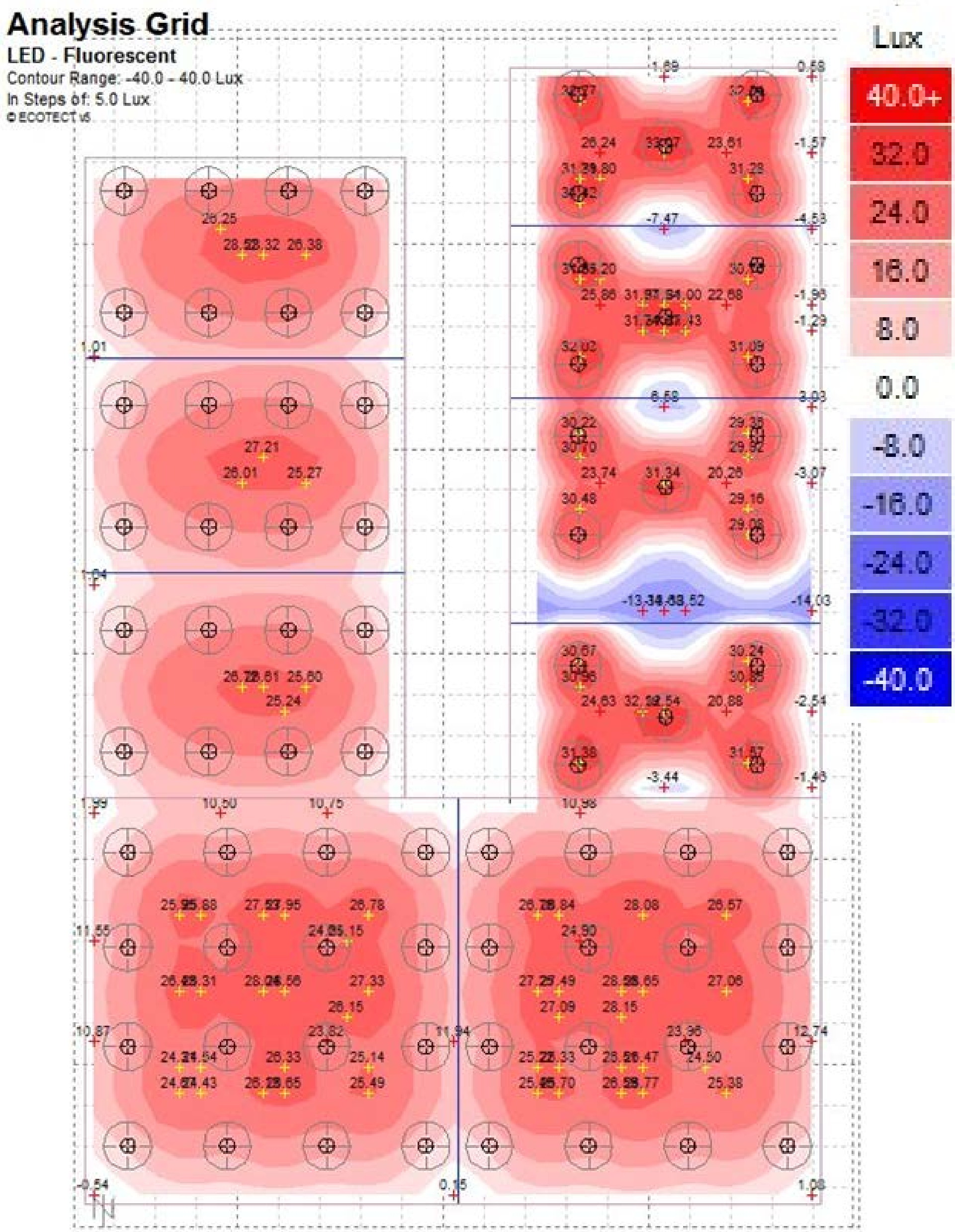


Figure 9.3 Differences in lux levels between fluorescent and LED lighting, when fluorescent lux levels are subtracted from LED lux level at each point. Blue colours indicate a deficit of lux level and red colours and surplus of lux levels compared to fluorescent. White, indicates that lux levels are exactly the same.

Note: Only parts of the building with ceiling tile lighting are shown

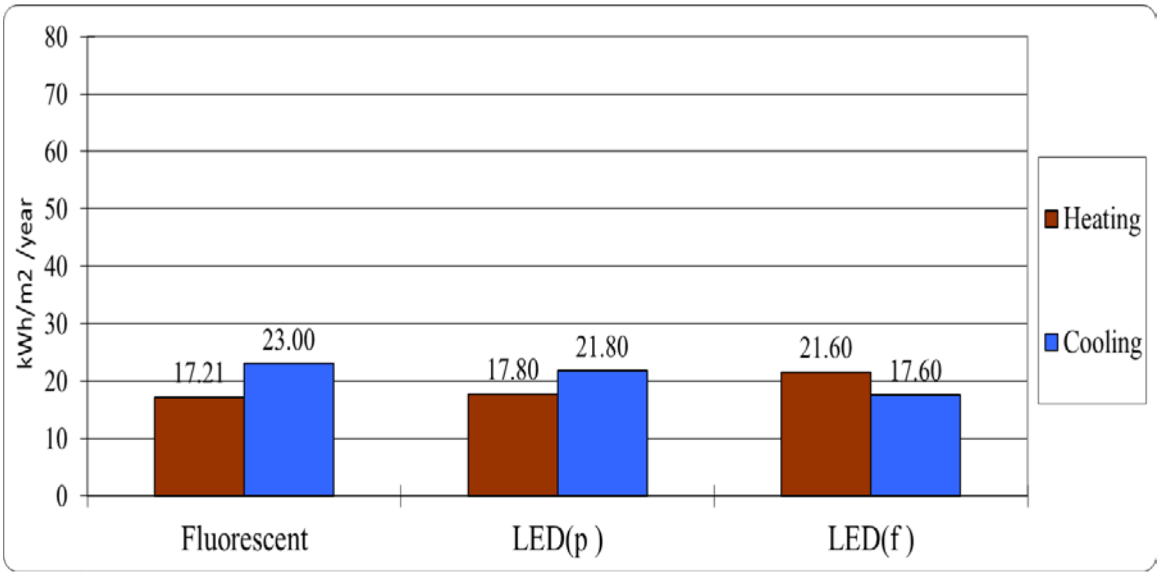


Figure 9.4 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

Figure 9.5, shows the CO2e emissions for all three lighting scenarios, when all electrical consumption (cooling, small power, lighting) and heating energy is taken into account and converted to kg of CO2e. Emissions are highest under fluorescent lighting and lowest under the future LED lighting scenario. More specifically, presently available LEDs provide a 6% reduction in emissions compared to fluorescent, while future LEDs provide a 12% reduction.

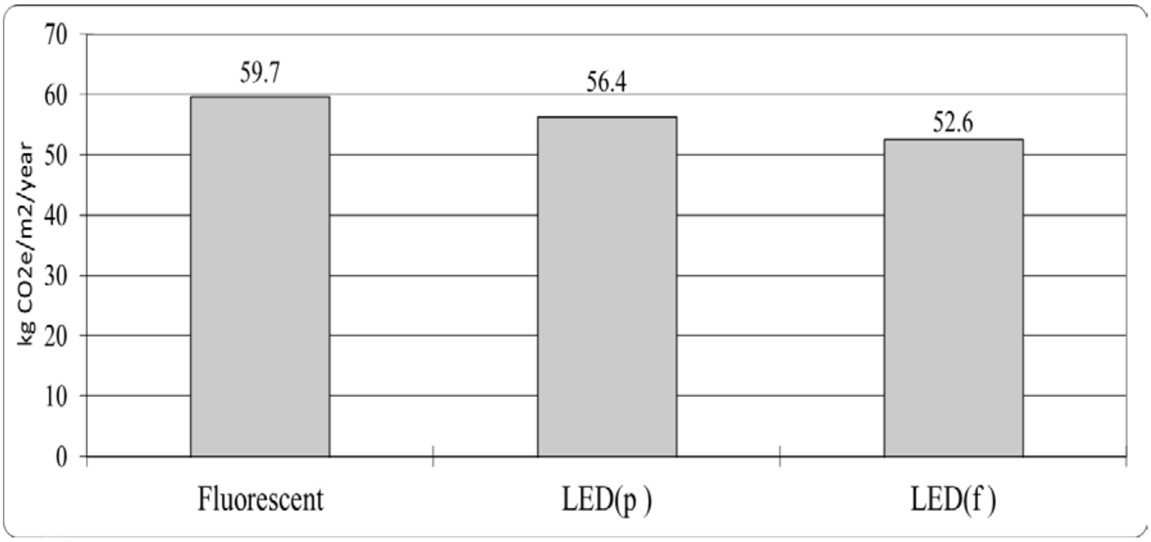


Figure 9.5 CO2e emissions (in Kg CO2e/m^2/year) for all the modelled zones of the building, under three types of lighting

In order to establish the actual reduction in primary energy terms that these percentages represent, a conversion is made. The differences in CO2 emissions between the three cases are caused by reduced electrical lighting consumption as well as an increase in heating energy and a reduction in cooling loads when LEDs are used, compared to fluorescent. As heating uses gas and electricity from the grid uses a variety of sources to supply electricity to a building, it is not possible to make a direct comparison between the two, since the exact mix of fuels and other sources to generate electricity is not known. Hence, an assumption is made here to aid in this comparison and convert the kg of CO2e, into an equivalent unit, as the ones calculated for heating primary energy. To do this, it is assumed that all electricity supplied to the building is generated from natural gas, hence the same conversion factor will be used to convert kg of CO2e/m^2, into kWh/m^2. Thus:

Primary Load[1] = kg of CO2e x (0.52037[2] / 0.18521[3])

[1] worked on a heat equivalent using natural gas

[2] Grid rolling average GHG factor

[3] GHG factor for natural gas

So, if all the electrical loads are assumed to be derived from a heating equivalent scenario using gas, then the actual reduction in energy that these percentages represent is about 18 kWh/m^2 for LED(present) and 38 kWh/m^2 for LED(future) compared to fluorescent.

The analysis of the results suggests that LEDs show a great potential for reducing cooling loads in the summer while increasing the heating loads in the winter. In terms of CO2e emissions, LEDs again show a great potential for reductions. This trend becomes more obvious with the use of LED products that will be available in the near future and it is expected to be even more profound if LEDs develop and become more efficient as predicted by the industry.

9.5 Case Study 2: NewBridge Gateway Office

This is a three storey office building, located in Caerphilly, Wales. Ceiling tile fluorescent lighting was used in all three floors, although there were areas that used other forms of lighting as well. All details for drawings, construction, lighting design and layout and other relevant information were provided by ARUP architecture.

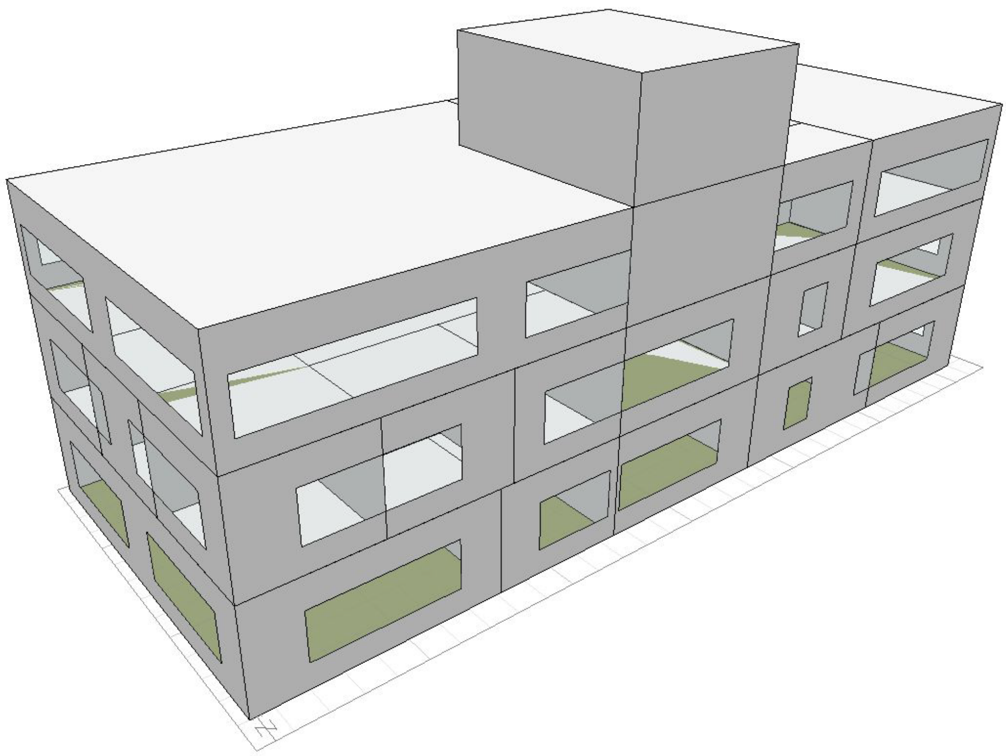


Figure 9.6 ECOTECT model used for lighting and thermal analysis

In order to perform simulations, some assumptions were made as to the usage of the building after consulting with the architects and engineers of the building. A list of those assumptions, together with a list of simulation settings and details of luminaires used, can be found in Table 9.2.

Table 9.2 Modelling settings and assumptions

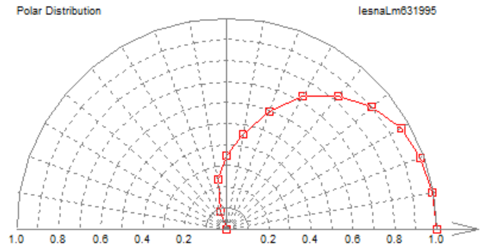
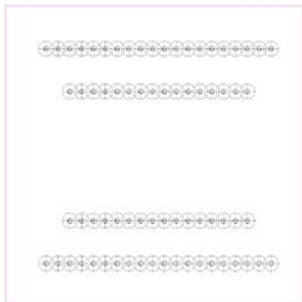
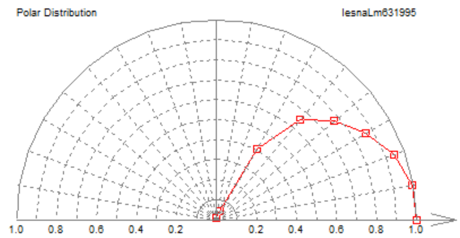
Hours of operation	8am-7pm (**same schedule used for lights)*
Temperature Band	21-24 °C
Internal Gains (excluding lighting)	25 W/m^2 *(some rooms have 10 W/m^2)*
Fluorescent Lighting	51 W per luminaire *[Zumtobel Mellow Light IV]* *(Number of luminaires varies per room)*  *[Longitudinal section of IES profile]*
LED(present) Lighting	45 W per luminaire  *[72 LEDs, arranged in 4 rows]*  *[Longitudinal section of IES profile]*
LED(future) Lighting	30 W per luminaire *[same arrangement as LED(present)]*
Occupant Gains	Varies per room (2-18 people per room)
Fabric thermal properties	As specified by the architect **in line with UK Building Regulations*

Figure 9.7, presents the differences in illumination levels in various rooms on the first floor of the building, when illumination under fluorescent lighting is subtracted from illumination under LED lighting for each of the points on the working plane grid. For all locations in the room directly under each luminaire, illumination under LED lighting is higher than fluorescent by 20-415 lux, whereas closer to the walls of each room and away from the luminaires, illumination under LED lighting is in deficit of 1-28 lux. Similar patterns were observed for the other floors and rooms of this building. Overall, the illumination pattern is very similar under both lighting conditions with LED lighting providing higher lux levels directly under each luminaire.

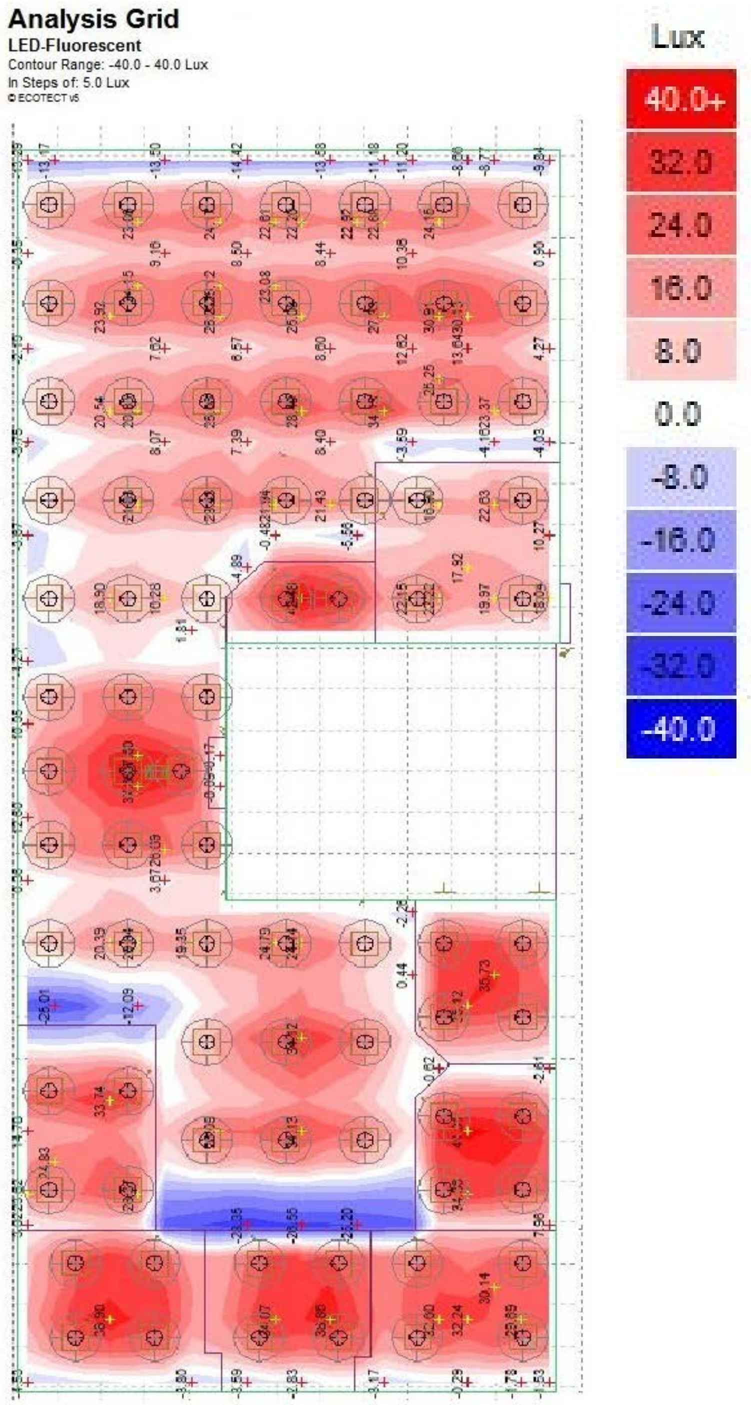


Figure 9.7 Differences in lux levels between fluorescent and LED lighting, when fluorescent lux levels are subtracted from LED lux level at each point. Blue colours indicate a deficit of lux level and red colours and surplus of lux levels compared to fluorescent. White, indicates that lux levels are exactly the same.

Note: Only parts of the building with ceiling tile lighting are shown

Figure 9.8, presents the results obtained from the energy simulations in EnergyPlus. It shows the predicted annual heating and cooling load demand (in kWh/m^2) under fluorescent lighting; LED(present); and LED(future) lighting luminaires. Results show a reduction in cooling loads of 12% under LED(present) lighting and 18% under LED(future) lighting, compared to fluorescent. On the other hand, an increase in heating demand loads of 27% for LED(present) and 47% for LED(future) lighting.

