MASTER

Dynamic lighting
energy savings by use of atypical daylight responsive lighting control

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Master's Thesis:

Dynamic Lighting – Energy Savings by Use of Atypical Daylight Responsive Lighting Control

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Preface

This Master's thesis is a full report of the research carried out during my internship at Philips Lighting from April to December 2007.

I would like to thank the following people, who have been of great help in the preparation of this thesis: my supervisors Martine Knoop, Martin de Wit, and Mariëlle Aarts for their support during my internship; Jan Diepens, Laurens Zonneveld, and Christoph Reinhart for their technical assistance with Radiance and DAYSIM. I would also like to thank Dominique Dumortier and ENTPE for providing extensive measurements of the colour temperature of daylight in Lyon, France. Finally, I would like to express my appreciation for the clear explanation of the geographical distribution and chromaticity of natural daylight by Javier Hernandez.

Matthijs Schriek,
December 2007.

Abstract

Due to new European regulation for the energy performance of buildings, the high energy consumption of algorithmic lighting solutions, such as Dynamic Lighting, forms a mayor issue. To provide higher levels of illuminance and correlated colour temperature, the total installed lighting load needs to be much greater than that of non-algorithmic lighting systems. Although this lighting load is not used at maximum demand for long periods of time, its annual energy use is still considerably higher than that of regular lighting systems.

By making use of daylight entering the office, the energy consumption of Dynamic Lighting systems can be reduced. Two energy saving methods are investigated in this report: daylight responsive control and time switching. It was found that with a simple modification of the original system (time switching), it is already possible to achieve energy savings up to 12%. A drawback of this method is that the illuminance curve is always distorted by daylight. With more complex modifications of the original system (daylight responsive control), it is possible to achieve energy savings up to 67%, while maintaining the illuminance curve rather accurately. It should, however, be born in mind that: (1) Dynamic Lighting cannot be used in zones directly behind the window, and (2) the correlated colour temperature curve cannot be achieved in daylit environments.

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1 Introduction

1.1 Problem statement

In recent years there has been an increasing interest in the effects of dynamic (or: algorithmic) lighting on the wellbeing, comfort, and productivity of people working in office environments. The detection of a third type of photoreceptor in the human eye, which mediates and controls a large number of biochemical processes in the human body, was a mayor breakthrough in this field of research. A significant finding to emerge from this study was that cool-white light is particularly effective in mediating the circadian rhythm, mood and behaviour of people.

Today, building regulations secure that every lighting system provides a constant illuminance level that allows visual tasks to be performed comfortably, prevents discomfort from glare, and ensures good colour rendering. Dynamic lighting systems aim to further improve the overall quality of the design by also controlling the timing, duration, and colour of the light in such a way that the wellbeing of office workers is optimized.

However, since this is a relatively new field of lighting application, several aspects still need to be investigated. One important field of research in this regard is the energy use of the system. Due to the higher level of illuminance provided by dynamic lighting systems at certain moments of the workday, dynamic lighting systems consume more energy than regular lighting systems. The recent introduction of a new EC directive on the energy performance of buildings further emphasizes the necessity of accurately investigating energy saving measures.

This report therefore examines the feasibility of using daylight responsive control with dynamic lighting systems. Daylight responsive control is a well-known method to reduce the energy use by dimming the lighting system when daylight provides sufficient task illumination. Although this is a frequently applied strategy for regular lighting systems, it is much more difficult to implement with dynamic lighting systems due to the continuous changes in colour temperature of daylight. These variations make it difficult to provide the desired colour temperature 'curve' over the day.

The purpose of this report is to assess the feasibility of saving energy in offices by installing daylight responsive control, while maintaining the desired illuminance and colour temperature 'curves'. Based on this assessment, several strategies are proposed to successfully implement dynamic lighting in daylit office environments.

1.2 Aim and methodology

To make a reliable assessment of the annual energy savings by daylight responsive control, it is crucial to create a good estimate of the amount of daylight that is transmitted through the windows onto the work plane over the course of a year, and to match this with corresponding values of the correlated colour temperature (CCT) of daylight. Since the of CCT of dynamic lighting systems fluctuates roughly between 3,000 K and 5,000 K, and the normative CIE-value for daylight is set to 6,500 K, it is apparent that daylight will not only disrupt the required illuminance curve of the Dynamic Lighting system, but it will also disrupt the required CCT-curve.

Based on this observation, the aim of this project was to quantify the amount and colour of daylight that reaches the work plane of a standard open plan office over the course of one year, and to assess whether or not it is possible to maintain the dynamic lighting curves. This data was obtained for different window orientations and sizes, and repeated for four geographical locations in Europe (approximately 1,000 km apart). Automatic blinds blocked out any direct sunlight (> 50 W/m^2 on the work plane), and standard clear glazing was applied.

The amount of daylight was accurately simulated with DAYSIM, an add-on program to Radiance that efficiently calculates the work plane illuminance for any location and geometry. Additionally, one-year measurements of the daylight CCT in Lyon, France (courtesy of ENTPE) were processed and analysed to obtain factual values for the bandwidth of daylight CCT over the course of one year. In these measurements, the daylight CCT was logged every 10 minutes for 12 months and for four orientations.

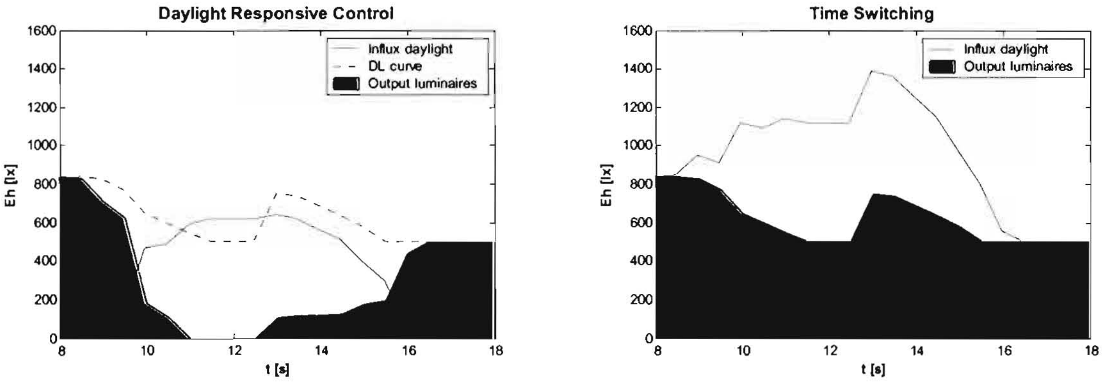


Fig. 1.1 - Energy saving strategies, simulation data plotted for: Paris, 21 Dec 2000 (North oriented façade, largest window size, back of room)

After the amount and colour of daylight had been quantified, day-by-day curves were constructed that evaluated: (1) how much the lighting system could be dimmed in response to the influx of daylight, i.e. the daily energy savings; and (2) if it was possible to maintain the CCT-curve by adapting the CCT of the lighting system in response to the colour of daylight. These results were then contrasted to a less complex energy saving solution: time switching, which simply turns off the lighting system when a threshold-value is crossed. From this analysis several implementation strategies for dynamic lighting systems in daylit offices were put together.

1.3 Outline of the thesis

This report has been divided into five parts. Chapter 2 provides the reader with a brief historical overview of previous research on this topic and outlines the most important underlying concepts. The third Chapter describes the methodology, and explains in detail all steps that were taken to obtain the results. In the fourth Chapter, the results are presented and discussed in Chapter 5. The last Chapter gives the conclusions and recommendations for further research.

2 Background

2.1 Light and vision

2.1.1 Rods and cones

In the past, rods and cones were thought to be the only photoreceptor cells in the human eye. The names rod and cone were assigned in early anatomical studies, when it was noted that the outer segments of the cells tended to have a cylindrical or conical shape. There are approximately 100 million rods in the human eye that are adapted for dim light and night vision, and roughly 6 million cones that can distinguish daylight luminance, contrast and colour. For indoor lighting situations, the cones are to a large extent decisive.

The lens of the eye projects an image on the light sensitive retina, which is a very thin layer of nerve tissue covering most of the inner surface of the eye (Fig. 2.1). The retina consists of a large network of about 200 million specialized nerve cells. Approximately 50 per cent of these cells are photoreceptor cells that process light information; the others are secondary cells that combine and recode the photoreceptor outputs and transfer them to the brain. When light falls on these photoreceptor cells, a complex chemical reaction takes place. A chemical called activated rhodopsin is formed that induces electrical impulses in the optic nerve that connects the photoreceptor cells with the visual cortex in the back of the brain (Fig. 2.1). In the visual cortex of the human brain these electrical impulses are then interpreted as "vision".

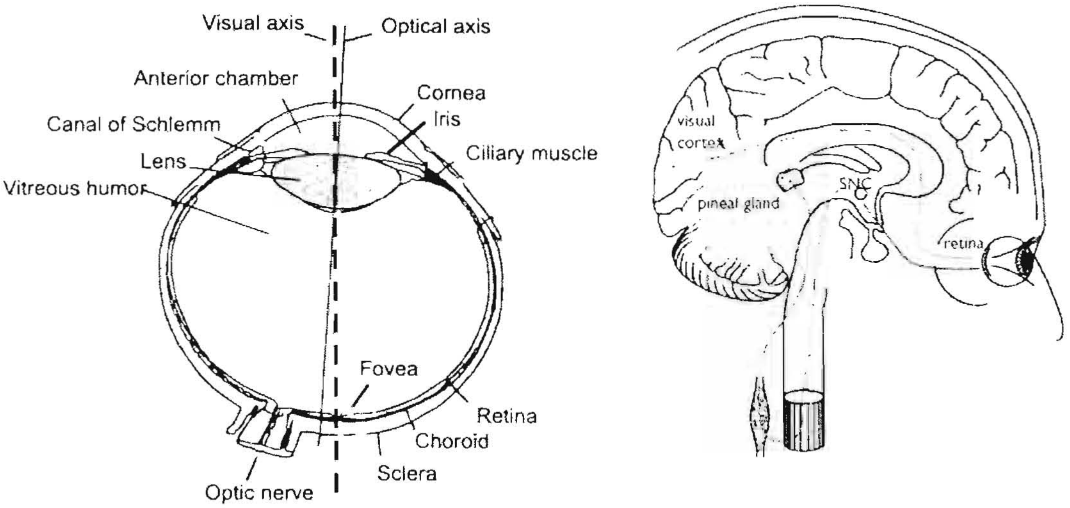


Fig. 2.1 – Cross section through the human eye [4],
Visual and biological pathways in the brain [6]

2.1.2 Novel photoreceptors

Provencio et al. demonstrated in 1995 that mice without rods could still maintain their circadian rhythm [1], and in 1999 Freedman et al. found that rodless-coneless mice could also be phase shifted and have their melatonin repressed by light [2]. In addition to these findings it was also discovered in 1995 that the melatonin level in human beings could be suppressed by exposing the eyes to light both in visually blind [3] and colour blind people [4] with undamaged neural pathways between the eye and the suprachiasmatic nucleus (SCN) of the hypothalamus. Taken together, these findings "imply that besides the rods and cones for vision, the eye has an additional retinal photoreceptor for non-visual effects" [5].