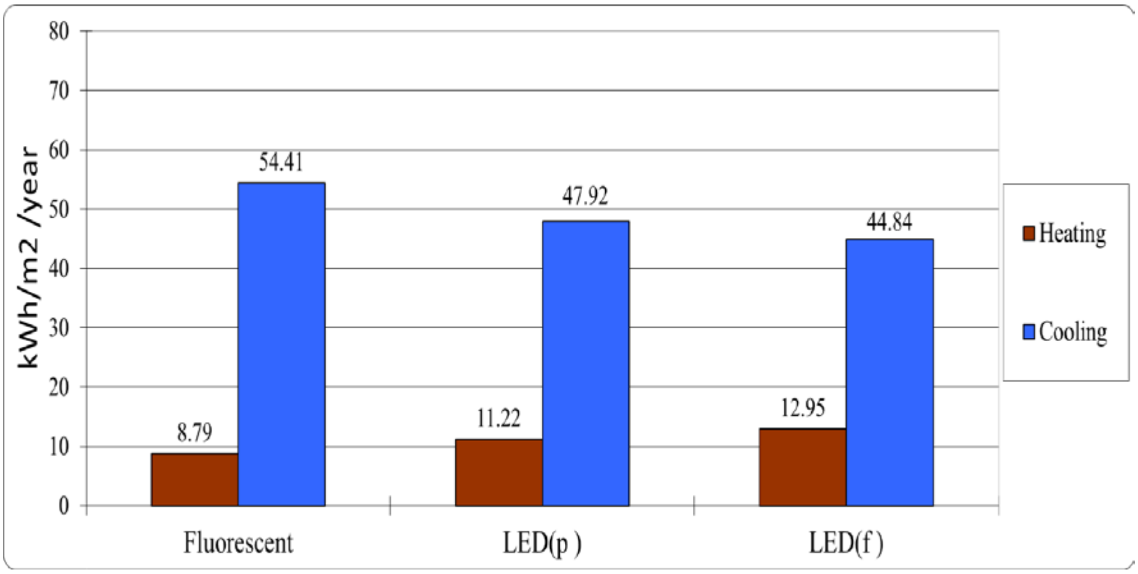


Figure 9.8 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

Figure 9.9, shows the CO2e emissions for all three lighting scenarios, when all electrical consumption (cooling, small power, lighting) and heating energy is taken into account and converted to kg of CO2e. Presently available LEDs provide a 9% reduction in emissions compared to fluorescent, while future LEDs provide a 12% reduction. Making the same assumptions as in the previous case study, this represents a reduction of 32 kWh/m^2 for LED(present) and 44 kWh/m^2 for LED(future) respectively of primary energy worked on gas equivalent (via emissions), when compared to fluorescent.

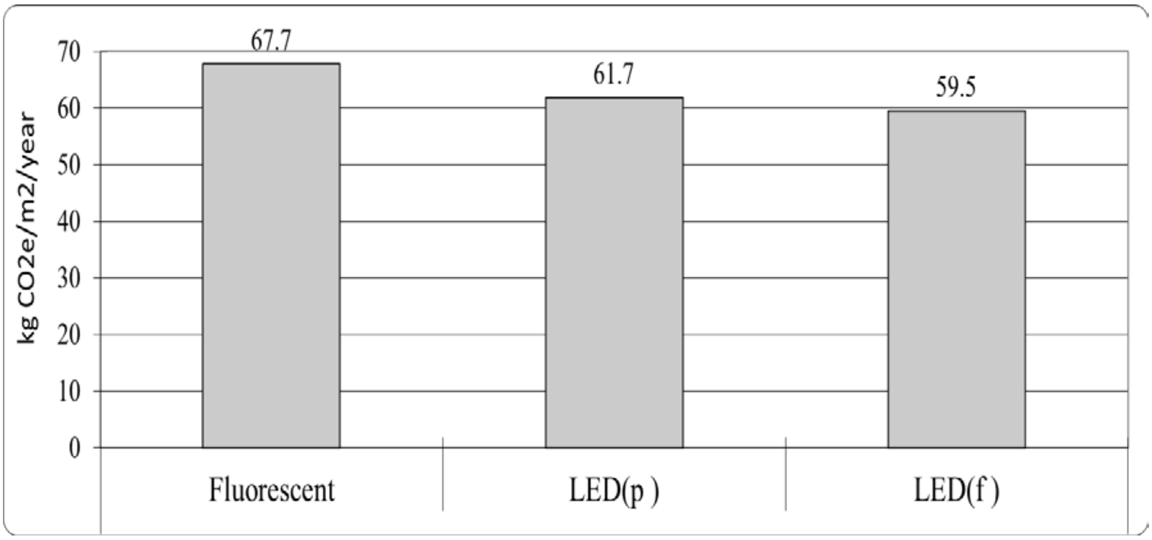
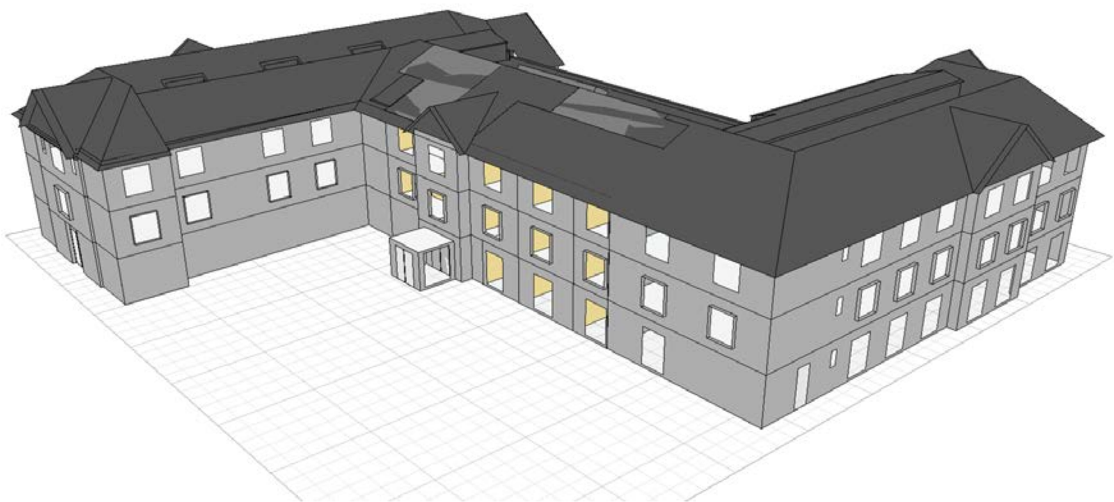


Figure 9.9 CO_2e emissions (in Kg CO_2e/m^2/year) for all the modelled zones of the building, under three types of lighting

9.6 Case Study 3: Pulborough Building

This is a three storey building incorporating office space and other general use rooms located outside West Sussex in the UK. Ceiling tile fluorescent lighting was used in selected rooms throughout the two floors, although there were areas that used other forms of lighting as well. All details for drawings, construction, lighting design and layout and other relevant information were provided by Pentan Partnership.



Fugure 9.10 ECOTECT model used for lighting and thermal analy

In order to perform simulations, some assumptions were made on the usage of the building, after talking to the architects and engineers of the building. A list of those assumptions together with a list of simulation settings and details of luminaires used can be found in Table 9.3.

Table 9.3 Modelling settings and assumptions

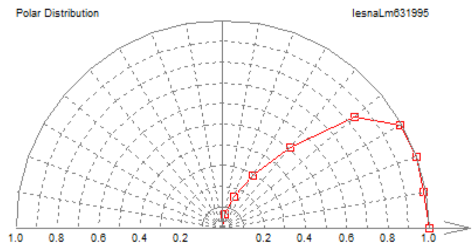
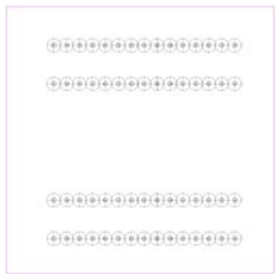
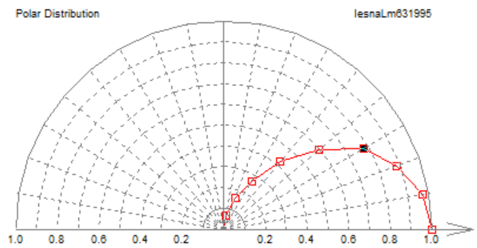
Hours of operation	8am-7pm (**same schedule used for lights)*
Temperature Band	21-24 ^{o}C
Internal Gains (excluding lighting)	17 W/m^2
Fluorescent Lighting	47 W per luminaire *[Thorn QUATROT5 HF FEFL]* *(Number of luminaires varies per room)*  *[Longitudinal section of IES profile]*
LED(present) Lighting	41 W per luminaire  *[60 LEDs in 4 rows]*  *[Longitudinal section of IES profile]*
LED(future) Lighting	28 W per luminaire *[same arrangement as LED(present)]*
Occupant Gains	Varies per room (1-10 people per room) *Higher occupancy in the summer due to higher number of visitors
Fabric thermal properties	As specified by the architect **in line with UK Building Regulations*

Figure 9.11, presents the differences in illumination levels in various rooms on the first floor of the building, when illumination under fluorescent lighting is subtracted from illumination under LED lighting for each of the points on the working plane grid. For all locations in the room directly under each luminaire, illumination under LED lighting is higher than fluorescent by 15-24 lux, whereas closer to the walls of each room and away from the luminaires, illumination under LED lighting is in deficit of 6-17 lux.

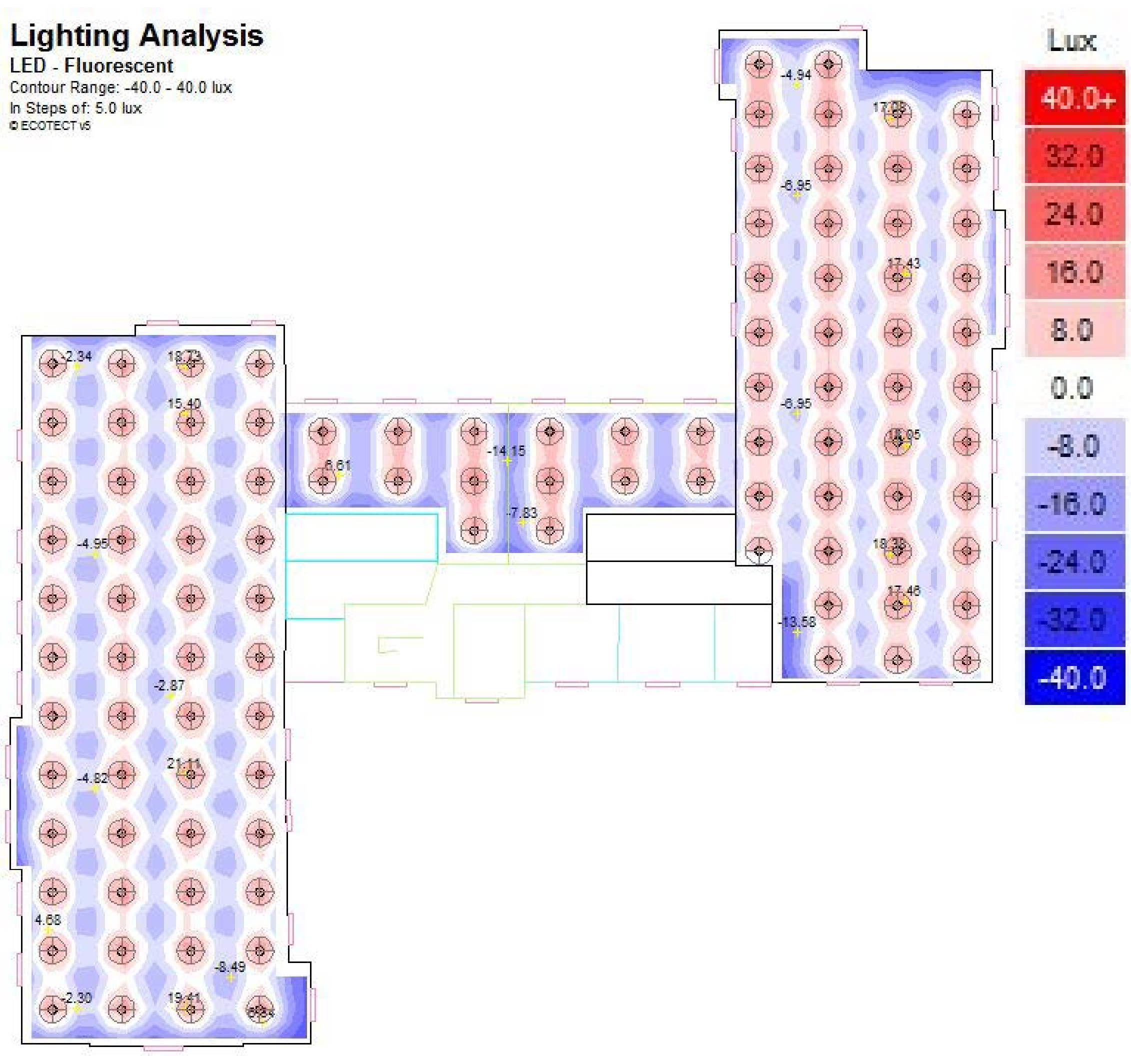


Figure 9.11 Differences in lux levels between fluorescent and LED lighting, when fluorescent lux levels are subtracted from LED lux level at each point. Blue colours indicate a deficit of lux level and red colours and surplus of lux levels compared to fluorescent. White, indicates that lux levels are exactly the same.

Differences are shown for 1st floor only for rooms that employ ceiling tile lighting

Similar patterns were observed for the other floors and rooms of this building. Overall, the illumination pattern is very similar under both lighting conditions with LED lighting providing higher lux levels directly under each luminaire.

Figure 9.12, presents the results obtained from the energy simulations in EnergyPlus. It shows the predicted annual heating and cooling load demand (in kWh/m^2) under fluorescent lighting; LED(present); and LED(future) lighting luminaires. Results show a reduction in cooling loads of 22% under LED(present) lighting and 44% under LED(future) lighting, compared to fluorescent. On the other hand, an increase in heating demand loads of 9% for LED(present) and 17% for LED(future) lighting.

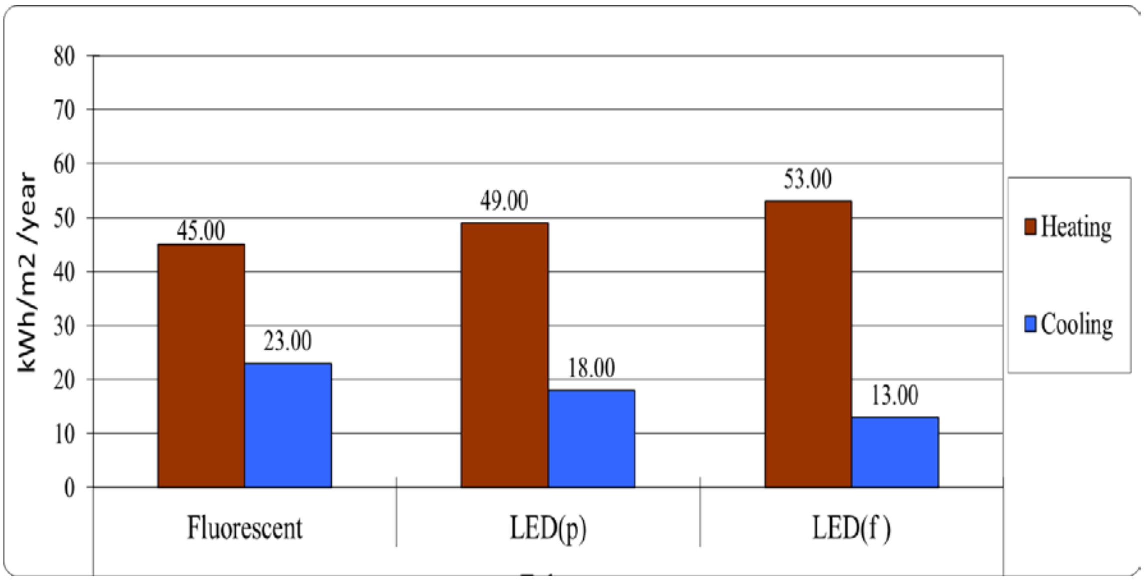


Figure 9.12 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

Figure 9.13, shows the CO2e emissions for all three lighting scenarios, when all electrical consumption (cooling, small power, lighting) and heating energy is taken into account and converted to kg of CO2e. Presently available LEDs provide a 5% reduction in emissions compared to fluorescent, while future LEDs provide an 11% reduction. Making the same assumptions as in the previous case study, this represents a reduction of 14 kWh/m^2 for LED(present) and 31 kWh/m^2 for LED(future) respectively of primary energy worked on gas equivalent (via emissions), when compared to fluorescent.

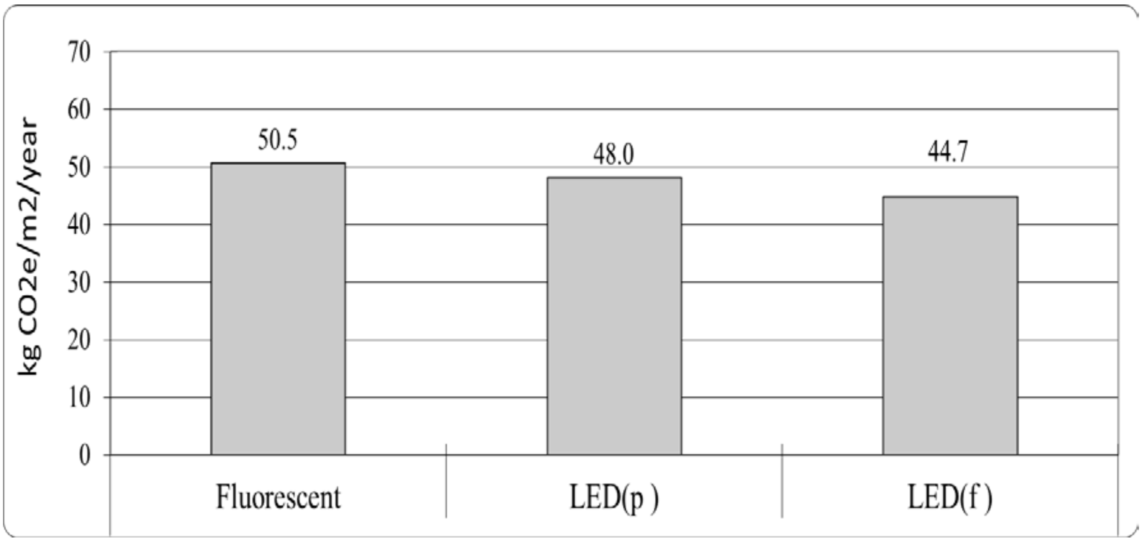


Figure 9.13 CO2e emissions (in Kg CO2e/m^2/year) for all the modelled zones of the building, under three types of lighting

9.7 Case Study 4: Warmere Building

This is a two storey building incorporating office space and other general use rooms, located outside Brighton in Essex, UK. Ceiling tile fluorescent lighting was used in selected rooms throughout the two floors, although there were areas that used other forms of lighting as well. All details for drawings, construction, lighting design and layout and other relevant information were provided by Pentan Partnership.

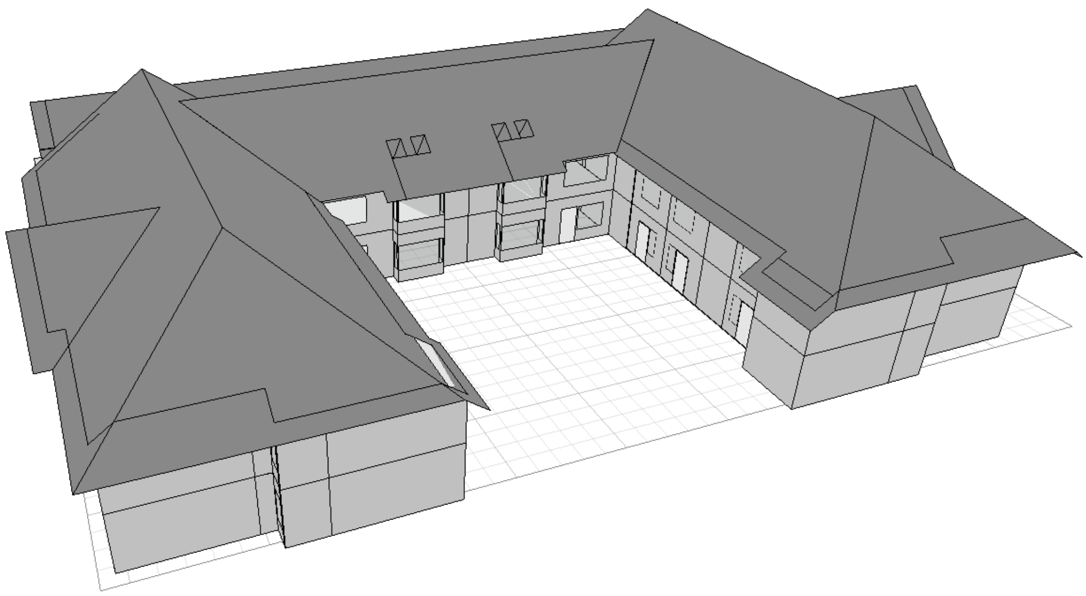


Figure 9.14 ECOTECT model used for lighting and thermal analysis

In order to perform simulations, some assumptions were made on the usage of the building, after talking to the architects and engineers of the building. A list of those assumptions together with a list of simulation settings and details of luminaires used can be found in Table 9.4.