In their seminal article in 2002, Berson et al. [6] discovered a third type of photoreceptor in the retina of mammals. This new photoreceptor cleared up "how light also mediates and controls a large number of biochemical processes in the human body" [7,8]. More recent studies have recognised melanopsin, which is a light sensitive protein detected in retinal ganglion cells in rodent, primate and human retinas, as the new photoreceptor [9–11]. Moreover, in rodents the responses to light of the melanopsin containing ganglion cells "match those for melatonin suppression and light entrainment" [6] and the cells hold a "dendritic network extending to the SCN" [6]. These specific ganglion cells depolarise in response to light even when all the input from rods and cones is prevented.

Light that falls on the retina and is processed by approximately three thousand of these specific photoreceptor cells (or: intrinsically photosensitive retinal ganglion cells) does not contribute to the visual image. These cells have separate nerve connections to the SCN and the pineal gland that control important light reflexes – regulation of our circadian rhythms, modulation of core body temperature, contraction of the iris, and production of hormones. In other studies it was shown that rods and cones also have some input to the SCN [12,13]. The precise roles of rods, cones and melanopsin in the control of circadian cycles therefore still need to be resolved, but the novel non-visual photoreceptor "may provide for new methods of lighting to benefit health and well-being" [6].

2.1.3 Spectral eye sensitivity

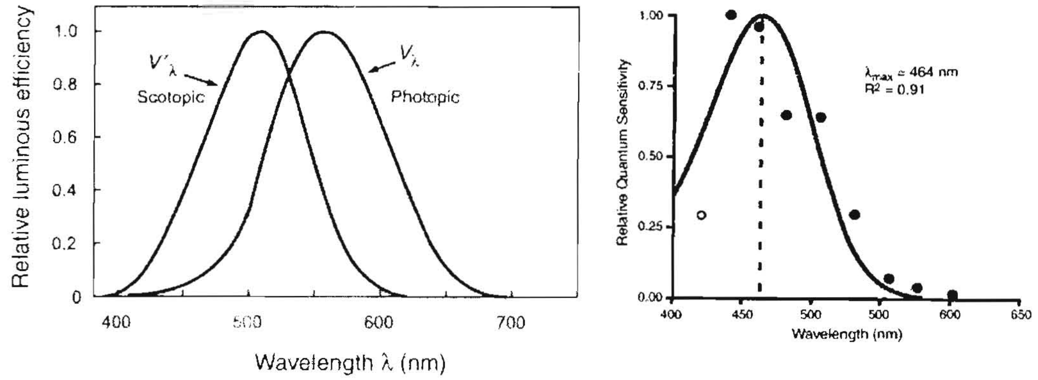


Fig. 2.2 – Spectral luminous efficiency curves for daylight and night vision [14], Action spectrum for melatonin suppression [15]

A light-adapted eye typically has a maximum sensitivity at around 555 nm, in the green region of the visible spectrum. As can be seen from Figure 2.2, the eye sensitivity can be represented as a graph where the relative luminous efficacy of radiant energy is a function of the wavelength. The graph represents the stimulating power of light that falls on the retina: one unit of visible radiation has a different luminous efficiency based on its wavelength. Basically, it means that light of wavelengths close to 555 nm appears brighter to human observers than light that consists of shorter or longer wavelengths, even when the amount of radiation for each wavelength is equal.

The sensitivity of the novel photoreceptor cell also varies for different wavelengths of light, and thus for different colours of light. Several action spectra associated with non-visual effects of light have been studied in both humans and animals, and they all "peak in the wavelength region from 446 to 488 nm" [14]. As can be seen from the action spectrum for melatonin suppression in human beings shown in Fig. 2.2, it has a peak at 464 nm in the blue region of the visible light spectrum. The action spectra in other animals and for other endpoints do not match this graph exactly, but the consensus is that melanopsin is most sensitive to short wavelength visible light [14,15]. It follows therefore that lighting designs that are optimised for vision, are not necessarily effective for non-visual effects.

2.1.4 Direct biological effects

For the purpose of this report the direct effects of light, which are independent of the circadian rhythms, are most important. In particular, it should be noted that light regulates changes in the hormone concentration in the human body; the hormones cortisol (the "stress hormone") and melatonin (the "sleep hormone") have an important role in governing alertness and sleep.

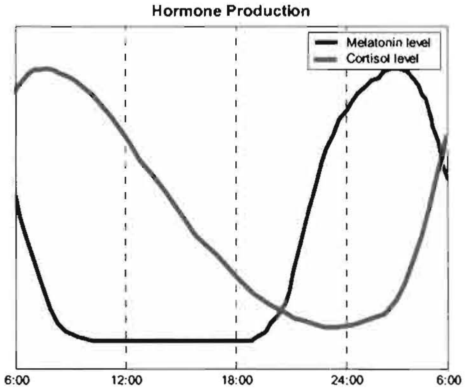


Fig. 2.3 – Daily patterns of hormone levels in the human body, adapted from [16]

Cortisol increases blood sugar to give the body energy and enhances the immune system, but when cortisol levels are too high over an extended period, the system becomes exhausted and inefficient. Fig. 2.3 (red graph) shows that the daily cortisol levels naturally increase in the morning to prepare the human body for the coming day's activity, and then gradually decrease over the course of the day to a minimum at midnight. As can be seen from the green graph of Fig. 2.3, the level of the sleep hormone melatonin follows a different daily pattern. It drops in the morning, reducing sleepiness, and it rises again when it becomes dark, permitting healthy sleep.

A growing body of literature has been published on the direct biological effects of light. First, for good health it is of importance that the melatonin and cortisol rhythms are not disrupted too much. In case of a disruption of the rhythm, bright light in the morning helps restoring the normal rhythm [16]. Second, it has been found that daytime bright light can reduce sleepiness and fatigue even though melatonin is virtually absent and core body temperature is nearly constant [17], and in the early morning results in an immediate increase of cortisol [17,18]. Third, a temporary boost of light levels and/or an increased direct component can improve alertness and stimulated productivity, whereas warm-white light provokes relaxation [19]. These findings suggest that bright light can be used to stimulate the human body and to decrease sleepiness, which will enhance the working conditions. High (ocular) light levels and light with a high blue component are most effective [17-20].

2.1.5 Describing the colour of light

The colour of light can be described by its x and y coordinates in the CIE 1931 chromaticity diagram. This is a system for colour measurements (or: colorimetry), introduced by the International Commission on Illumination (CIE) in 1931. The coordinates of this system can be regarded as the responses of three light-sensitive devices (e.g. photocells or diodes) for measuring light intensity: three light detectors X, Y, and Z with different spectral responses, where X has a maximum response for long-, Y for middle-, and Z for short-wavelength lights [40]. The CIE chromaticity diagram does not show all three variables, but only shows the chromaticity two-dimensionally, where: $x = X / (X+Y+Z)$ and $y = Y / (X+Y+Z)$. If, for example, the luminance of a light source with a constant colour is increased, X and Y increase by the same ratio as (X+Y+Z), leaving the chromaticity unchanged. Since the variable Y indicates the luminance of a colour, the diagram is also referred to as the "xyY" or "Yxy" colour space. Two later chromaticity diagrams have been adopted by the CIE, one in 1960 (with variables *u* and *v*) and one in 1976 (with variables *u'* and *v'*), but the CIE 1931 system is still widely used whenever a technical specification of colour stimuli is required [40,41].

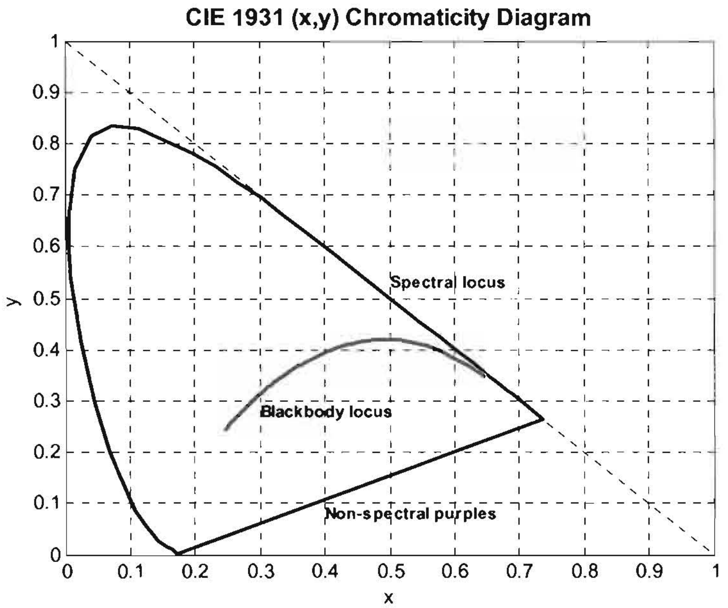


Fig. 3.2 – CIE 1931 chromaticity diagram with blackbody locus

The CIE 1931 chromaticity diagram (Fig. 3.2) is formed by two loci: the locus of spectral colours, and the locus of non-spectral purples. All points on the spectral locus correspond to the chromaticity of monochromatic light of a particular wavelength, and have the highest possible saturation (i.e. they are "pure colours"). The points joining the open ends of the spectral locus are called the non-spectral purples. These colours do not appear in the light spectrum and are not monochromatic. Any point in the interior of the region bounded by the spectral locus and the non-spectral locus represents a chromaticity which is not 100% saturated.

The blackbody locus represents the chromaticity of a black body, an object that absorbs all radiation falling on it. As the temperature of a black body increases, the emitted spectral distribution shifts toward the shorter wavelengths. For higher temperatures, the chromaticity shifts toward blue hues; for lower temperatures, toward red hues. So any arbitrary "white" chromaticity, which happens to lie on the blackbody locus, can be described precisely by stating the temperature at which a black body would emit light of that same chromaticity. Chromaticities falling near the blackbody locus, but not on it, are referred to by their correlated colour temperature (CCT). This is the colour temperature of the point on the blackbody locus that is "closest in appearance" to the chromaticity of interest. Technically, this means that the CCT can be determined by locating the point on the blackbody locus that is geometrically closest to the point of interest. This is done in the CIE 1960 uniformity chromaticity scale diagram, since in this diagram equal geometric distances represent equal perceived differences in chromaticity. By connecting points of constant CCT isothermal lines are formed.

2.2 Algorithmic lighting

2.2.1 Concept

Based on the non-visual effects of lighting, a new form of office lighting was developed in which the amount and colour of light are changed over the course of a day to let users benefit from the biological effects of lighting. Generally, these novel office lighting systems are referred to as algorithmic lighting systems. This report focuses on an algorithmic lighting system developed by Philips, called 'Dynamic Lighting'.