Table 9.4 Modelling settings and assumptions

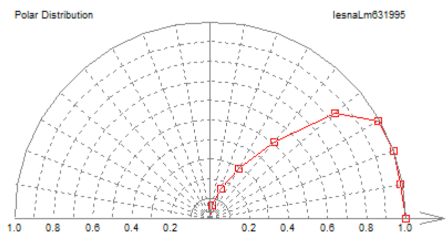
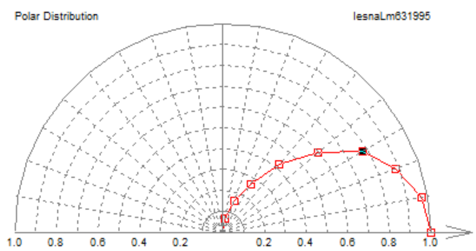
Hours of operation	8am-7pm (**same schedule used for lights)*
Temperature Band	21-24 ^{o}C
Internal Gains (excluding lighting)	8 W/m^2
Fluorescent Lighting	47 W per luminaire *[Thorn QUATROT5 HF FEFL]* *(Number of luminaires varies per room)*  *[Longitudinal section of IES profile]*
LED(present) Lighting	41 W per luminaire  *[60 LEDs in 4 rows]*  *[Longitudinal section of IES profile]*
LED(future) Lighting	28 W per luminaire *[same arrangement as LED(present)]*
Occupant Gains	Varies per room (1-3 people per room) *Higher occupancy in the summer due to higher number of visitors
Fabric thermal properties	As specified by the architect **in line with UK Building Regulations*

Figure 9.15, presents the differences in illumination levels in various rooms on the first floor of the building, when illumination under fluorescent lighting is subtracted from illumination under LED lighting for each of the points on the working plane grid. For all locations in the room directly under each luminaire, illumination under LED lighting is higher than fluorescent by 22-34 lux, whereas closer to the walls of each room and away from the luminaires, illumination under LED lighting is in deficit of 1-21 lux. Similar patterns were observed for the other floors and rooms of this building. Overall, the illumination pattern is very similar under both lighting conditions with LED lighting providing higher lux levels directly under each luminaire.

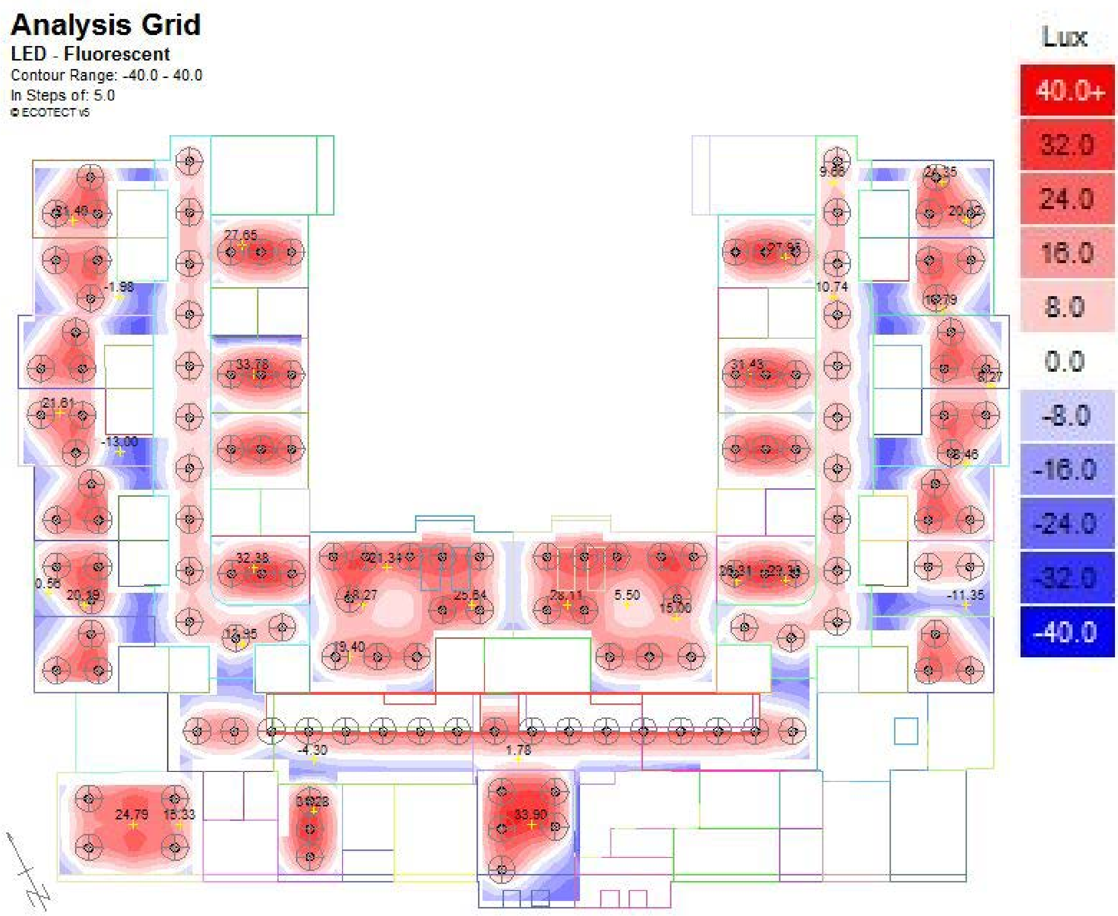


Figure 9.15 Differences in lux levels between fluorescent and LED lighting, when fluorescent lux levels are subtracted from LED lux level at each point. Blue colours indicate a deficit of lux level and red colours and surplus of lux levels compared to fluorescent. White, indicates that lux levels are exactly the same.

Note: Only parts of the building with ceiling tile lighting are shown

Figure 9.16, presents the results obtained from the energy simulations in EnergyPlus. It shows the predicted annual heating and cooling load demand (in kWh/m^2) under fluorescent lighting; LED(present); and LED(future) lighting luminaires. Results show a reduction in cooling loads of 12% under LED(present) lighting and 24% under LED(future) lighting, compared to fluorescent. On the other hand, an increase in heating demand loads of 6% for LED(present) and 17% for LED(future) lighting.

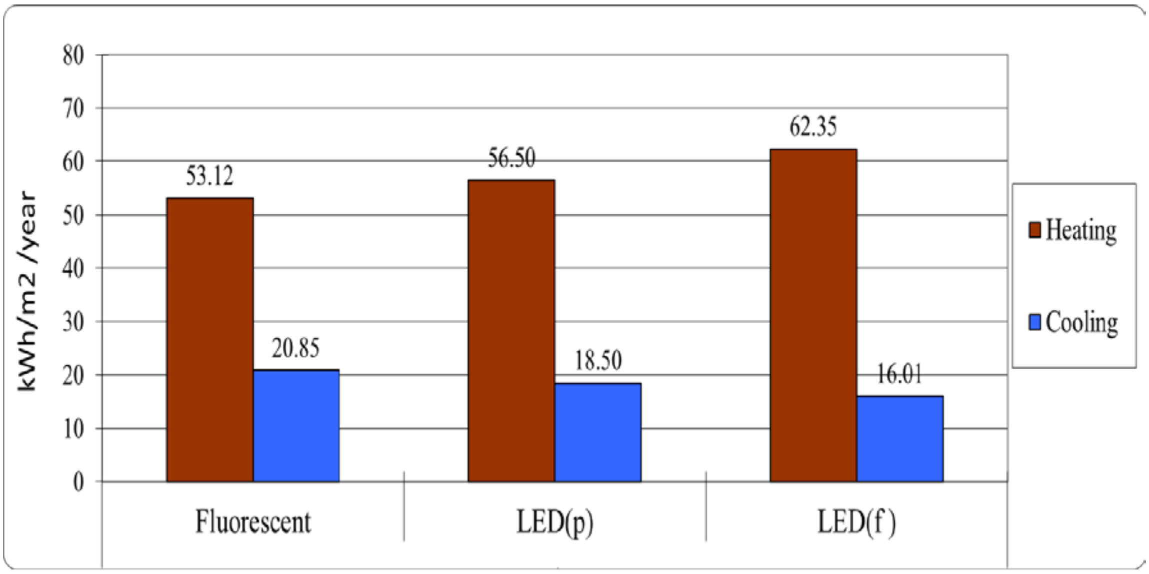


Figure 9.16 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

Figure 9.17, shows the CO2e emissions for all three lighting scenarios, when all electrical consumption (cooling, small power, lighting) and heating energy is taken into account and converted to kg of CO2e. Presently available LEDs provide a 4% reduction in emissions compared to fluorescent, while future LEDs provide an 10% reduction. Making the same assumptions as in the previous case study, this represents a reduction of 9 kWh/m^2 for LED(present) and 19 kWh/m^2 for LED(future) respectively of primary energy worked on gas equivalent (via emissions), when compared to fluorescent.

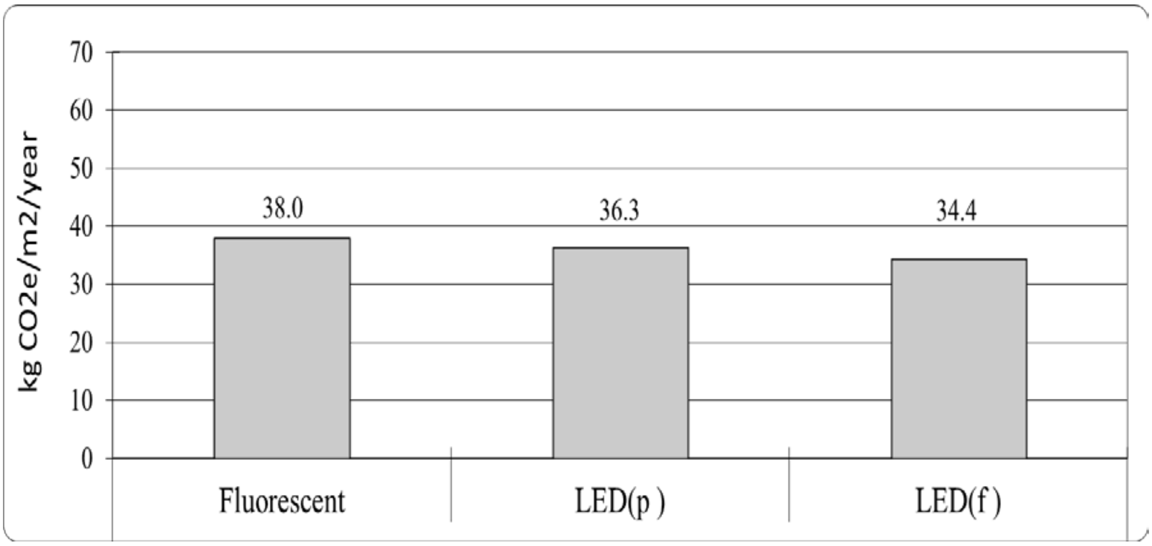


Figure 9.17 CO2e emissions (in Kg CO2e/m^2/year) for all the modelled zones of the building, under three types of lighting

9.8 Case Study 5: Notional Office

This is a three storey open plan office building, of 25m by 15m positioned in the climate of Cardiff, that was designed as an open plan office of typical dimensions, that can easily be found throughout the world. Ceiling tile fluorescent lighting was used throughout all three floors. This notional office was designed based on UK regulations in terms of U values for construction. Since this was a custom building design, an artificial lighting layout did not exist. Therefore a lighting layout design was devised with the help of DIALux (reviewed in Chapter 6), which provides a function for devising a lighting layout based on a given luminaire. All the fluorescent luminaires used in the other case studies were tested here too and the most energy efficient luminaire and layout were chosen.

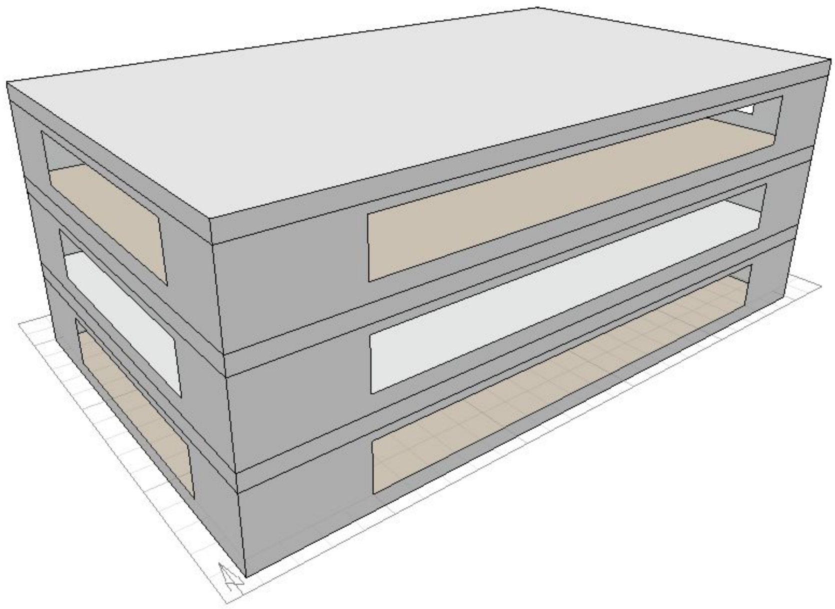


Figure 9.18 ECOTECT model used for lighting and thermal analysis

In order to perform simulations, some assumptions were made on the usage of the building, after talking to the architects and engineers of the building. A list of those assumptions together with a list of simulation settings and details of luminaires used can be found in Table 9.5.

Table 9.5 Modelling settings and assumptions

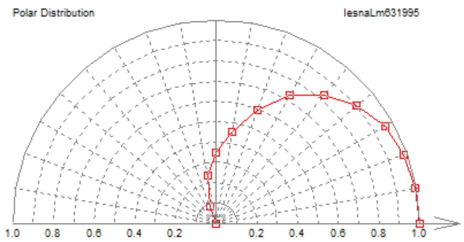
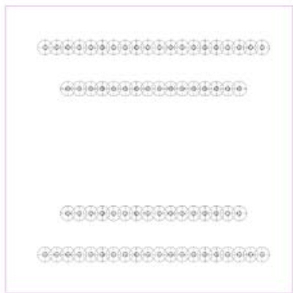
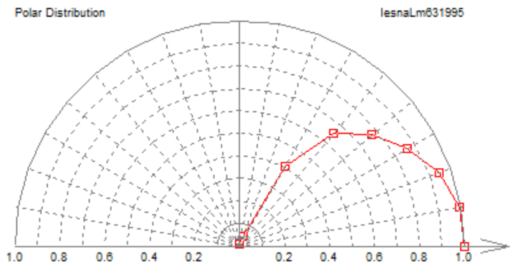
Hours of operation	8am-7pm (**same schedule used for lights)*
Temperature Band	21-24 °C
Internal Gains (excluding lighting)	25 W/m^2
Fluorescent Lighting	51 W per luminaire *[Zumtobel Mellow Light IV]*  *[Longitudinal section of IES profile]*
LED(present) Lighting	45 W per luminaire  *[72 LEDs, arranged in 4 rows]*  *[Longitudinal section of IES profile]*
LED(future) Lighting	30 W per luminaire *[same arrangement as LED(present)]*
Occupant Gains	Varies per room (1-3 people per room)
Fabric thermal properties	Built to UK Part L 2010 regulation standards

Figure 9.19, presents the differences in illumination levels in the open floor of the building, when illumination under fluorescent lighting is subtracted from illumination under LED lighting for each of the points on the working plane grid. For all locations in the room directly under each luminaire, illumination under LED lighting is higher than fluorescent by 7-16 lux, whereas closer to the walls of each room and away from the luminaires, illumination under LED lighting is in deficit of 1-9 lux. The same patterns were observed for the other floors as in this notional building all three floors were the same. Overall, the illumination pattern is very similar under both lighting conditions with LED lighting providing higher lux levels directly under each luminaire.

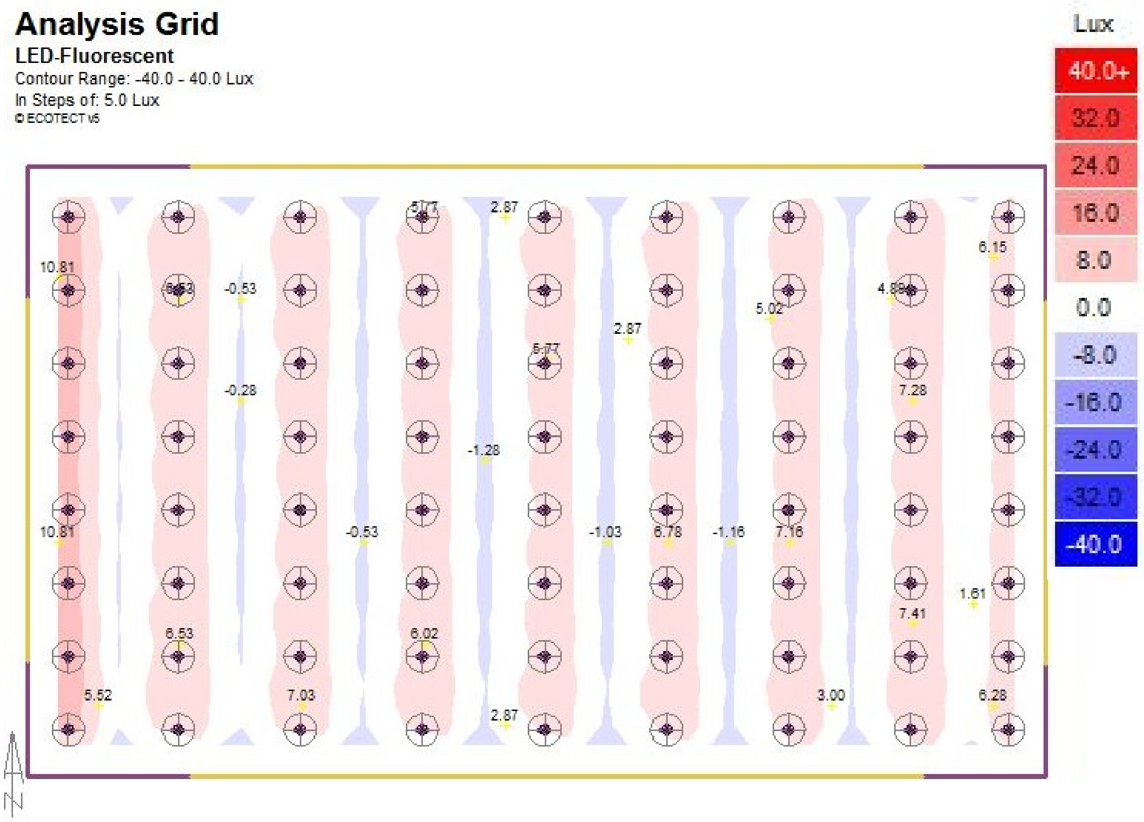


Figure 9.19 Differences in lux levels between fluorescent and LED lighting, when fluorescent lux levels are subtracted from LED lux level at each point. Blue colours indicate a deficit of lux level and red colours and surplus of lux levels compared to fluorescent. White, indicates that lux levels are exactly the same.

Figure 9.20, presents the results obtained from the energy simulations in EnergyPlus. It shows the predicted annual heating and cooling load demand (in kWh/m^2) under fluorescent lighting; LED(present); and LED(future) lighting luminaires. Results show a reduction in cooling loads of 2% under LED(present) lighting and 8% under LED(future) lighting, compared to fluorescent. On the other hand, an increase in heating demand loads of 5% for LED(present) and 15% for LED(future) lighting.

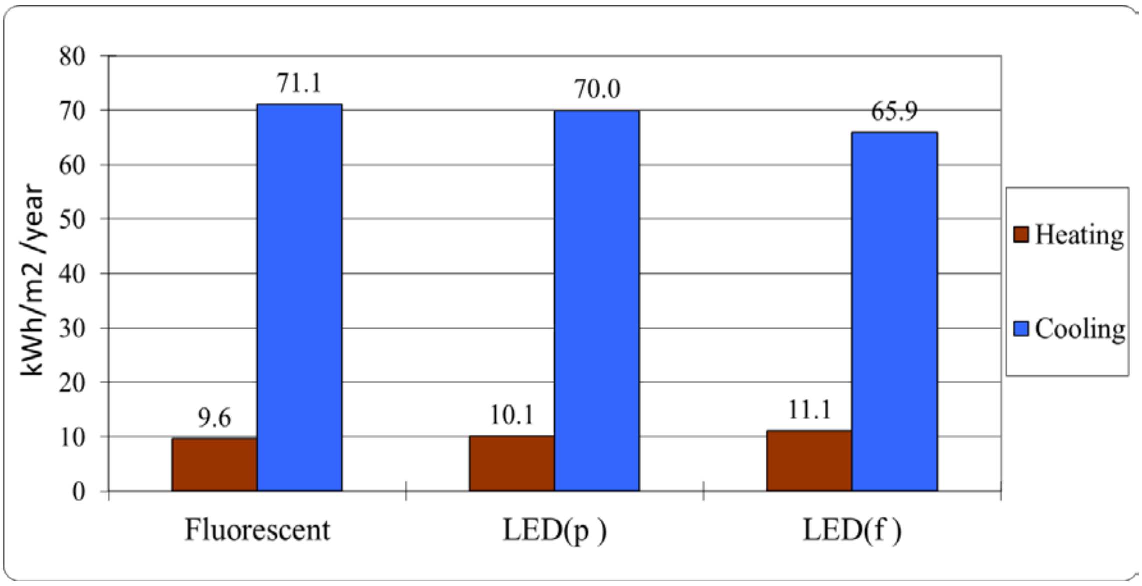


Figure 9.20 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

Figure 9.21, shows the CO2e emissions for all three lighting scenarios, when all electrical consumption (cooling, small power, lighting) and heating energy is taken into account and converted to kg of CO2e. Presently available LEDs provide a 2% reduction in emissions compared to fluorescent, while future LEDs provide an 7% reduction. Making the same assumptions as in the previous case study, this represents a reduction of 10 kWh/m^2 for LED(present) and 29 kWh/m^2 for LED(future) respectively of primary energy worked on gas equivalent (via emissions), when compared to fluorescent.

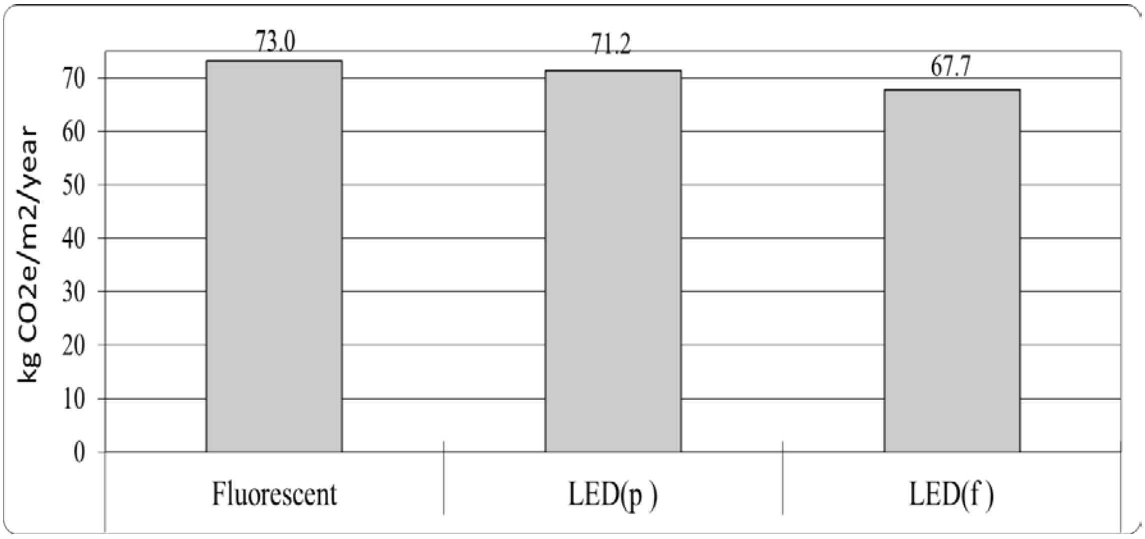


Figure 9.21 CO2e emissions (in Kg CO2e/m^2/year) for all the modelled zones of the building, under three types of lighting

9.9 Discussion of Results

The five case studies presented in the previous sections showed that commercially available LEDs currently available, when used as replacement luminaires for existing fluorescent luminaires, provided reductions in kg of CO2e that ranged from 2-9% compared to the existing fluorescent lighting system used in each case. When those figures were converted to a heating (gas) equivalent scenario for primary energy, then the reductions from fluorescent ranged from 9 to 32 kWh/m^2/y. More specifically, the LED(present) scenario provided a reduction in cooling energy demand, with an increase in heating energy demand. Cooling energy demand reductions ranged from 2 to 22%, whereas heating load demand increases ranged from 3 to 27%. It is important to remember at this point, that the case study buildings selected employed presently available fluorescent ceiling tile luminaires, hence the measure of comparison is higher to older fluorescent luminaires used in many older buildings, in which case the differences between fluorescent and LED luminaires would be greater.

When future LED technology is used with higher efficacies, that should be commercially available in the near future, reductions in kg of CO2 ranged from 7 to 12% and when those figures were converted to a heating (gas) equivalent scenario for primary energy, then the reductions from fluorescent ranged from 19 to 44 kWh/m^2/y. In terms of cooling load demands, reductions ranged from 8 to 44%, whereas heating load demands increases ranged from 15 to 47%.

This suggests that in the future when efficacies of LEDs are expected to be higher, there can be even greater saving made in cooling load demands. However, there will also be an increase in heating load demands. Overall though, in terms of kg of CO2 emitted, there is a reduction in all cases, as it is when these figures are converted into primary energy terms.

Chapter 10. Target Market Price for LED Retrofit Luminaires

10.1 Introduction

In Chapter 4, the case was made for a low energy retrofitting solution using LEDs with the following chapters demonstrating that it is possible to replicate an existing lighting layout in an office using LEDs and that there are energy and CO2 emission reductions to be had. Furthermore, in Chapter 3, the longer lifespan of LEDs was discussed which can lead to significant cost saving by reducing the need for maintenance or replacement.

Even though LEDs can provide such savings, they are currently significantly more expensive than fluorescent in their purchase cost, which presents a barrier to their adoption. Therefore, there is a need to determine a market price for LEDs that would remove this barrier and allow for their wider adoption.

To this end, a study is conducted in this chapter to determine a target market price for LED replacement luminaires.

LED ceiling tile type luminaire purchase costs are changing every few months, due to rapid changes in LED efficacies, reduced manufacturing costs due to economies of scale, as well the ever changing LED luminaire design options. This makes it difficult to predict LED luminaire purchase costs for the end user.

This is also true for the case of LED luminaires that are meant to be used to retrofit existing ceiling tile fluorescent luminaires, that this thesis is focusing on, with the added difficulty that such luminaires are meant to be custom designed on a case-by-case basis to replicate lighting from an existing fluorescent lighting system in an office.

On the other hand, fluorescent luminaire purchase costs for the end user are more predictable and stable as the technology is well known and has been used extensively in the industry for many years.

Therefore, the point of this study is to use the fluorescent ceiling tile luminaire market price as the basis for determining a target market price for custom LED retrofit luminaires. Such a target market price would be defined as the one that custom LED luminaires would need to meet, so that the total cost of purchasing the luminaire as well as the energy savings made within a 2 (and 4) year period would equal the same costs incurred when a fluorescent luminaire is purchased and used for the same period. Hence, a target market price that would create a financial equivalence between a fluorescent and custom LED retrofit luminaire. It is assumed that if such a target market price would be reached, then it would remove financial barriers to the wider adoption of LEDs.

10.2 Methodology

In order to determine a target market price for LED retrofit luminaires that takes into account potential energy savings over a 2 year period, a range of variables would need to be known. For example the current market price for fluorescent ceiling tile luminaires, the energy cost difference between fluorescent and LED lighting for heating and cooling of a building.

Therefore, as the point of this study is to determine a target market price, then the total cost of purchasing and using fluorescents over a period of years should be the same as with LEDs, hence:

$$\mathbf{T_y}(LED) = \mathbf{T_y}(Flu)$$

Where $\mathbf{T_y}(LED)$ is considered to be the total cost over *y* years and is defined here as the luminaire purchase cost P_{LED} (in this case the LED luminaire purchase cost is also considered as the target market price), plus the heating (**HE_{LED}**) and cooling (**HE_{LED}**) energy cost over y years. The same would be true for fluorescent lighting. Hence, the equation would be as follows:

$$\mathbf{P_{LED} + HE_{LED} + CE_{LED} = P_{Flu} + HE_{Flu} + CE_{Flu}}$$

$$\mathbf{P_{LED} = P_{Flu} + (HE_{Flu} - HE_{LED}) + (CE_{Flu} - CE_{LED})}$$

Where:

- **P_{LED}** = Target market price for LED retrofit luminaire (in British pounds £)
- **P_{Fluo}** = Current market price for fluorescent ceiling tile luminaire (in British pounds £)
- **y** = years of usage
- **HE** = Primary Heating Load (x) unit cost of energy (x) number of years

  Heating Energy Cost over y years (in British pounds £)
- **CE** = Primary Cooling Load (x) unit cost of energy (x) number of years

  Cooling Energy Cost over y years (in British pounds £)

In Chapter 9, we calculated the heating and cooling energy demand loads when fluorescent and LED lighting was used for a range of case studies. Based on a series of assumptions, these figures were converted into primary energy and then into CO2e emissions. Therefore, by obtaining current cost figures for energy, as well as the market price for a fluorescent luminaire we will be able to determine the target market price for the LED retrofit replacement luminaire.

The figures calculated in Chapter 9 though, take into account the overall energy performance of building. Hence the effect of lighting on these figures is not isolated, but as the calculations were performed under fluorescent and LED lighting conditions, it was possible to determine the differences between them and hence entirely attribute this increase or reduction in energy consumption to lighting. This difference is what is required in the above calculations, in order to determine P_{LED}.

Furthermore, the energy figures calculated in Chapter 9 are given in kWh/m^2/year and relate to the whole floor area of each building, which would include all luminaires present in that building. As in this methodology we are trying to determine the target market price for 1 LED luminaire, then all energy figures would need to be multiplied by the floor area of each building to get the total in units kWh and then divided by the total amount of luminaires in that building, so that a unit price can be determined.

Finally, as the trend in the performance of LEDs is to increase their efficacies, the LED(future) energy scenario was used in the calculations in this chapter, as it was assumed that such efficacies will be reached by the industry in the near future (see Section 3.9.1).

In Table 10.1, current average prices for purchasing energy during 2013 can be seen for both for heating and cooling. As heating in all case studies was through gas and cooling was through electricity, the values presented are relevant to those sources. What is clear from this table is the significantly higher cost of electricity compared to gas, which means that improvements in electrical (i.e. cooling energy loads) would have a greater impact than in heating.

Table 10.1 Costs for purchasing energy (source: www.energysavingtrust.org.uk, 2013)

	Heating (GAS)	**Cooling (Electricity)**
Average price for 1st quarter of 2013 (pence/kWh)	4.64	15.32 (Standard Rate)

A survey of prices for fluorescent luminaires that were used in this thesis can be found in Table 10.2. Three cases are presented from highest to lowest cost so that a range of cases can be examined.

Table 10.2 Average Market Price for 3 Fluorescent Luminaires

Luminaire Index	**Fluorescent Luminaire**	**Average Market Price**
1	Thorn Planor	£ 85 (source: Thorn Lighting)
2	Zumtobel Mellow Light IV	£70 (Source: Zumtobel Lighting)
3	Thorn Quattro T5 HF FEFL	£ 63 (Source: Thorn Lighting)

The costs and prices quoted in Tables 10.1 and 10.2 will be used in the equations derived in this section so that a target market price can be determined for LED retrofit luminaires.

10.3 Limitations

The method developed in this chapter has some limitations, with the main one being the omission of maintenance costs. Maintenance costs have a significant impact on any lighting related calculations, as the man hours usually required to replace luminaires in a whole office are substantial which, together with the specialist nature of the job, can determine the success of a financial investment in lighting - as seen in section 3.13 with the case of a building in the US and a 10 year investment plan.

Due to the time frames considered in this analysis (2 and 4 years), where it is not expected (especially in the 2 years option) that luminaires would have to be replaced, together with the lack of reliable information on maintenance costs, this factor was omitted and the focus was solely on savings due to reduced energy costs.

Moreover, it is important to note that fluorescent luminaire market prices can change, as well as energy costs, therefore this would mean that the target market price for retrofit LEDs would change accordingly.

Another factor that can influence the target market price of retrofit LED luminaires is the changing properties of LEDs, which are improving every year. Obviously more efficient LEDs would mean less LEDs used per luminaire as well as higher efficiencies and thus reduced energy consumption.

Finally, the energy cost implications of using fluorescents or LEDs are worked on a primary energy basis. If CO2 emissions from buildings were to have a financial implication, then the benefits of using LEDs would stand out even more and this would have an impact on their target market price.

10.4 Results and Discussion

Table 10.3, shows the target market price for three different LED luminaires that would be suitable to retrofit the previously mentioned fluorescent luminaires. The results are shown both for a 2 year calculation period, as well as a 4 year period. Associated percentage increase in LED luminaire market price compared to the relevant fluorescent are also shown.

Table 10.3 Target Market Price of Custom Retrofit LEDs over a 2 and 4 year cycle

LED Retrofit Luminaire	**Target Market Price** **based on a 2 year calculation*	% Increase compared to fluorescent	**Target Market Price** **based on a 4 year calculation*	% Increase compared to fluorescent
LED1 *replaces fluorescent 1	£103	+3%	£97	+14%
LED2 *replaces fluorescent 2	£106	+6%	£86	+22%
LED3 *replaces fluorescent 3	£107	+7%	£79	+26%

The results show that in all three cases, the target market price of LED retrofit luminaires should be close the fluorescent luminaires with an increase of 3-7% in the luminaire purchase cost, so that a financial point of equivalence is reached for a 2 year cycle between LEDs and fluorescent.

When a 4 year cycle is considered, then LED luminaires can be 14-26% higher than fluorescents in their market price for a point of financial equivalence to be reached.

This shows that the longer the calculation is considered, the higher the payoffs of using LEDs.

Currently, due to the high prices of individual LEDs and the custom design of the product, as suggested in this thesis, such market prices would be a challenge to the industry. However, with reductions in manufacturing costs and potential increases in the cost of energy, the suggested target market prices should be easier to achieve. In this case, a threshold will be reached where the cost of purchasing fluorescent or LEDs and associated energy costs over a 2-4 year cycle will be reached and therefore the additional benefits of using LEDs, such as longer life and thus less maintenance costs and no flicker among others, will outweigh any arguments against them.

The target market prices suggested in this Chapter can form a target for the industry to reach so that a wider adoption of LEDs can occur.

Chapter 11. Conclusions

11.1 Conclusions

There are a number of reasons why LED luminaires could be used in buildings. These include longevity (which could lead to savings on maintenance), flexibility and lack of mercury, which makes them more environmentally friendly in terms of disposal. But there are also a number of other reasons, as examined in this thesis.

In terms of replacing existing fluorescent lighting in offices with LEDs, LED luminaires need to be custom-designed to allow for retrofitting within the existing lighting layout while maintaining a similar light distribution at the working plane. Since most buildings are of older stock, this would constitute the majority of buildings and, hence, the wide applicability and impact of this work. When costs are also taken into account, especially during this period of global financial crisis, then the proposal for retrofitting existing systems with LEDs addresses this issue while offering additional energy and other benefits.

A novel application for RADIANCE has been proposed in this work, where it was used to successfully design custom LED luminaires and devise IES profiles to be used in lighting simulation. This work enables other researchers to look into other applications of LEDs and study their impact in buildings and elsewhere.

Through this thesis, it was shown that current fluorescent ceiling tile technology can be successfully replicated by custom LED luminaires, providing an equivalent lighting environment. This work has identified a big market for the use of LEDs, whereby the focus is to custom retrofit an existing lighting system with LEDs and therefore significantly reducing the use of materials and overall costs, while reducing energy consumption and CO_2 emissions, thus making them a more environmentally friendly solution compared to the full re-design and fitting of an entirely new lighting system.

The visual performance study showed that, in the context of an office, the retrofitting of existing fluorescent lighting with LED lighting did not have an impact on performance and that there was no preference between fluorescent and LED lighting, thus confirming that the retrofitting of fluorescent luminaires with LEDs will not have an adverse impact.

In terms of energy performance in the context of annual space conditioning load demands in offices, LED lighting offers a reduction in cooling load demands while at the same time increases the heating load demand, when compared to fluorescent lighting.

When presently available LED technology is used, results from the case studies in this thesis suggest a reduction in cooling load demands from 2% to 22%, with an increase of 3% to 27% in heating load demands, when compared to fluorescent lighting. When LEDs with higher efficacies are used, which will be available in the near future, results suggest a reduction in cooling load demands from 8% to 44%, with an increase of 15% to 47% in heating load demands, when compared to fluorescent lighting. For the case studies presented in this thesis, the cooling demand loads were significantly higher that heating demand loads in most cases. Therefore, in offices where the cooling loads are excessive, there could be great energy benefits to be had.

In terms of CO_2equivalent emissions and when all energy loads are taken into account, results suggest a reduction of 2% to 9% in kg of CO_2e emitted when presently available LEDs are used, compared to fluorescent, whereas the reduction is 7% to 12% when future LED technology is used. Therefore, a significant reduction in overall CO_2e emissions can be had, by simply retrofitting existing fluorescent lighting systems with LEDs. This held true for case studies that were dominated by cooling load demands, as well as others that were dominated by heating load demands, therefore suggesting savings in CO2 emissions regardless of the dominant seasonal conditioning load.

The work conducted in this thesis, suggests that LEDs are a viable replacement to existing office ceiling tile technology with some energy benefits to be had now (in specific circumstances), as well as significantly more in the near future. From the findings of this work, it would follow that existing offices with high internal gains and high cooling loads are the ones to have the greatest benefits. This would also hold true for buildings that do not necessarily have high internal gains, but still have high cooling loads due to excessive solar gains for example.

The target market price suggested in Chapter 10, can form a basis for the industry to aim for, so that a wider adoption of LEDs can occur even in cases where an investment is short term. The results suggest that custom LED retrofit luminaires would be at almost the same price as fluorescent luminaires, so that the threshold of financial equivalence is reached between the two.

With the expected increase in the efficacies of LEDs, the electrical load consumption of LEDs will reduce even further, but it is important to also take into account the impact that LEDs will have on heating and cooling loads in a building, as this thesis has demonstrated.

11.2 Future Work

This thesis investigated the use of LED lighting in one particular area, where their energy benefit would be more apparent due to the way in which heat in emitted from them. There are many more applications and conditions for LEDs that the work in this thesis can be extended to.

One of the findings of this research was that one of the main energy benefits of LEDs is their ability to reduce building cooling load demands when used as ceiling tile luminaires. It would be interesting to investigate their effect when used to replace other types of luminaires, such as free standing luminaires, where all the heat of the luminaire ends up in the room. The difference between LEDs and other light sources is that this heat would largely remain close to the luminaire itself, rather than being radiated towards the direction of light on room surfaces, as is with other light sources.

It would also be interesting to investigate their effect on air conditioned buildings located in other climates and, in particular, warmer climates where there is a more pressing need to reduce overheating, and hence the effect of LEDs would be more significant. Contrasting that to colder climates where heating loads dominate would also provide useful insights on their use throughout the world.