The Dynamic Lighting system aims to support and enhance the natural rhythm of activity of office workers, by providing higher levels of illuminance and colour temperature at certain moments of the workday. Bright light with a high colour temperature will provide a good start of the day, due to suppression of the remaining melatonin in the body and an increase of the cortisol level [17,18]. The circadian rhythm of alertness peaks in the morning and in the early evening, where additional support of light in not necessary. The so-called "post-lunch dip" is a time period of decreased alertness that occurs roughly between 1 PM and 4 PM, taking into account individual differences. For those workers that are not able to take a long lunch break or a nap, lighting is a solution. In contrast to the morning, the post lunch dip cannot be addressed by means of hormone production [17,18]. Although not clarified yet, it is clear that other pathways besides the mechanisms of hormone production affect alertness; research has shown an increase of alertness in the afternoon induced by the use of higher colour temperatures and higher light levels [17,19].

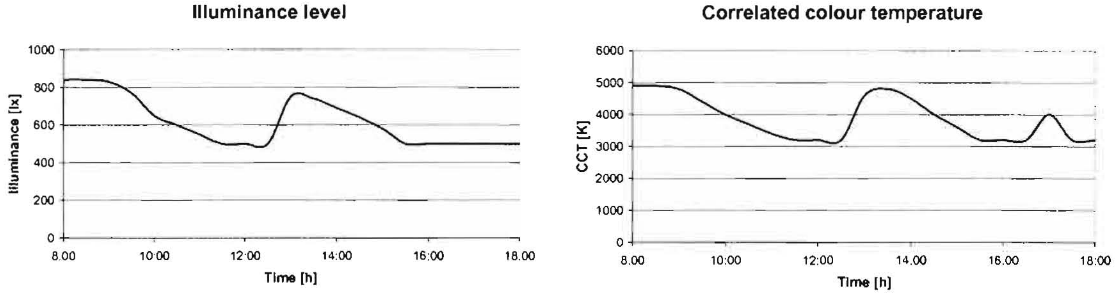


Fig. 2.4 – Dynamic Lighting: illuminance and CCT curves during the workday

As can be seen from Fig. 2.4, the working day starts with cool-white light and an increased lighting level, to raise the energy level and provide a good start of the day. Towards lunchtime, warm light and a decreased lighting level is created. After lunch cool-white light and an increased lighting level counter the "post lunch dip". The colour temperature is raised again (without increasing the lighting level) to increase concentration before going home.

2.2.2 Energetic aspects

As part of the EU measures to satisfy the Kyoto Agreement concerning the reduction of greenhouse gases, the new EU Energy Performance of Buildings Directive [27] was devised to establish conventions and procedures for the estimation of energy requirements of lighting in buildings, and to give a methodology for a numeric indicator of the energy performance of buildings, the so-called LENI-number. The Lighting Energy Numeric Indicator (LENI) is a rating index for the annual energy usage of lighting installations. The lighting's energy efficiency in the building will be rated by an index expressed in kWh/m^2/year. The LENI-number is to be presented for the entire building and can be used to compare the energy consumed for lighting. A comparison can than be made between different buildings with the same function, but of a different size and design.

In view of this new energy performance regulation, the high annual energy consumption of Dynamic Lighting forms a mayor issue. To provide higher levels of illuminance and colour temperature, the total installed lighting load needs to be much greater than that of a non-algorithmic lighting system. Although this lighting load is not used at maximum demand for long periods of time (the actual power used is between 50% and 84% of the installed load), its net annual energy use is still considerably higher than regular lighting systems.

2.2.3 Daylight responsive control

The main focus of this report is to assess the effectiveness of daylight responsive control in reducing the annual energy use of Dynamic Lighting systems. Daylight responsive control can steer both the amount of daylight that enters the office (i.e., the position and angle of blinds), and the electric lighting output of the lighting system. The first is critical for providing adequate quantity and quality of daylight in interior spaces. The second saves energy for the artificial lighting system and improves the overall distribution of light when daylight is insufficient.

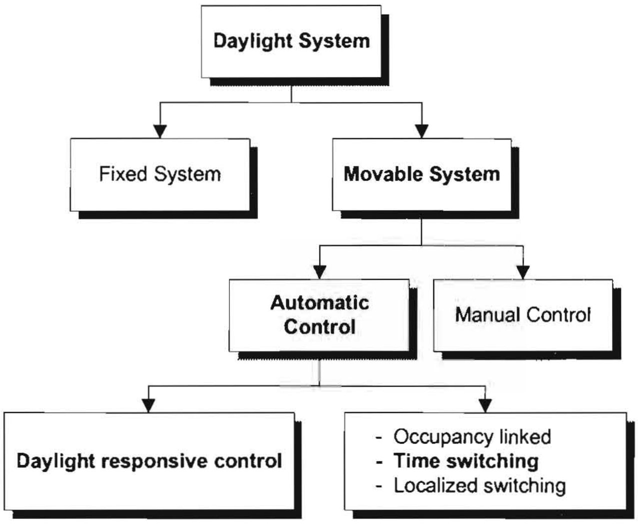


Fig. 2.5 – Overview of types of shading systems, adapted from [26]

A fundamental difference between daylight and electric lighting is the constant variation of skylight. The sky luminance and resultant internal illuminances vary with latitude, time of day, and the seasons; random variations in sky luminance also result from the density and movement of clouds. In side lit rooms, the illuminance at points near windows is rarely more than one-tenth of that outdoors and is often considerably less at points far from the window.

Nevertheless, the daylight in an interior space is of sufficient magnitude to make a useful contribution to the lighting of building interiors for much of the year. The introduction of target illuminance or luminance levels and variability about those targets is therefore a practical solution to the lighting of building interiors.