Also, again in warm climates, to investigate the effect of significantly elevated room temperatures (assuming a cooling system is not present) which would cause a rise in temperature of the P-N junction of the LEDs and hence on the longevity, heat and light performance of the LED modules. As the performance of LEDs is largely governed by the temperature on the P-N junction, an investigation in warmer climates would be of interest.

The visual performance study conducted in this thesis, examined the short term effects on performance, as it was not possible due to budget and time constraints to look at more long term effects in performance when exposed to LED lighting, which is an area worth investigating.

Due to the properties of LEDs which include a high level of control and good maintenance of their efficacy under dimming, when compared to other light sources, it would be interesting to investigate their potential energy savings compared to other light sources, in daylight linking scenarios with ON/OFF and dynamic dimming lighting systems for offices and other types of buildings. Their potential effect on energy and CO2 emissions with varying occupancy and equipment scenarios would also be worth investigating.

Finally, because of the custom nature of LED luminaires proposed in this thesis for retrofitting, it would be interesting to investigate ways of designing LED luminaires where components can be taken off or put on as needed, so that the same modular LED luminaire can be used to replicate a range of existing fluorescent luminaires, hence improving the market price of custom retrofit LED luminaires through economies of scale.

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Appendix A. Scripts Used in Modelling

A1. Sample of script for determining optimum positioning of LEDs on a flat surface of a ceiling tile luminaire

```
NoOfLEDs = getUserInput("Define number of LEDs in luminaire:", 8.0)
NoOfLEDs = tonumber(NoOfLEDs)
TargetLux = getUserInput("Define target lux level:", 8.0)
TargetLux = tonumber(TargetLux)
TargetDeviation = getUserInput("Define acceptable deviation in lux levels:", 8.0)
TargetDeviation = tonumber(TargetDeviation)
cmd("app.activate")
selectedObject = -1
selectionCount = get("selection.count")
dayFact = 0
for i = 1,selectionCount do
        selectedObject = get("selection.next", selectedObject)
        if selectedObject >= 0 then
                ok = 1
                inc = 0.02
                x, y, w, h = get("object.child.extents", selectedObject)
                printf("Object %d - Inital: u=%g, v=%g, wu=%g, hv=%g", selectedObject, x, y, w, h)
                x = tonumber(x)
                y = tonumber(y)
```

```
w = tonumber(w)
h = tonumber(h)
repeat
    set("object.child.extents", selectedObject, x, y, w, h)
    cmd("view.redraw")
        cmd("calc.lighting.grid 0");
    dayFact = get("grid.average");
    printf("Area: %g, Lux %0.2f%%", get("object.area", selectedObject), LuxLevel)
    if w < 1-inc then
        w = w + inc;
        x = 0.5-(w/2);
    elseif h <= 1-(2*inc) then
        h = h + inc;
        if (y + h) > 1-(2*inc) then
            y = (1-inc) - h;
        end
    else
        ok = 0;
    end
until ok < 1 or dayFact >= TargetLux
printf("Object %d - Final: u=%g, v=%g, wu=%g, hv=%g", selectedObject, x, y, w, h)
printf("Final Area: %g", get("object.area", selectedObject))
cmd("model.load C:\\*.eco")
cmd("model.export.rad c:\\temp\\*.rad")
pause (400000)
.......
.......
```

```
            .......
            .......
        end
end
cmd("view.redraw")
```

A2. Script for extracting energy, geometry and other properties from models for further analysis

```
delimiter = "\t";
zones = get("model.zones")
zoneCount = 0
row = 1
col = 2
rowmonth = 0
rownew = o
zoneList = {}
zoneList[0] = 0
mon = { "Jan",  "Feb",  "Mar",  "Apr",  "May",  "Jun",  "Jul",  "Aug",  "Sep",  "Oct",  "Nov",
        "Dec"}
for z = 1,zones-1 do
        if ((get("zone.thermal", z) > 0)
   and (get("zone.hidden", z) < 1)
   and (get("zone.off", z) < 1)) then
                zoneCount = zoneCount + 1
                zoneList[zoneCount] = z
```

```
        end
end
excel("start", "")
excel("newsheet", "H_and_C_Loads")
excel("cell", col, row)
excel("value", format("Model: %s (%d thermal zones)", get("model.file"), zoneCount))
row = row + 1
excel("cell", col, row)
excel("value", format("Monthly and Total Loads for all zones"))
row = row + 2
rowmonth = row + 2
for k = 1, 12 do
                        excel("cell", col, rowmonth)
                        excel("value", mon[k])
                        rowmonth = rowmonth + 1
end
column = col
rownew = row
colzone = 3
rowzonename = 4
colheating = 3
rowheating = 6
rowmonth = 6
colcooling = 4
rowcooling = 6
rowarea = 20
for z = 1, zoneCount do
        excel("cell", colzone, rowzonename)
```

```
        excel("value", get("zone.name", zoneList[z]))
        excel("cell", colzone, (rowzonename+1))
        excel("value", "Heating")
        floorarea = get("zone.floorarea", zoneList[z])
        excel("cell", colzone, rowarea)
        excel("value", floorarea)
        colzone = colzone +1
        excel("cell", colzone, rowzonename)
        excel("value", get("zone.name", zoneList[z]))
        excel("cell", colzone, (rowzonename+1))
        excel("value", "Cooling")
        colzone = colzone +1
                for month = 0, 11 do
                        heatload = get("zone.heating", zoneList[z], month)
                        excel("cell", colheating, rowheating)
                        excel("value", (heatload/1000))
                        coolload = get("zone.cooling", zoneList[z], month)
                        excel("cell", colcooling, rowcooling)
                        excel("value", (coolload/1000))
                        rowheating = rowheating + 1
                        rowcooling = rowcooling + 1
                end
        colheating = colheating + 2
        colcooling = colcooling + 2
        rowheating = 6
        rowcooling = 6
end
```

Appendix B. Energy Simulation Tools Tests

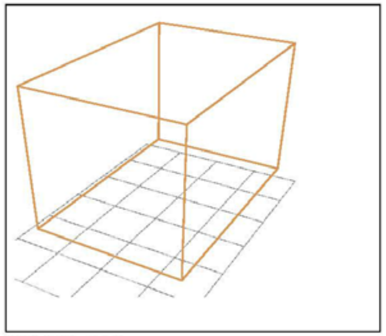
The following pages, provide an outline of the tests performed in ECOTECT, HTB2 and EnergyPlus, in order to test how modelling information and settings can be transferred between them to ensure consistency between the various models. Tests are also performed on how to accurately model the test room used in Chapter 7, so that comparisons could be made between simulated and measured data.

TRANFERRING ISSUES	ECOTECT	HTB2	EPLUS
Surface normal	Editable	No issues	Dependant on the order in which the nodes were drawn
Overlapping objects/surfaces	N/A	Creates dummy objects or auto-dived. (B2.2.1)	Report transfer error, will normally lead to crash
Materials: air layer	Ok	Need modify	Need modify
Schedule	Editable	Transferable	set 'Eplus mode' in Ecotect
Zone surrounding	Questionable results for both thermal/non-thermal surroundings	Ok	Ok
Surface edit	N/A	Edit can be done in Ecotect	Editable after transfer
AS1 in non-thermal zones		Not working-cannot be recognized by Htb2	**E1** Report error in transfer and result similar with AS4
AS1 in 'Outside'		Surface connection error	**E2** Only work for C1, see De..
AS1 in normal(and thermal) zones		Create dummy zone with volume. See H1	**E3** Crash in Eplus calculation
AS2 in normal zones		Same as **AS1 in non-thermal zones**	**E1**
AS2 in 'Outside'		Same as **AS1 in 'Outside'**	**E2**
AS3		OK- no heating & high cooling	**E4**
AS4	N/A	N/A (can edit if needed, but can be transferred from Ecotect)	Editable and correct
AS5	Not working, added partition worked as mass	Transfer error	Transfer error
Lighting gain consideration	Y	Y	Y
Split	N	Y	Y
Lighting gain as separate source	N	Y	Y
Toward other zones	N	Y	N
Heat gain Breakdown	N	Y	Y
Return air calculation	N	N	Y (B2.5.3.2)
Ventilation with other zones	N	Y	Y

Section B2

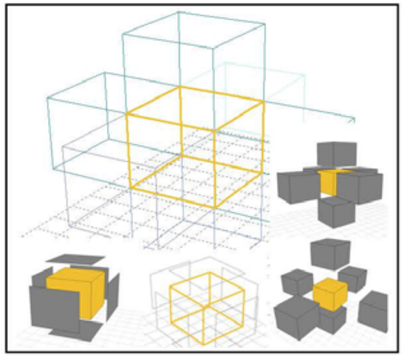
B2.1 Modelling concepts (more detail can be found in chap 3 to 6)

B2.1.1 Model 1



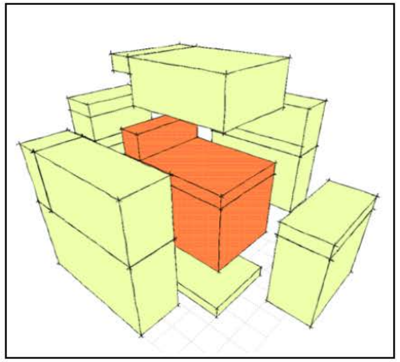
Model 1: Single cell connects with external environment: MD1

B2.1.2 Model 2



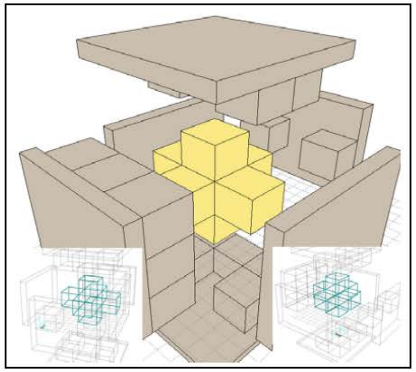
Model 2: Zones do not connect with environment (changing surface into adiabatic or surrounding it with non thermal zones) MD 2

B2.1.3 Model 3



Model 3: Test room connected with surrounding thermal zones and then external environment. MD3

B2.1.4 Model 4

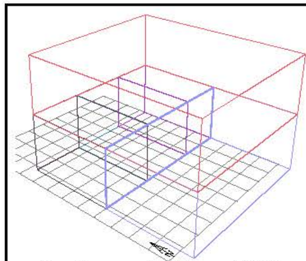


Model 4: Test room connected with surrounding thermal zones and then No external environment—surround thermal zones with non thermal zones or change surface into adiabatic MD4

B2.2 Setting up of models

B2.2.1 Issues related to the transferring of settings and properties

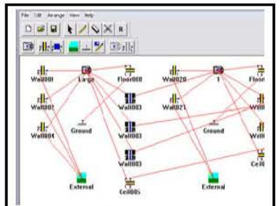
Htb2	Eplus
No Void, no air layer as external material	
Glass and air layer properties not transferred correctly	
Surface connection (No overlapping) *	Surface connect to no more than one object
	Schedule setting
	Surface normal(changes in Ecotect do not apply)



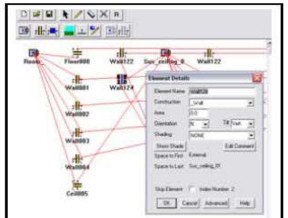
- Transfer connecting objects to Htb2: Two ways identified so far. Depending on how complex the geometry is, and those changes will not affect the simulation results.

1: Normally divide larger objects down in to the same amount with its connected.

2 Or, if the geometry is complicated, it will create dummy objects with 0 surface areas in transfer.



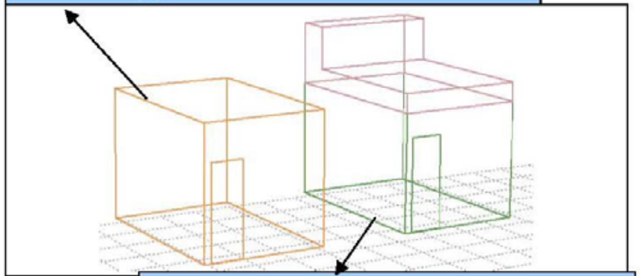
Transfer 1



Transfer 2

B2.2.2 Case types:

Case 2: Room and ceiling converted into one space, cannot split internal gain, thus a need to change gain values. C2



Case 1: Room and suspended ceiling. Internal gain split modification. C1

B2.3 Test models and transfer issues:

B2.3.1 Model setting: as existing test room condition

Simple materials, No windows and Air tight (0.25)
Weather data: Cardiff
Internal gain: 16.2w/m2 (lighting only)

B2.3.2 Ecotect---transfer---Htb2---calculation *

Transfer and calculation process:
Ecotect: Self calculation
Ecotect-----Htb2
Ecotect-----Eplus
Eplus ---- Setting modified in the software itself

* see B7 for detailed explanation

Method used for creating Adiabatic Surfaces
AS1 partition surfaces: attach partition surfaces at model's external façade (or surrounding zones') * partitions can be in thermal (**E3/H1**) and non thermal zones (**E1/H2**) in 'normal space' or in 'outside zone (**E2**)
AS 2 non-thermal zones: cover study zones (or surrounding zones) with non thermal zones * in normal space (**E1**) or outside (**E2**)
AS 3 change zone's (or surrounding zones') external surfaces in to partition in Ecotect (can then transfer) **E4**
AS 4 Manually edit: Assign surface as adiabatic in software
AS 5 Attach partitions in same zone (**E5/H3**)

B2.4 Results:

MD1	Eplus	Htb2	Ecotect
Heating kWh	2229.088	2289.212	3474.367
Cooling kWh	48.87575	39.564	38.982
MD2	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	0	0	
Cooling kWh	437.4673	250.883	
MD3	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	1908.585	2192.12	
Cooling kWh	0	0	
MD4	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	43.06161	529.2919	
Cooling kWh	158.5368	1.03	

Table 2-1: Heating and Cooling demand from C1

MD1	Eplus	Htb2	Ecotect
Heating kWh	3026.035	3095.277	3833.632
Cooling kWh	43.80424	47.738	54.791
MD2	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	0	1.18079	
Cooling kWh	541.6197	299.244	
MD3	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	2623.859	2696.395	
Cooling kWh	0.349672	2.157	
MD4	**Eplus**	**Htb2**	**Ecotect**
Heating kWh	1162.774	1313.904	
Cooling kWh	0	0	

Table 2-2: Heating and Cooling demand from C2

Each software has own way to understand adiabatic surface/non-thermal zones, so the model need to manually edit and the result do not match well. Ecotect error—do not suggest use adiabatic settings

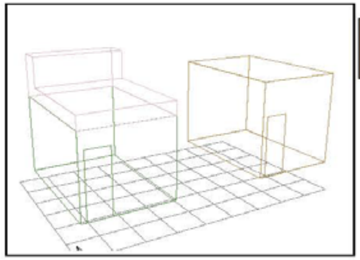
MD1 and MD3 are selected to do more detailed simulation—to identify the effect of changing lighting system and the effects to cooling load.

No big issue in MD1, results are close. (Not represent the real situation of building.

MD2 & MD4- tried many attempts, combined all possible ways to create adiabatic surfaces, Ecotect error with surrounding zones. Eplus errors in adiabatic on multi-zones. And time consuming to change every surface manually

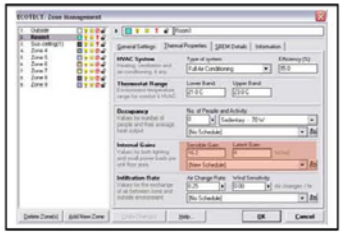
MD3 Most correct and transfer method of models (Ecotect error anyway) and the results are close, also represent close condition of real building

B2.5 Setup of lighting and internal gains



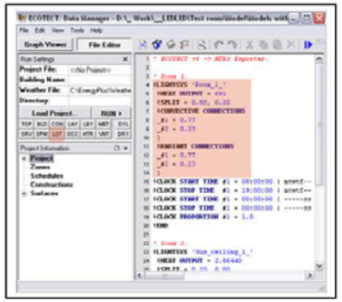
Simulation models selected:
(C1 + C2) * (MD1 + MD3)

B2.5.1 Ecotect



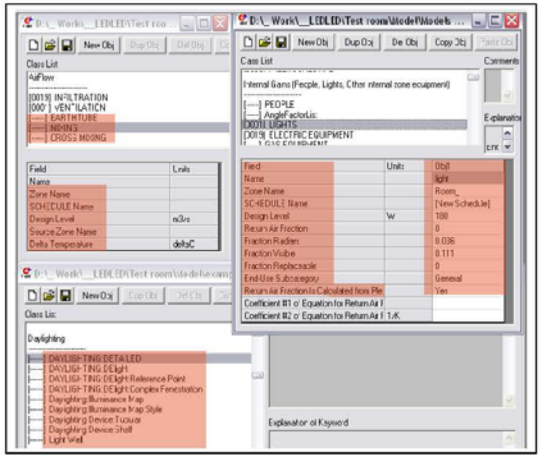
Ecotect: Lighting gain is considered as part of total internal gain. Gain cannot be distributed to other zones. Ventilation cannot be set between zones.

B2.5.2 Htb2



Lighting gain is considered separately, radiation and convection (default value 20% Ra 80% Conv), gains can be connected to other zones, and ventilation can be set between zones

B2.5.3 Energy Plus



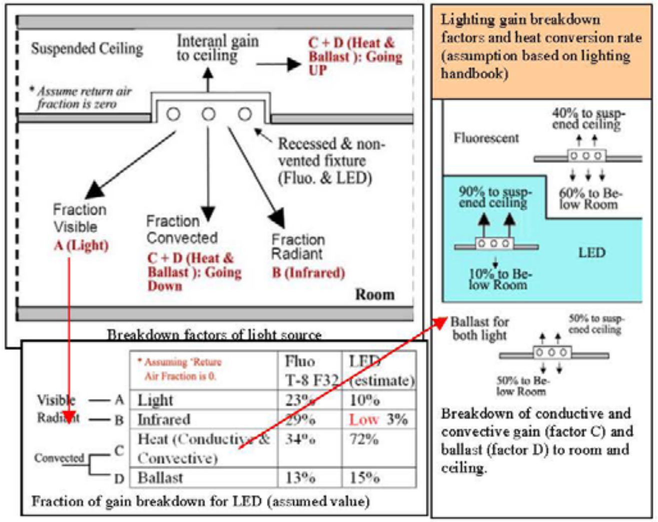
Lighting gain is considered separately, can be future breakdown into visible, radiant, convection and return air factors (percentage add up = 100%), return air factor can be automatically calculated (but not sure suitable for LED) ventilation can be set between zones. Daylight saving method simulation also available.

B2.5.3.1 Traditional lighting related gain distribution fractions:

Luminaire Configuration, Fluorescent Lighting	Recessed	Return-air ducted
Return Air Fraction	0.0	0.54
Fraction Radiant	0.37	0.18
Fraction Visible	0.18	0.18
$f_{convected}$	0.45	0.10

Lighting internal gain breakdown is affected by the placement of luminaries; however, the suggested setting in Eplus is for Florescent and other traditional light source. Breakdown of LED is assumed and is list below.

B2.5.3.2 Lighting related gain distribution fractions for LED:



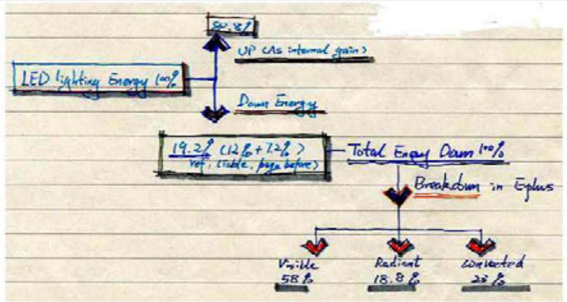
Breakdown factors of light source

* Assuming 'Reture Air Fraction is 0.		Fluo T-8 F32	LED (estimate)
Visible — A	Light	23%	10%
Radiant — B	Infrared	29%	Low 3%
Convected — C	Heat (Conductive & Convective)	34%	72%
Convected — D	Ballast	13%	15%

Fraction of gain breakdown for LED (assumed value)

Breakdown of conductive and convective gain (factor C) and ballast (factor D) to room and ceiling.

15% +72%*90%



Detailed simulation setting input for LED light in Eplus, developed based on above diagrams.

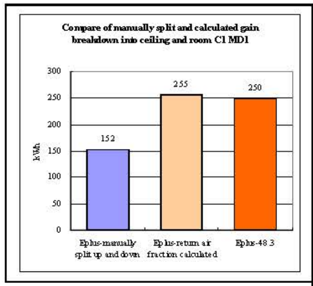
**** Return air fraction**

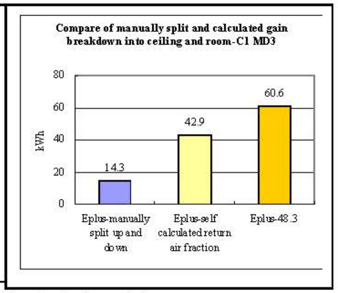
Placement of luminaries affect gain distribution, (percentage) amount of heat goes to the ceiling is called return air fraction; it can be manually set in Eplus but can also be calculated in it. However, this can only apply to tradition light sources.

Luminaire Configuration, Fluorescent Lighting	Recessed	Return-air ducted
Return Air Fraction	0.0	0.54
Fraction Radiant	0.37	0.18
Fraction Visible	0.18	0.18
$f_{convected}$	*0.45*	*0.10*

From IES lighting handbook (page unknown)

Return air fraction can be calculated based on the temperature difference of ceiling and room, but it is for the traditional lighting methods purely depend on the temperature difference between ceiling and room. (Assumes all heat goes to room and causes room temperature rise)





B2.6 Total internal gain value for the tested model

Internal Gain value

Equipment (17.5w/m2)

People (14.6w/m2)

Lighting (16.2w/m2 or 12.6)

58w*4/14.32m2-Florescent

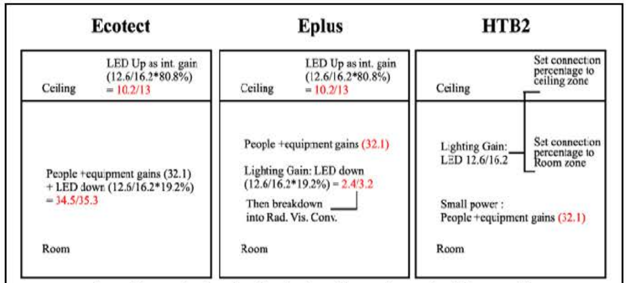
45w*4/14.32m2-LED

Total heat gain:

48.3 –florescent (17.5+14.6+16.2)

44.7- LED (some cases did not change to 45w LED, used 58W LED instead (17.5+14.6+12.6)

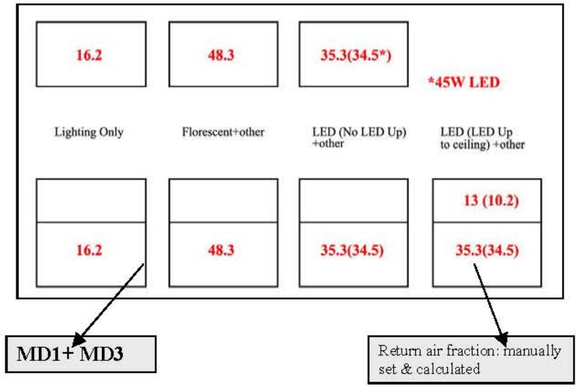
B2.6.1 Settings of models in different software

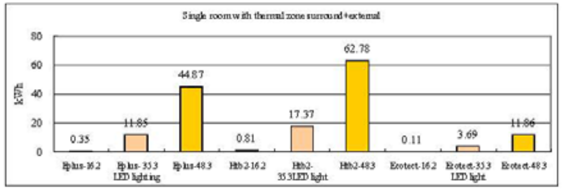


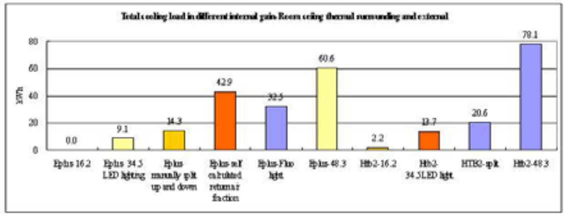
Settings of internal gains distribution in ceiling and room in different software

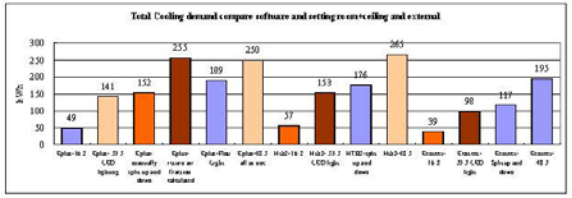
B2.6.2 Settings of tested models

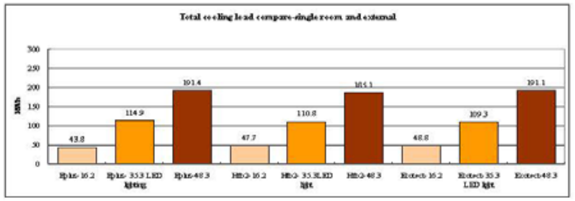
Result generating, different cases and also testing effect of internal gain toward cooling load



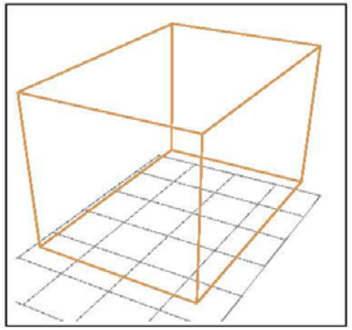




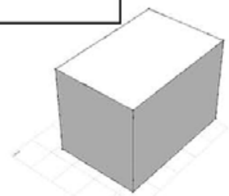




B3 Setting up of model MD 1:



Model 1: Single cell connects with external: MD1



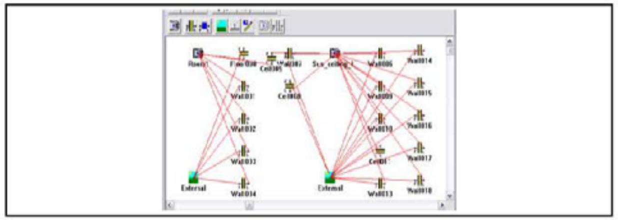
B3.1 Issues

B3.1.1 Ecotect:

No issues to report

B3.1.2 Htb2

Just normal issues mentioned in 2.2.1, no 'air' layers as the external layer of materials, besides that no big issues to report. Transfer to HTB2 and Eplus is smooth and the geometry/surface connection is fine



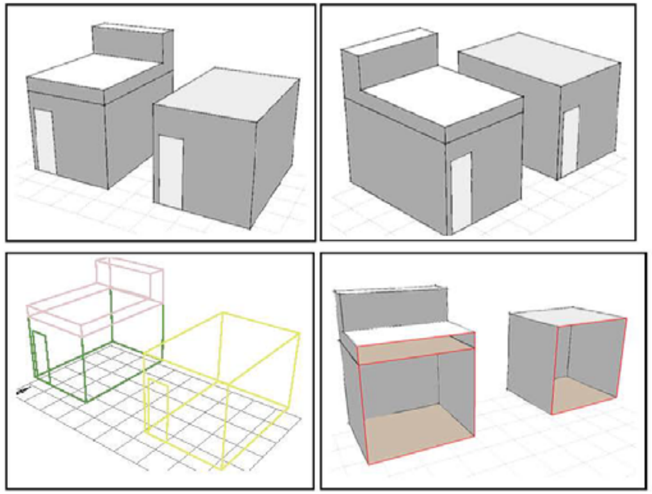
B3.1.3 Eplus

Same as in Htb2

B3.2 Details:

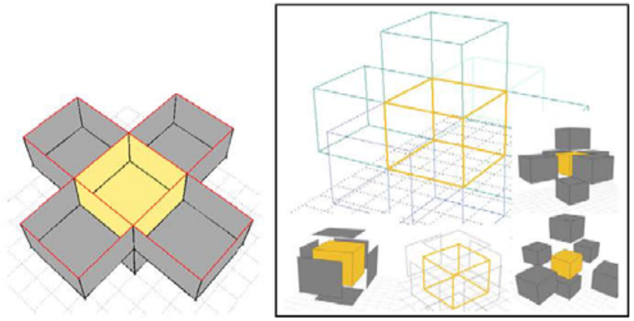
Too much connection with external environment, might affect the results, compare with the existing condition.

B3.3 More pictures



B4 Setting up of model: MD2

Model 2: Single cell does not connect with environment (changing surface into adiabatic or surrounding it with non thermal zones) MD 2

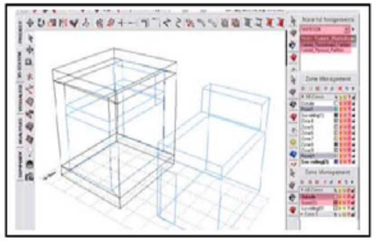


4.1 Issues

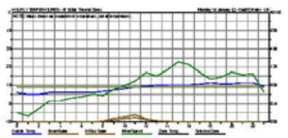
To create a thermal zone not connecting with environment, methods AS1 to AS4 can be applied.

B4.11 Ecotect

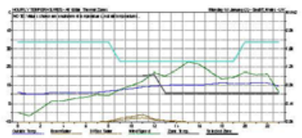
Ecotect self calculation: not working well with non-thermal zones or adiabatic surfaces



AS1 & AS2 & AS3—
surfaces and zones in normal spaces and 'Outside' zone



Result from AS3



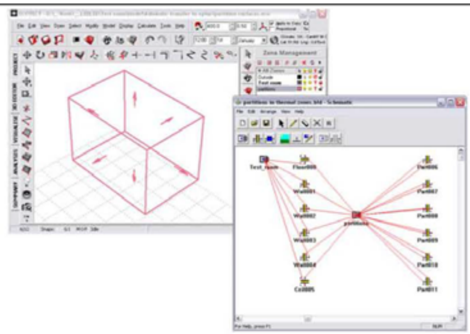
Result for AS1 & AS2

Adiabatic and non thermal zone calculation resulted in some errors.

B4.1.2 Htb2

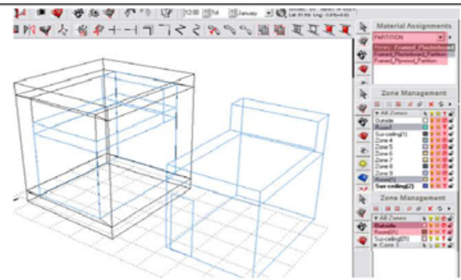
B4.1.2.1

AS1 —in thermal zone in normal space transfer to htb2 is ok but will create a dummy zone with actual volume. * **HT1** in detailed document

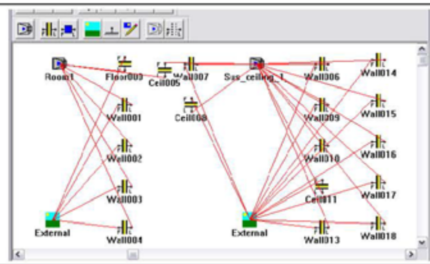


B4.1.2.2

AS1 —in normal non thermal space & AS2 (non thermal zones)



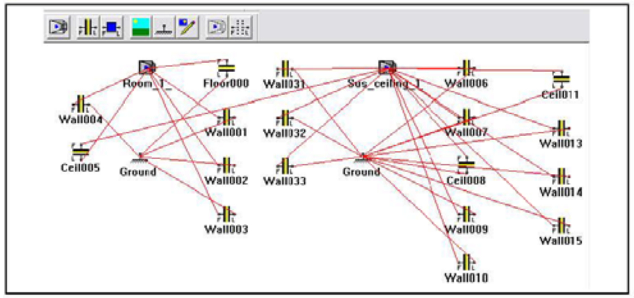
Non-thermal zones in Ecotect cannot be transferred into HTB2, so the zone separation cannot be recognized. Result attached below.



AS1 in normal non thermal space. HTB2 crashed in C2.
***HT2** error 'ERROR!: INPUT,3: Spaces used in Layout are inconsistent with those used in Building definition'.

B4.1.2.3

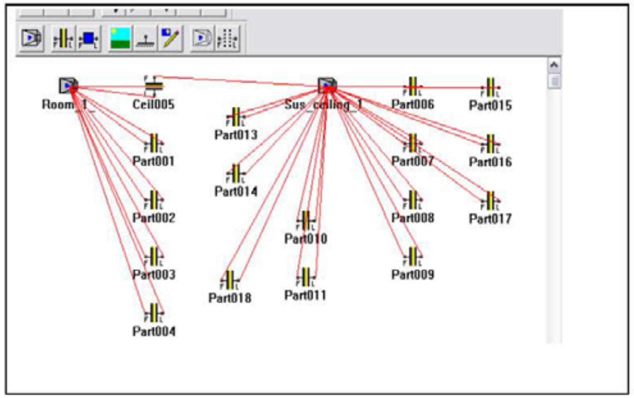
AS2 —in 'Outside' zone/ Same of AS1 in 'outside'



Will cause transfer issues and surface connection will go wrong-in different ways

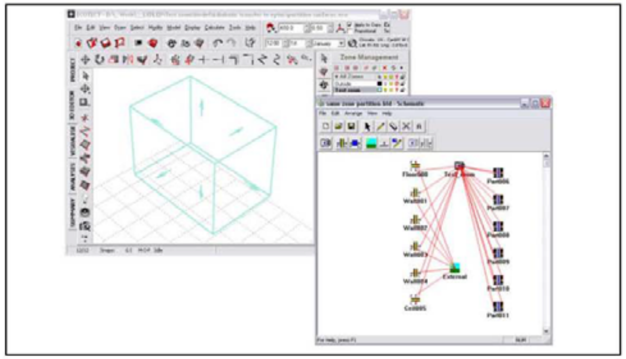
B4.1.2.4

AS3: Transfer and surface connection are correct, but there is no heating demand and cooling load is high – due to the no heat loss to external

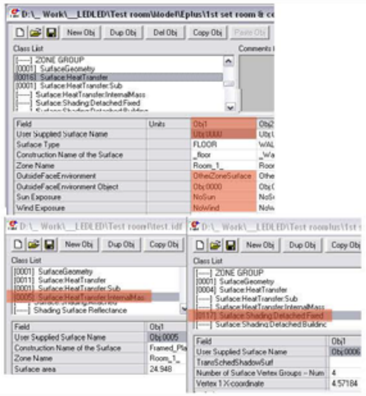


B4.1.2.5

AS5 Partition in same zone resulted in transfer error. HT3

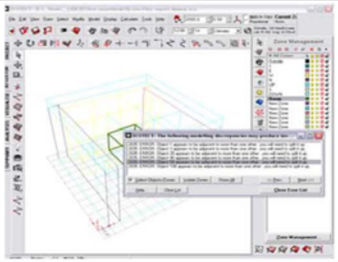


B**4.1.3 Eplus**



B4.1.3.1

1 AS1 in & AS2 —all in normal non-thermal zones will cause transfer error, if keep doing simulation, results similar with manually edited. Result refer to table down below. * see detailed document **EP1**



B4.1.3.2

AS1 & AS2—if put in 'Outside Zone'. Objects will be considered as detached shading. No report in transfer to Eplus, but surface and the connected partition will be considered as one object. Can only work in C1, resulted only need cooling and demand is higher than 4.1.3.1. * see detailed document **EP2**

cooling	Manually edited (same result from 4.1.3.1)	zone/surfaces in outside zone for C1	
January	29.56	41.04	
February	27.45	36.34	
March	29.75	39.57	
April	34.92	44.37	
May	39.15	46.76	C2 crashed
June	40.75	47.41	
July	48.71	54.47	
August	47.09	51.30	
Sep.	42.62	49.43	
October	43.73	50.58	
Nov.	28.62	38.83	
Dec.	25.13	37.96	

B4.1.3.3

AS3—transfer ok but partitions were considered as 'internal mass' and the result of heating demand (only) is higher than zone with external. C2 crashes in Eplus * see detailed document **EP4**

Heating C1	room and ceiling only + external	Surface partition transferred
Jan	346.72	458.60
Feb	274.04	380.55
Mar	242.86	337.41
Apr	183.39	290.25
May	122.33	211.78
Jun	63.96	153.80
Jul	47.91	134.55
Aug	36.17	131.03
Sep	98.98	200.60
Oct	133.53	269.23
Nov	251.10	312.12
Dec	428.10	418.00

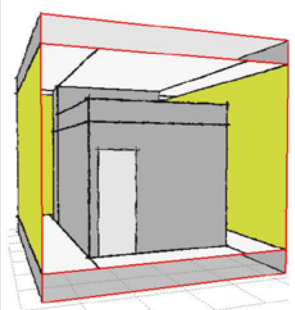
B4.1.3.4

AS4—no transfer problem but edit surfaces takes a long period

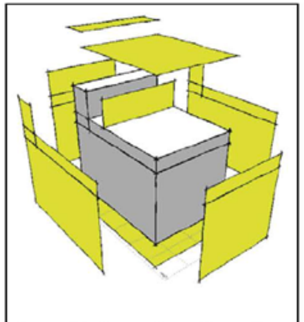
AS1 Partition surfaces in thermal zones will cause Eplus calculation crash in both C1 and C2.
* see detailed document EP3

AS5 case will crash in Eplus calculation EP5

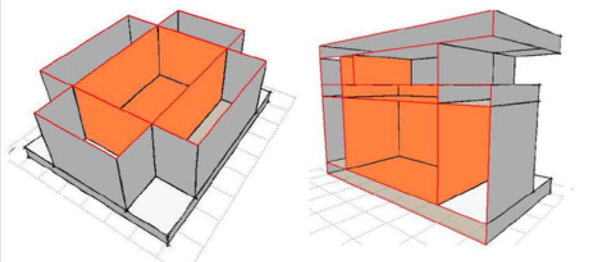
More pictures:



Attempts of surrounding study zones with one big space failed, it will cause too many transfer errors, especially into Eplus. Worked relatively ok with transfer into HTB2, but need to keep the model similar with each other.