There are two types of control strategies for daylight responsive artificial lighting control:

- Closed loop systems *(individual or with a limited number of luminaires)*
- Open loop systems *(central systems)*

A control system is considered to be closed loop when the photo sensor is located so that it is able to detect both the electric light that the system controls and the available daylight. In this case, the sensor needs to allow for the output of the lighting system that it controls. In contrast, an open loop control system's photo sensor is designed and located so that it detects only daylight and does not measure the electric light that it controls. In this report a closed loop system will be evaluated.

3 Methodology

3.1 Daylight availability

The first step in the evaluation of the Dynamic Lighting system in daylit office environments was to make an accurate estimate of the actual daylight availability over the course of one year. For the purpose of this report Radiance was used to simulate the annual daylight characteristics. Radiance is a lighting visualisation system based on backward raytracing algorithms, developed by Lawrence Berkeley Laboratories. This software basically traces imaginary rays of light from a viewer's eye to the objects of a rendered scene to determine the visibility of surfaces. Although very accurate, it takes a lot of time to calculate a single lighting scene. Obviously, it would take too much time to calculate annual daylight availability, for several locations and orientations in Europe and with multiple timesteps per day.

For this purpose the Lighting Group of the National Research Council (Canada) and the Solar Building Design Group of the Fraunhofer Institute for Solar Energy Systems (Germany) developed a separate program, called DAYSIM. This software is an add-on to Radiance, which makes several simplifications to the original algorithms in order to speed up annual calculations for daylight availability. DAYSIM uses routine irradiance measurements to calculate the sky luminance distribution, using the sky model developed by Perez [26,27]. In addition to this, it further reduces the complexity by determining the sensitivity of the internal illuminance of surfaces to changes in the brightness of one sky element. This approach was developed by Tregenza [28], and is called the daylight coefficient approach.

3.1.1 Simulation accuracy

Mardaljevic carried out extensive tests and found that Radiance combined with a daylight coefficient approach and real sky scanner data "should be considered almost equivalent in accuracy to a standard timestep by timestep calculation of the horizontal illuminance" [29-32]. Since sky scanner data are rare and generally not publicly available, Reinhart also tested the Radiance with a Perez sky model instead of real sky scanner data and found an average simulation error of approximately 10% [33-35]. For complex geometries (e.g. offices with complex shading systems) and low ambient simulation parameters, an additional error of maximal 10% needs to be taken into account [33-35].

3.1.2 Geometry, materials and location

An algorithmic lighting system is a high-end solution that will most often be implemented in large offices. For the purpose of this study, a standard open plan office was therefore used with standard reflection factors for floor, walls, and ceiling (Table 3.1).

Table 3.1 – Model characteristics

Length:	14.4 m
Width:	7.2 m
Height:	3.0 m
Reflection factors:	20%, 50%, 70%
Distance to window:	1.2 m, 3.6 m, 6.0 m
Office orientation:	North, East, South, West
Window size:	5.2, 10.0, 20.0, 25.0, 32.0 m^2
Glazing:	Clear glass, no (thermal) coatings

In order to take into account the site-specific differences in daylight availability, all calculations were repeated for 4 different locations in Europe, approximately 1,000 km apart: Madrid, Paris, Berlin, and Helsinki. These cities have different monthly distributions of sky conditions and therefore have different annual daylight availability characteristics. From the comparison between the different locations, it was possible to determine whether or not the simulation results were representative for only one location, or if the results were site-independent.

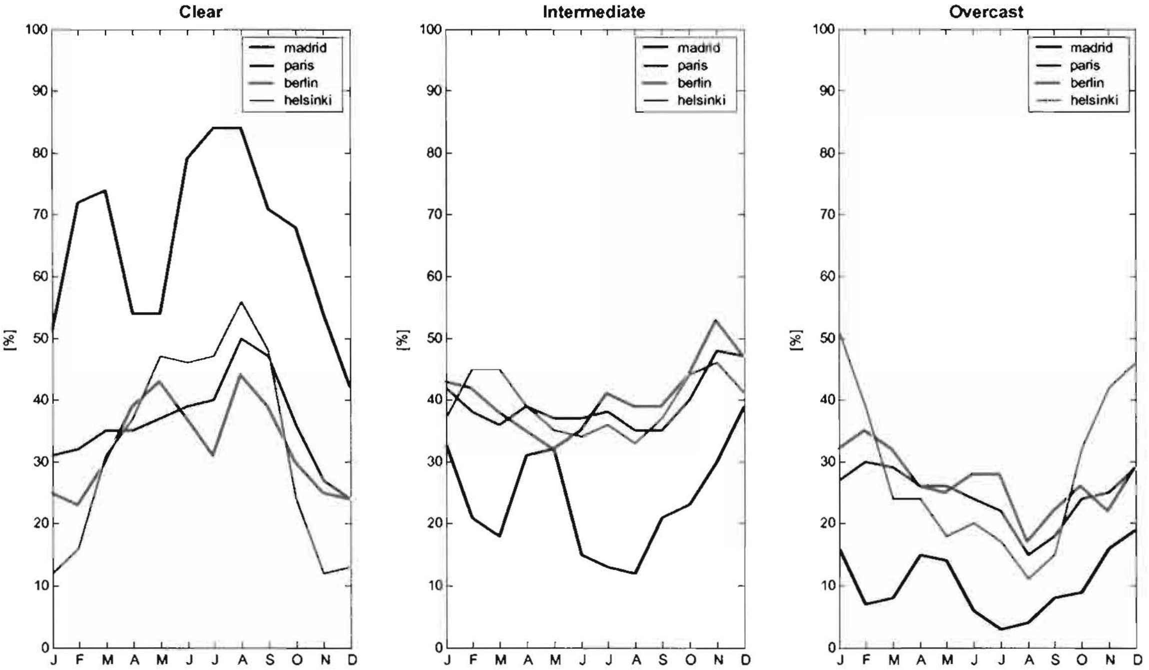


Fig.3.1 – Monthly availability of sky conditions for 4 different locations in Europe, adapted from [www.satel-light.com]