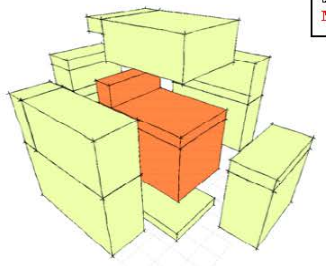
Surround study zones by partition surfaces (all surfaces in 'outside zone')



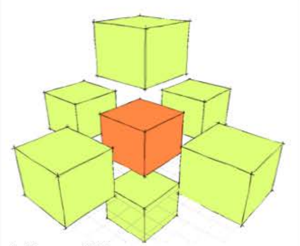
Zones surrounded by none-thermal zones (in outside zone)

B5 Setting up of model MD3:

Model 3: Test room connect with surrounding thermal zones and then external environment. **MD3**



Setting up of C1



Setting up of C2

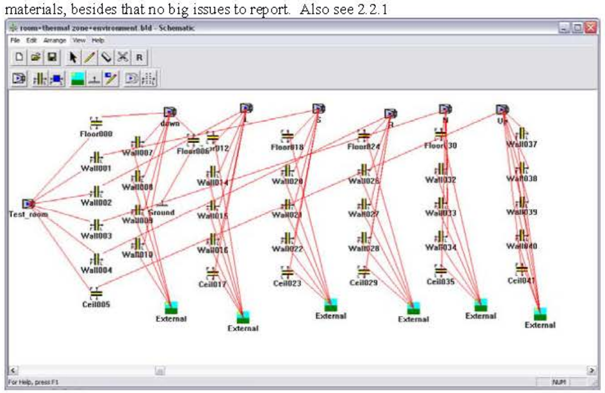
B5.1 Issues

B5.1.1 Ecotect

In Ecotect calculation: too high temperature occurred in both C1 and C2. Similar results as the issue from AS1 & AS2 in MD2 (see 4.x.x)

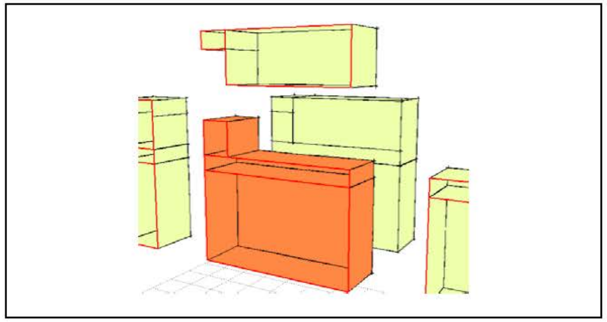
B5.1.2 Htb2

Transfer to HTB2 is smooth and the geometry/surface connection is fine, no 'air' layer as the external layer of materials, besides that no big issues to report. Also see 2.2.1



B5.1.3 Eplus

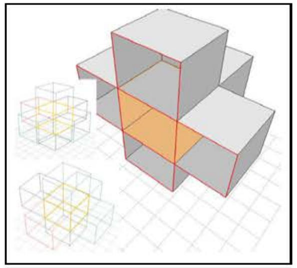
Need to make sure no surface connects with more than one surfaces, besides that no transfer issues, transfer to Eplus is smooth and the geometry/surface connection is fine

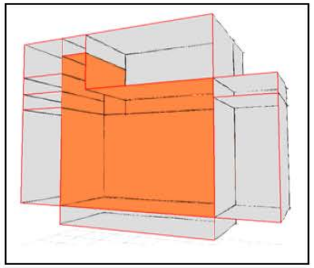


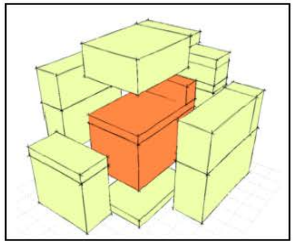
B5.2 Details:

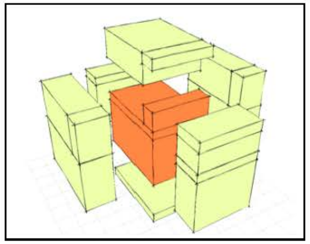
Represents the most similarity with real case studies

B5.3 More pictures



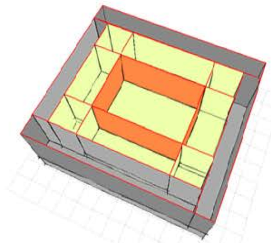


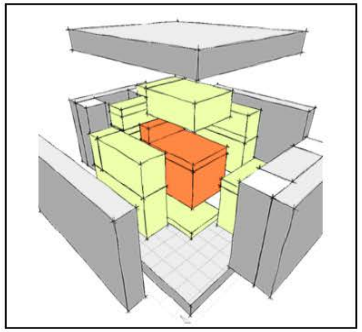




B6 Setting up of model: MD4

Model 4: Test room connect with surrounding thermal zones and then No external environment—surround thermal zones with non thermal zones or change surface into adiabatic
MD 4



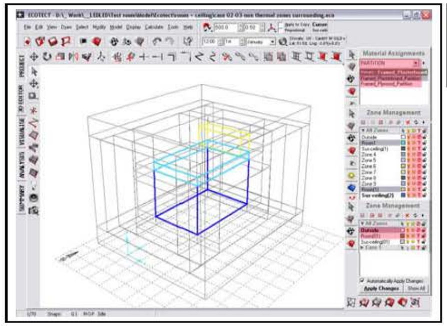


6.1 Issues

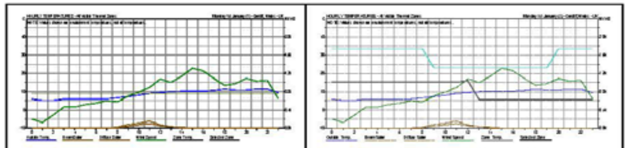
To create a thermal zone not connecting with environment, methods AS1 to AS4 can be applied.

B6.11 Ecotect

Ecotect self calculation: not working well with non-thermal zones or adiabatic surfaces



AS1 & AS2 & AS3—surfaces and zones in normal spaces and 'Outside' zone



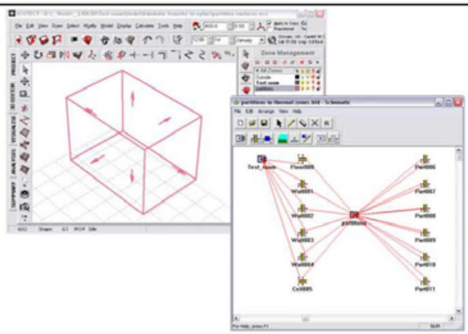
Result from AS3 | Result for AS1 & AS2

Adiabatic and non thermal zone calculation resulted in strange errors.

B6.1.2 Htb2

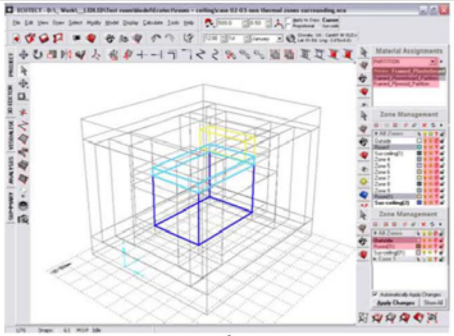
B6.1.2.1

AS1 —in thermal zone in normal space transfer to htb2 is ok but will create a dummy zone with actual volume. * **HT1** in detailed document



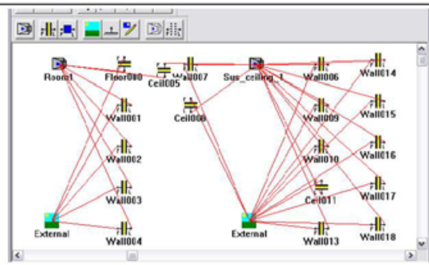
B6.1.2.2

AS1 —in normal non thermal space & AS2 (non thermal zones)



d

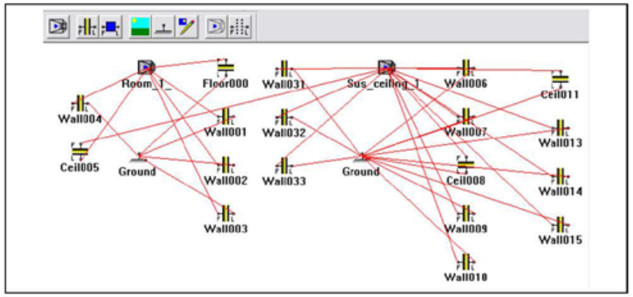
Non-thermal zones in Ecotect cannot be transferred into HTB2, so the zone separation cannot be recognized. Result attached below.



AS1 in normal non thermal space. HTB2 crashed in C2.
***HT2** error 'ERROR!: INPUT,3: Spaces used in Layout are inconsistent with those used in Building definition'.

B6.1.2.3

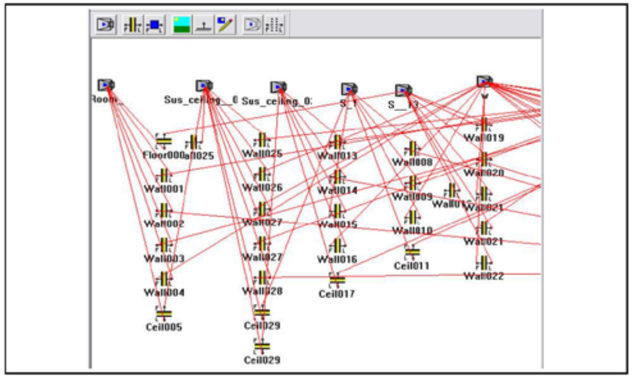
AS2 —in 'Outside' zone/ Same of AS1 in 'outside'



Will cause transfer issues and surface connection will go wrong-in different ways

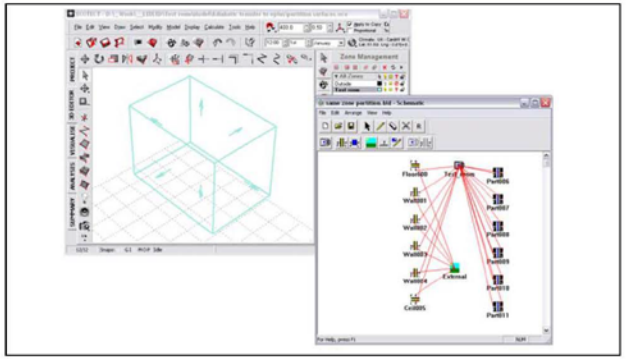
B6.1.2.4

AS3: Transfer and surface connection are correct, but there is no heating demand and cooling load is high – due to the no heat loss to external

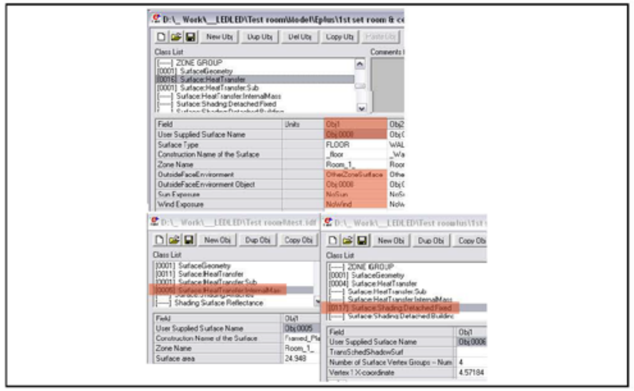


B6.1.2.5

AS5 Partition in same zone resulted in transfer error. **HT3**

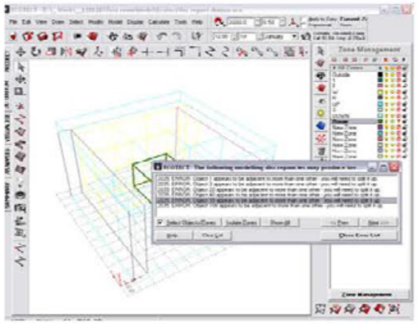


B6.1.3 Eplus



B6.1.3.1

1 AS1 in & AS2 —all in normal non thermal zones will cause transfer error, if keep doing simulation, results similar with manually edited. Result refer to table down below. * see detailed document **EP1**



B6.1.3.2

AS1 & AS2—if put in 'Outside Zone'. Objects will be considered as detached shading. No report in transfer to Eplus, but surface and the connected partition will be considered as one object. Can only work in C1, resulted only need cooling and demand is higher than 4.1.3.1. * see detailed document **EP2**

cooling	Manually edited (same result from 4.1.3.1)	zone/surfaces in outside zone for C1	
January	29.56	41.04	
February	27.45	36.34	
March	29.75	39.57	
April	34.92	44.37	
May	39.15	46.76	C2 crashed
June	40.75	47.41	
July	48.71	54.47	
August	47.09	51.30	
Sep.	42.62	49.43	
October	43.73	50.58	
Nov.	28.62	38.83	
Dec	25.13	37.96	

B6.1.3.3

AS3—transfer ok but partitions were considered as 'internal mass' and the result of heating demand (only) is higher than zone with external. C2 crashes in Eplus * see detailed document EP4

Heating C1	room and ceiling only + external	Surface partition transferred
Jan	346.72	458.60
Feb	274.04	380.55
Mar	242.86	337.41
Apr	183.39	290.25
May	122.33	211.78
Jun	63.96	153.80
Jul	47.91	134.55
Aug	36.17	131.03
Sep	98.98	200.60
Oct	133.53	269.23
Nov	251.10	312.12
Dec	428.10	418.00

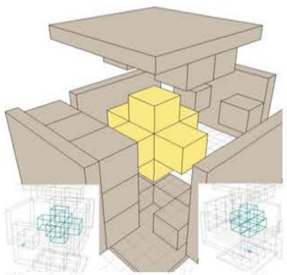
B6.1.3.4

AS4—no transfer problem but edit surfaces takes a long period

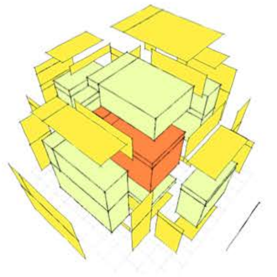
AS1 Partition surfaces in thermal zones will cause Eplus calculation crash in both C1 and C2. * see detailed document EP3

AS5 case will crash in Eplus calculation EP5

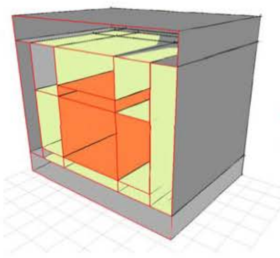
B6.2 More pictures:

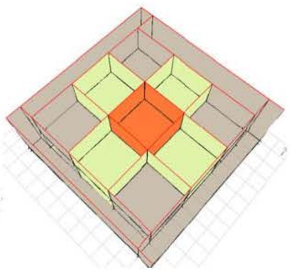


Attempts of surrounding study zones with one big space failed, it will cause too many transfer errors, especially into Eplus. Worked relatively ok with transfer into HTB2, but need to keep the model similar with each other.



Surround study zones by partition surfaces



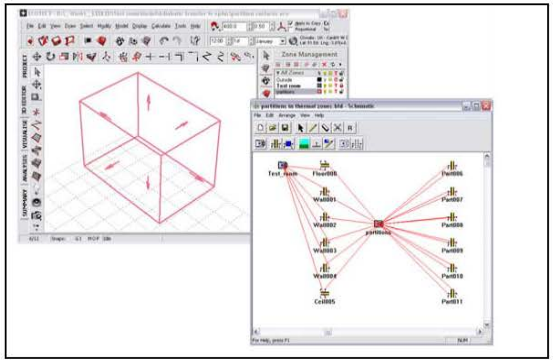


Zones surrounded by none-thermal zones

B7.1 Issues in HTB2

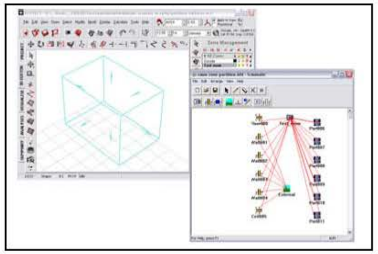
B7.1.1 HT1: Putting partition surfaces in a thermal zone:

Transfer to htb2 is ok but will create a dummy zone with actual volume. So did not consider in future tests.



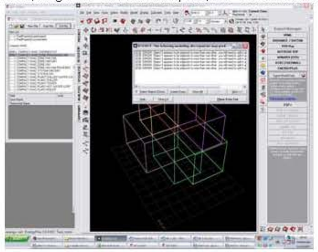
B7.1.2 HT2 Putting partition surfaces in a non-thermal zone: transfer to htb2 is ok but file were not readable in htb2. error 'ERROR!: INPUT,3: Spaces used in Layout are inconsistent with those used in Building definition'. So it is not considered in future tests.

B7.1.3 HT3 Partition in same zone resulted in transfer error.



B7.2 **Settings of adiabatic to transfer into Eplus**

7.2.1 EP1. Non-thermal zones / Partition surfaces in Non-thermal zones (issue same in V5.6)
Issues: 1A: report error in transfer: "Object X appears to be adjacent to more than one other - you will need to split it up'. However, if ignore the error report, the calculation went through.



1B: future issue: hard to identify which is caused by non-thermal zones and which is caused by actual modelling error.

Study zones' surfaces will connect with itself and rest object in non-thermal zones will be considered as 'detached shading'.

Results are similar with manually edited in Eplus model.
Example: Result in C2:

	Manually edited	Non-thermal zones/partition surfaces- in normal space
January	42.49	42.47
February	37.81	37.79
March	40.95	40.94
April	45.13	45.11
May	47.10	47.09
June	47.03	47.01
July	53.60	53.58
August	50.12	50.11
September	48.87	48.85
October	50.11	50.09
November	38.96	38.94
December	39.46	39.45

B**7.2.2 EP2. Non-thermal zones / Partition surfaces in 'Outside' zones**

Surfaces that connect with objects in 'outside' zone will be considered as shading.

Issues in Ecotect 5.5: 2A: No report error in transfer to Eplus
2B: Surface and the partition (or the surface of the zone in outside zone) it connects will be considered as one object- 'Surface shading: Detached: Fixed'.

So, in the C2 case, all surfaces that the single cell has were considered as shading. So calculation reported fatal error as there is no object left in normal zone. This problem was not noticed because only tested in multi-zone model, and in single cell test, manually edited the surface into adiabatic.

Issues in Ecotect 2011: 2A: the same,
2B: All surfaces of the studies were not considered as one object with its connection, but they were all connected with 'Ground'

And in C2 case, there is no crash as there are still objects left in study zones but the result was not correct as all surfaces were connected with ground.

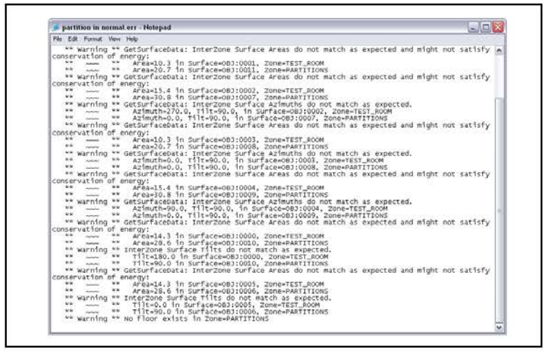
In 'room + ceiling' cases, since there are internal surfaces therefore the results can be generated. Higher than the results from manually edited in Eplus model.

cooling	Manually edited	zone/surfaces in outside zone for C1	
January	29.56	41.04	
February	27.45	36.34	
March	29.75	39.57	C2 crashed
April	34.92	44.37	* Calculation in V5.6 is ok but the result was not correct as surface connection error
May	39.15	46.76	
June	40.75	47.41	
July	48.71	54.47	
August	47.09	51.30	
September	42.62	49.43	
October	43.73	50.58	
November	28.62	38.83	
December	25.13	37.96	

B7.2.3 EP3. Partition surfaces in thermal zone (Same in V5.6)

Objects were considered as connected with 'internal mass' (objects of partition in Ecotect)

Issues: 3A: reported error: 'Zone Partition surfaces' has a too low volume.
3B: In Eplus calculation, surface area cannot match, surface tile also cannot match, for some reason, area of partition surfaces are twice as it should be.
3C: Also reported no floor objects in case C2
No results can be generated.


partition in normal.err - Notepad
File Edit Format View Help

```
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=10.3 in Surface=OBJ:0001, Zone=TEST_ROOM
   **   ~~~   **   Area=20.7 in Surface=OBJ:0011, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=15.4 in Surface=OBJ:0002, Zone=TEST_ROOM
   **   ~~~   **   Area=30.8 in Surface=OBJ:0007, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Azimuths do not match as expected.
   **   ~~~   **   Azimuth=270.0, Tilt=90.0, in Surface=OBJ:0002, Zone=TEST_ROOM
   **   ~~~   **   Azimuth=0.0, Tilt=90.0, in Surface=OBJ:0007, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=10.3 in Surface=OBJ:0003, Zone=TEST_ROOM
   **   ~~~   **   Area=20.7 in Surface=OBJ:0008, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Azimuths do not match as expected.
   **   ~~~   **   Azimuth=0.0, Tilt=90.0, in Surface=OBJ:0003, Zone=TEST_ROOM
   **   ~~~   **   Azimuth=0.0, Tilt=90.0, in Surface=OBJ:0008, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=15.4 in Surface=OBJ:0004, Zone=TEST_ROOM
   **   ~~~   **   Area=30.8 in Surface=OBJ:0009, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Azimuths do not match as expected.
   **   ~~~   **   Azimuth=90.0, Tilt=90.0, in Surface=OBJ:0004, Zone=TEST_ROOM
   **   ~~~   **   Azimuth=0.0, Tilt=90.0, in Surface=OBJ:0009, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=14.3 in Surface=OBJ:0000, Zone=TEST_ROOM
   **   ~~~   **   Area=28.6 in Surface=OBJ:0010, Zone=PARTITIONS
   ** Warning ** InterZone Surface Tilts do not match as expected.
   **   ~~~   **   Tilt=180.0 in Surface=OBJ:0000, Zone=TEST_ROOM
   **   ~~~   **   Tilt=90.0 in Surface=OBJ:0010, Zone=PARTITIONS
   ** Warning ** GetSurfaceData: InterZone Surface Areas do not match as expected and might not satisfy
conservation of energy:
   **   ~~~   **   Area=14.3 in Surface=OBJ:0005, Zone=TEST_ROOM
   **   ~~~   **   Area=28.6 in Surface=OBJ:0006, Zone=PARTITIONS
   ** Warning ** InterZone Surface Tilts do not match as expected.
   **   ~~~   **   Tilt=0.0 in Surface=OBJ:0005, Zone=TEST_ROOM
   **   ~~~   **   Tilt=90.0 in Surface=OBJ:0006, Zone=PARTITIONS
   ** Warning ** No floor exists in Zone=PARTITIONS
```

B7.2.4 EP4. Change zone's surfaces into partition and then transfer into Eplus Same in V5.6

Surfaces were considered as 'internal mass'

Issues: 4A reported error: 'Zone X' has a too low volume.
4B: Also reported no floor objects in case C2 This problem was not noticed because only tested in multi-zone model, and in single cell test, manually edited the surface into adiabatic.