3.1.3 Annual energy use

A database with the average daylight availability for all timesteps was created with DAYSIM, using an array of 40 sensors in the front, centre, and back of the office. From this database the dimming percentage of the lighting system was derived, as well as the average daily distortion by daylight. Additionally, the number of luminaires in the office was determined using standard lighting software (DAILUX). It was found that 6 luminaires in 3 zones would secure a good overall artificial lighting level in the office. The annual energy use was then calculated by:

$$Q_{light} = \sum_{t_{step}=1}^{t_{step}=i} \left[\frac{E_{h,luminaires}(i)}{1000} \left(n_{luminaires} \times \frac{t_{step}(i) \times 162\ W}{3.6 \times 10^6} \right) + \left(n_{luminaires} \times \frac{t_{step}(i) \times 21\ W}{3.6 \times 10^6} \right) \right] \quad (3.1)$$

Where :

Q_{light} = Annual energy consumption, ballasts included $[kWh]$

$n_{luminaires}$ = Number of luminaires installed in the office $[-]$

t_{step} = Simulation time step $[s]$

The first term of Equation 3.1 represents the energy consumption to power the lighting system during a given time period. As can be seen, the term goes to zero when the required task illuminance is fully provided by daylight. The second term of Equation 3.1 represents the energy used when the lighting system is extinguished, i.e. when there is sufficient daylight to fully dim the system. This term basically represents the energy used by the ballast in standby mode or for charging emergency luminaires. The total annual energy consumption was then determined by summing the energy required to provide the desired task illuminance for all timesteps during office hours over the course of one year. For the purpose of this report, the system was switched on from 8 AM to 6 PM, from Monday to Friday (no weekends). This resulted in a total annual operating time of 2600 hours: 260 workdays per year, 10 hours per day.

From this data two main results were derived:

1. The annual energy savings (Section 3.1.4)
2. The days that the Dynamic Lighting system was:
    a) Completely dimmed (with daylight responsive control)
    b) Switched off (with time switching)

At times when the system was only partly dimmed, the Dynamic Lighting curve was realised exactly, but at times when situation 2a occurred the resulting internal illuminance curve effectively 'ran free'. When the system was fully dimmed, there was no more 'control' over the amount of task illuminance. At these moments the task illuminance directly followed the influx (and colour) of daylight. In situation 2b, when the system was switched off because the threshold value was exceeded, the Dynamic Lighting curve was of course realised neither. For the overall assessment of the lighting system, the moments when this phenomenon occurred were determined and saved in a separate database.

3.1.4 Annual energy savings

Using Equation 3.1, the annual energy saving could be simply determined by:

$$Q_{sav} = \left(1 - Q_{light} / Q_{ref}\right) \times 100 \times SP \tag{3.2}$$

Where :

Q_{sav} = Total annual energy savings $[\%]$

Q_{light} = Annual energy consumption, with energy saving measures $[\%]$

Q_{ref} = Annual energy consumption, without energy saving measures $[\%]$

SP = System Potential $[-]$

It should be noted that the annual energy savings for a lighting system were reduced by a factor called the System Potential [36]. This is an experimentally determined value that takes into account the inaccuracies in steering the lighting system in response to daylight, such as delays between measurements and the response of the lighting system, and inaccuracies in exactly controlling the output of the luminaires. The System Potential is between 0.8 and 0.9; for daylight responsive artificial lighting control a factor of 0.9 is recommended.

3.2 Colour of daylight

In addition to the availability of daylight, an assessment of the corresponding colour of daylight was made. For this purpose, measurements of the correlated colour temperature (CCT) of daylight over the course of one year (courtesy of ENTPE, France) were analysed. These measurements were recorded in Lyon, approximately in the east of France. The results were compared to similar measurements taken in Granada in the south of Spain, which were published in Applied Optics in 1999 [37]. From this assessment it was possible to make a realistic estimate of the frequency and range of daylight CCT.

3.2.1 Range of daylight chromaticities

The colour of daylight is characterised by its *correlated* colour temperature (since its chromaticity coordinates are slightly off blackbody locus), and is a very complex quantity to describe. It varies substantially with geographic latitude and altitude, season, humidity, distance from the zenith, time of day and concentration of atmospheric ice, dust and smoke [39,40]. The distribution of colours across the sky is also very irregular and highly dependent on the sky conditions: less than 3,000 K at sunset near the sun, from 5,000 K for cloud patches, to more than 20,000 K for blue sky patches.

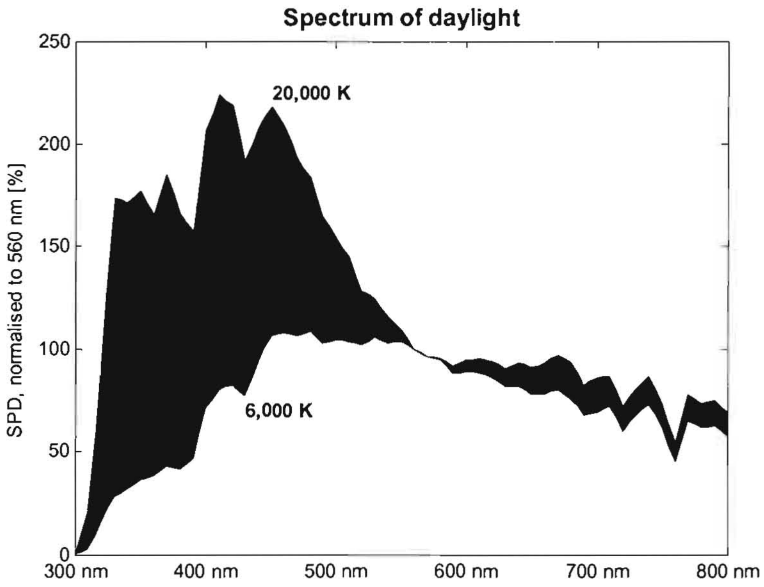


Fig. 3.2 – Spectral power distribution of daylight chromaticities ranging from 6,000 K to 20,000 K, based on the CIE recommendations [46]