Only work in C1 and resulted in high heating and no cooling.

Heating in C1	room and ceiling only +external-MD1	Surface partition transferred MD2
January	346.72	458.60
February	274.04	380.55
March	242.86	337.41
April	183.39	290.25
May	122.33	211.78
June	63.96	153.80
July	47.91	134.55
August	36.17	131.03
September	98.98	200.60
October	133.53	269.23
November	251.10	312.12
December	428.10	418.00

B7.2.5 EP5. Attach partition in same zone

Issues: surfaces and its connection will be considered as one. So there is no normal surface left in model. Report error same in 7.2.4.

V5.6: Partition surfaces: Same as in 7.2.3

Appendix C. Energy Calculation Results for Case Studies from HTB2

C1. Case Study 1: WJEC Building

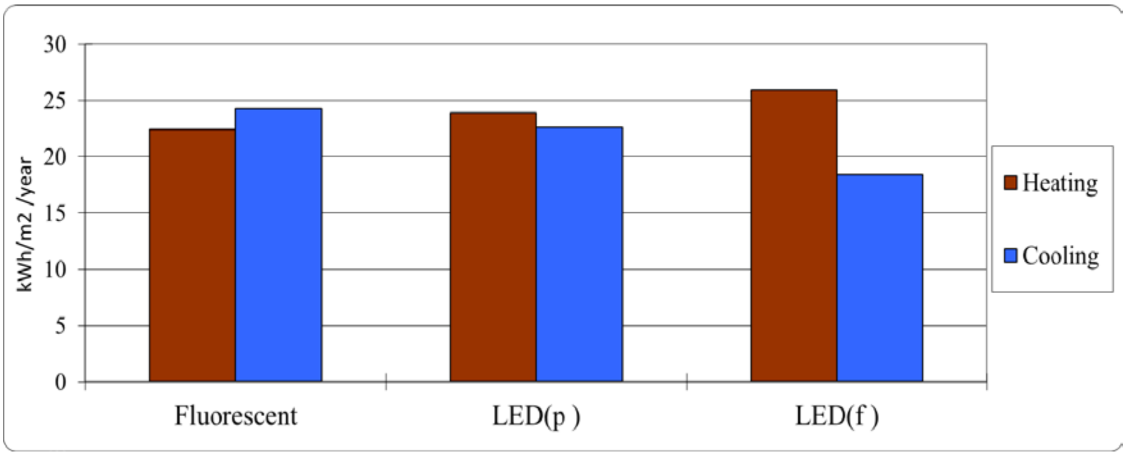


Figure C1. Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

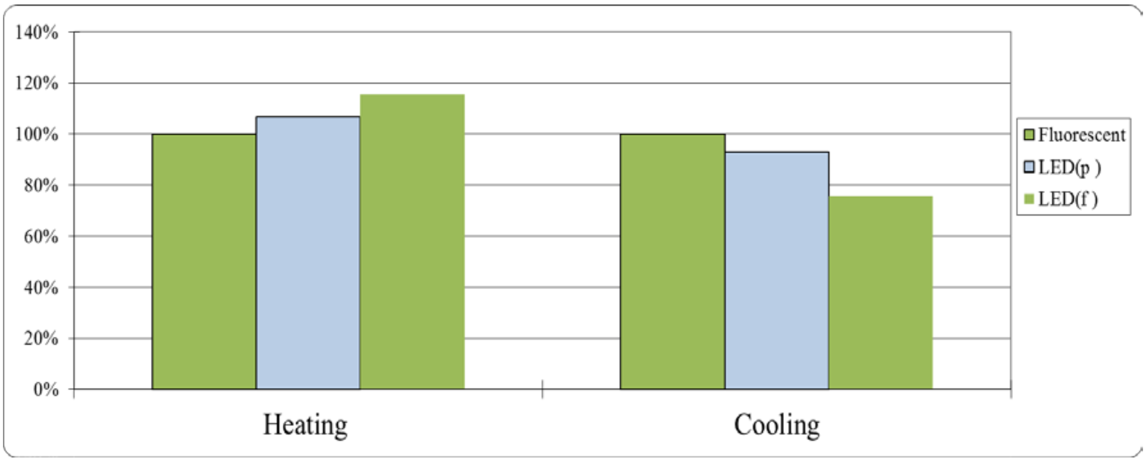


Figure C2. Relative differences in annual energy load demands from fluorescent lighting

C2. Case Study 2: NewBridge Gateway Building

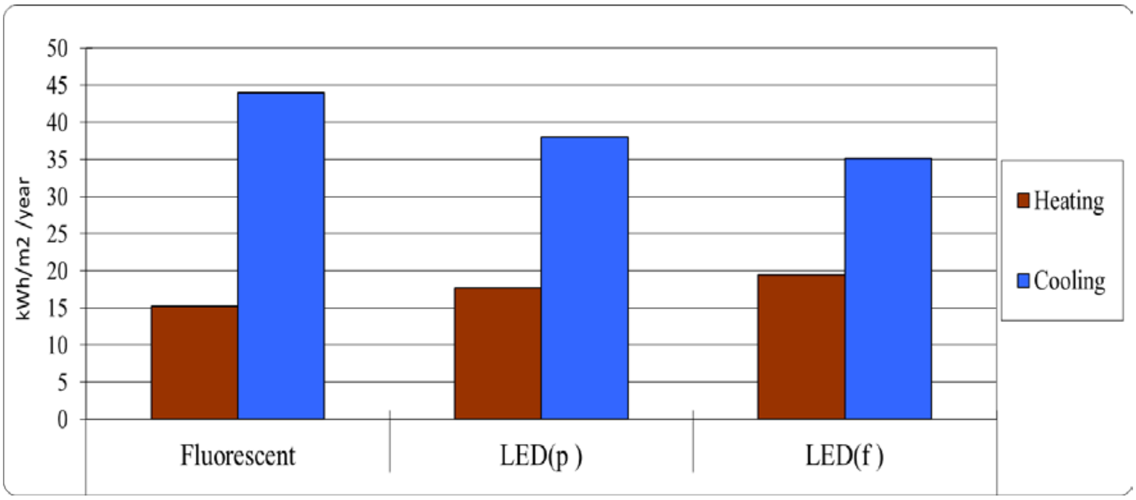


Figure C3 Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

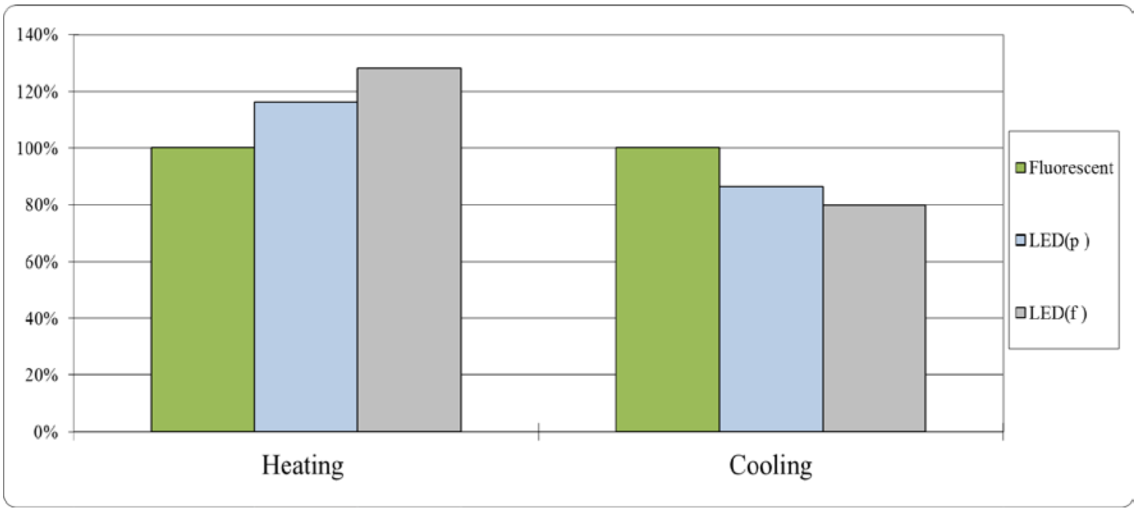


Figure C4. Relative differences in annual energy load demands from fluorescent lighting

C3. Case Study 3: Pulborough Building

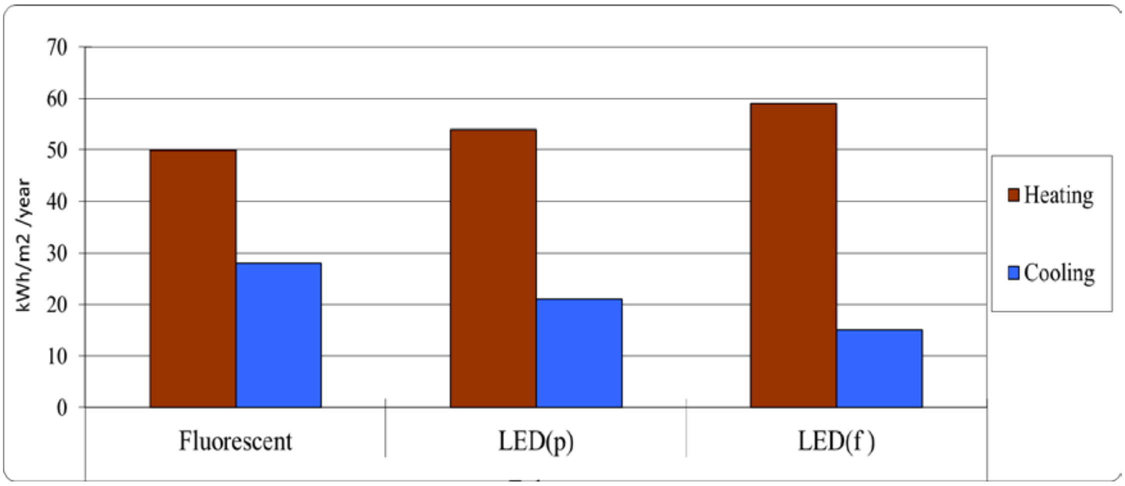


Figure C5. Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

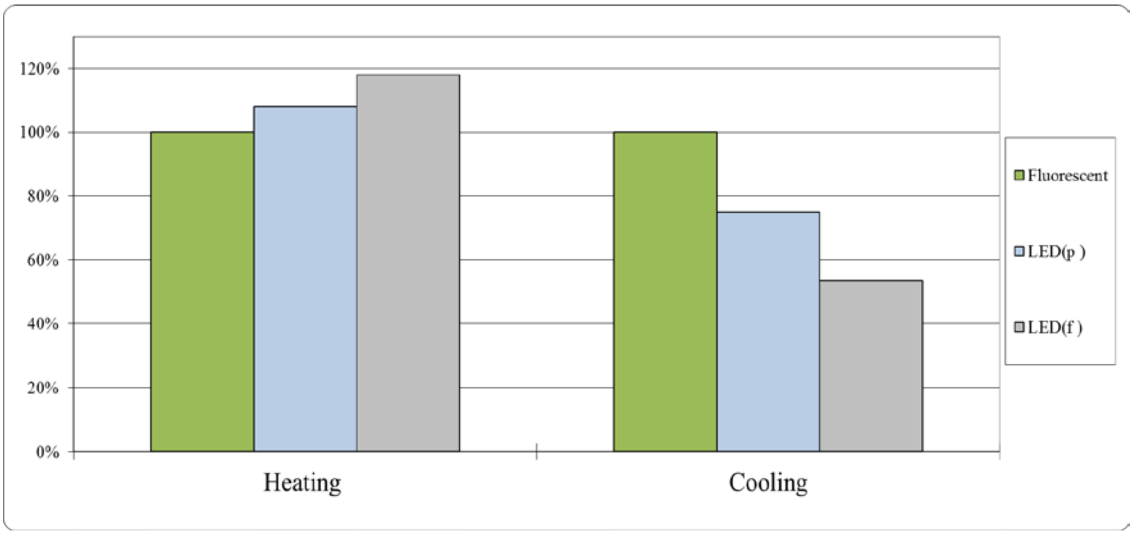


Figure C6. Relative differences in annual energy load demands from fluorescent lighting

C4. Case Study 4: Warmere Building

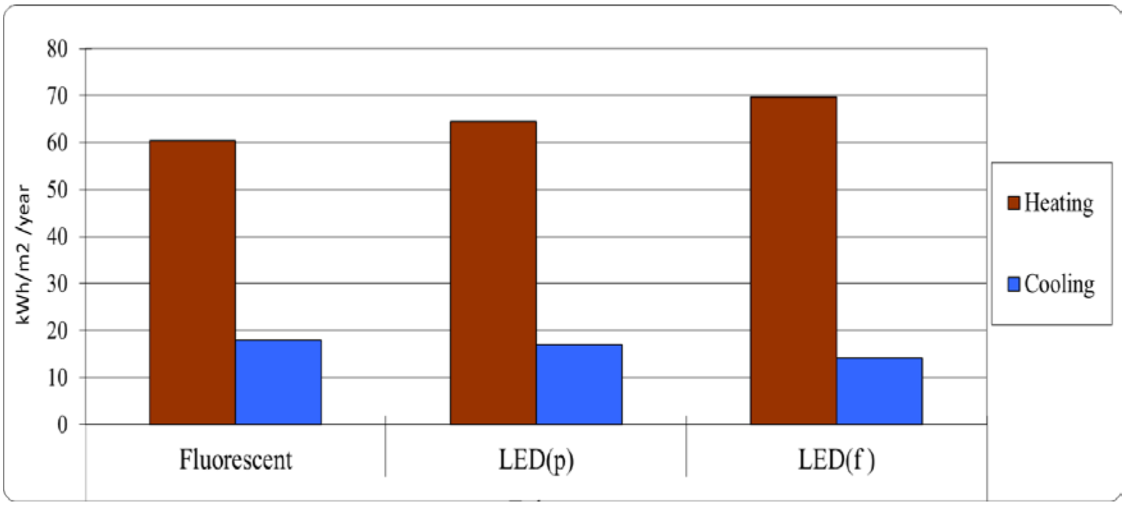


Figure C7. Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

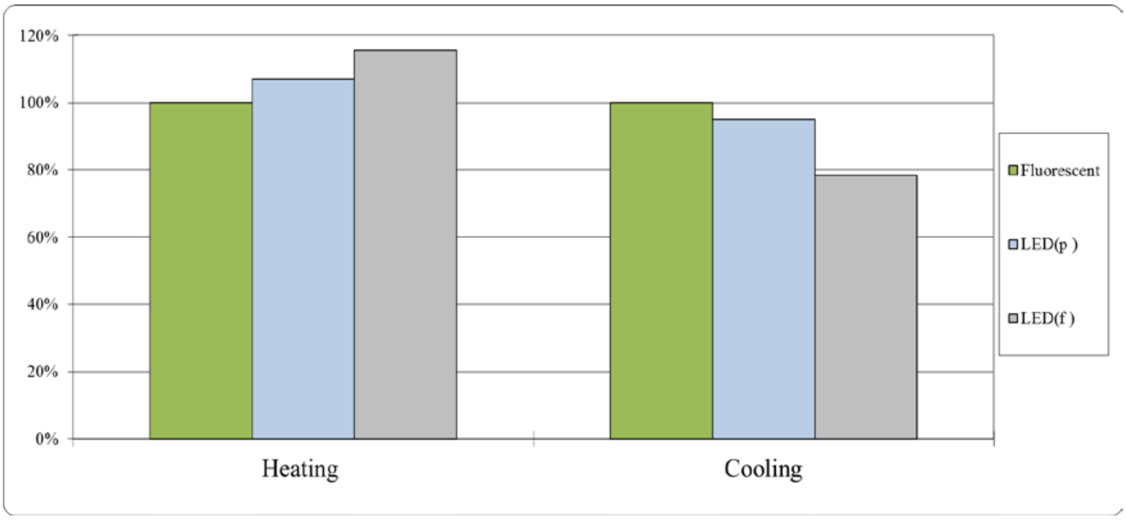


Figure C8. Relative differences in annual energy load demands from fluorescent lighting

C5. Case Study 5: Notional Office

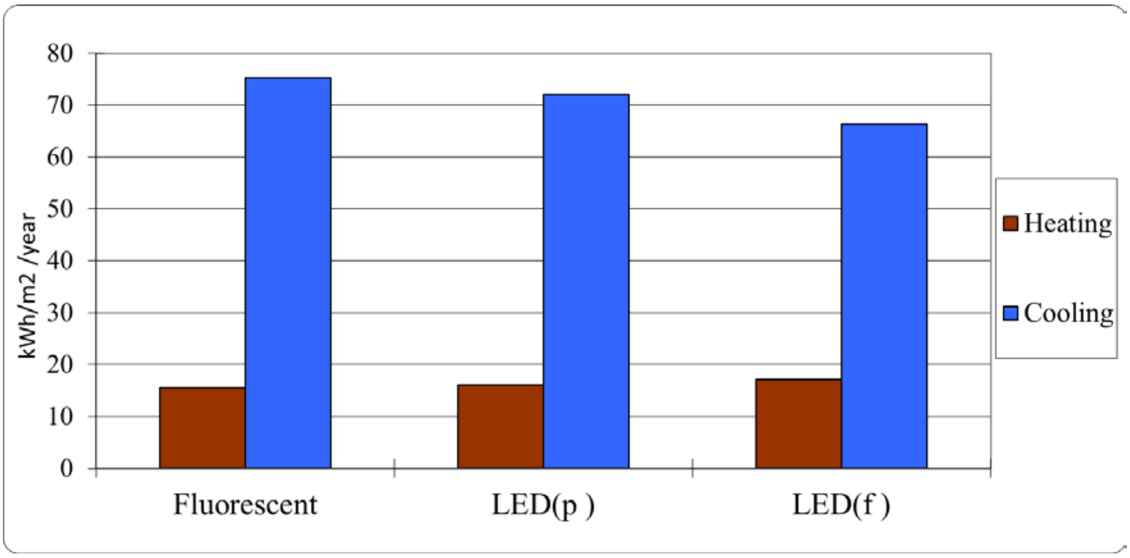


Figure C9. Annual heating and cooling energy load demand predictions under Fluorescent, LED(present) and LED(future) lighting conditions

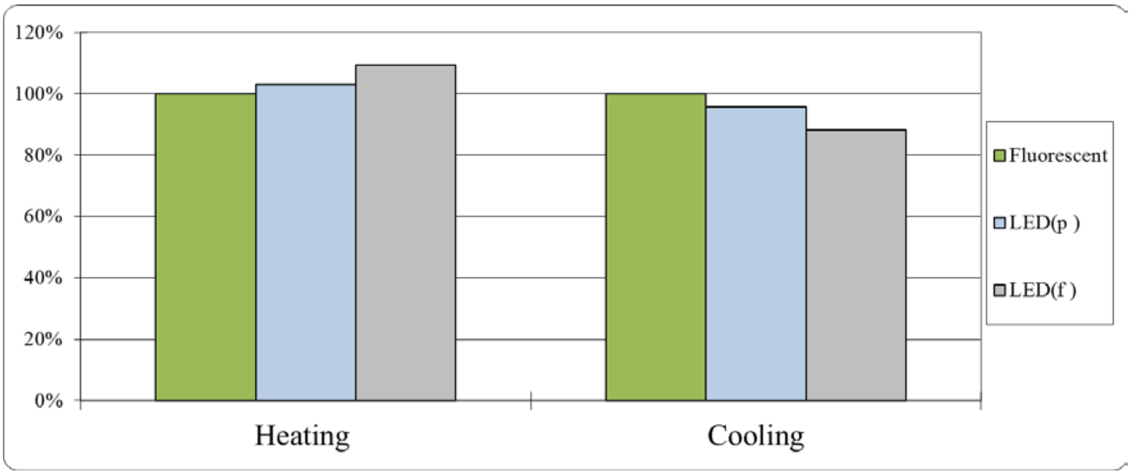


Figure C10. Relative differences in annual energy load demands from fluorescent lighting