From a small number of articles published on this specific topic [42-43], and based on the CIE recommendations [46], it possible to state in very broad lines, that:

- The CCT under overcast sky conditions is around 6,000 K
- The CCT varies greatly under cloudless skies, from 7,000 K near the sun to more than 20,000 K on the opposite side of the sun
- The CCT of intermediate skies consequently has values between 6,000 K and 20,000 K

3.2.2 Site-specific daylight chromaticities

To obtain a site-specific annual database with daylight chromaticities, the daylight chromaticity coordinates were logged every 10 minutes from December 1999 to December 2000 for 4 different orientations (North, East, South, West). This data was scanned for bad measurements and cleaned up. Next, the database was converted from x and y chromaticities into CCT values, resulting in an overview of the range and frequency of the daylight CCT in Lyon, France.

After removing any measurements that are flagged, i.e. the measurement equipment indicates that the connection between the sensor and the data logger was not good, the database was scanned for any values that were too far off the blackbody locus to be considered real chromaticity values. A common boundary for this, is a maximum distance of $\Delta uv = 0.02$ in the CIE 1960 uniformity chromaticity scale (UCS) diagram, since in this diagram equal geometric distances represent equal perceived differences in chromaticity. Values outside these boundaries are too far off the blackbody locus to still be considered daylight chromaticities. The boundaries can of course be easily converted from the CIE 1960 UCS to the CIE 1931 diagram:

- Upper boundary: $y_{upper} = -2.23 \cdot x^2 + 2.44 \cdot x - 0.18$
- Lower boundary: $y_{lower} = -3.25 \cdot x^2 + 2.44 \cdot x - 0.33$

After cleaning up the database for any remaining bad measurements, all values could be safely converted into CCT values. This conversion was done in two steps, depending on the location of the chromaticity coordinates in the CIE 1931 diagram: for values corresponding with CCT's lower than 10,000 K, the chromaticity coordinates were first converted to the USC diagram and then connected to the nearest point on the blackbody locus to find the corresponding black body temperature. This approach is used for instance to calculate the CCT of regular gas discharge lamps, which have a CCT lower than 10,000 K.

For daylight chromaticities that exceeded this range, a different method was applied. Hernández-Andrés et al. [37] have developed a method that does not calculate the colorimetric minimum-distance in the CIE 1960 diagram, but directly determines the daylight CCT by a polynomial equation that accurately maps CIE 1931 chromaticities *x* and *y* into CCT values. This equation is a polynomial approximation of nearly 7,000 daylight chromaticities measured in Spain and the United States. It relies on the observation that the isothermal lines for CCT's nearly converge toward a point on the chromaticity diagram: the colorimetric epicentre. Because there is no single convergence point for a broad CCT range, a best-fit epicentre (Table 3.2) was calculated for CCT's between 3,000 and 50,000 K.

$$n = \frac{(x - x_e)}{(y - y_e)} \qquad (3.3)$$

$$CCT = A_0 + A_1^{\left(\frac{-n}{t1}\right)} + A_2^{\left(\frac{-n}{t2}\right)} + A_3^{\left(\frac{-n}{t3}\right)} \qquad (3.4)$$

Where :

$n =$	Inverse line slope of the isotemperature line $[-]$
$CCT =$	Correlated color temperature $[K]$
$(x_e, y_e) =$	Best-fit colorimetric epicentre $[-]$

Table 3.2 – Best-Fit Constants for Formulae

A_0	A_1	t_1	A_2	t_2	A_3	t_3
-949.86315	6253.80338	0.92159	28.70599	0.20039	0.00004	0.07125

The resulting database with CCT's could then be analysed to construct four site-specific daylight loci for all orientations in Lyon (France). Furthermore, these loci were compared to the CIE daylight locus [43] and the site-specific locus for Granada (Spain), to assess the local differences in daylight chromaticity. Finally, a histogram that shows the frequency distribution for several bandwidths of daylight CCT's was constructed and compared to the Granada histogram.

3.3 Decision criteria

After the daylight availability (Section 3.1) and range of daylight chromaticities (Section 3.2) had been determined, the third step was to assess how these results compared with the required task illuminance and CCT. It was verified whether or not the resulting curves followed the Dynamic Lighting curves. For those days that the resulting curves diverged, it was determined for each time step what the exact deviation was. In order to do so, the resulting data first had to be presented in daily, monthly, and yearly overviews. These restructured databases were then used to draw conclusions about feasible implementation strategies for Dynamic Lighting.

3.3.1 Resulting databases

In Section 3.1 the simulation of daylight availability was discussed, but it is obvious that the data generated by DAYSIM still needed to be processed to: (1) remove all unnecessary time steps (non-working times and weekends); (2) take into account the effect of automatic blinds that block the direct sunlight; and (3) convert from 40 individual illuminance sensors to an averaged value over the sensor area (Fig. 3.3).

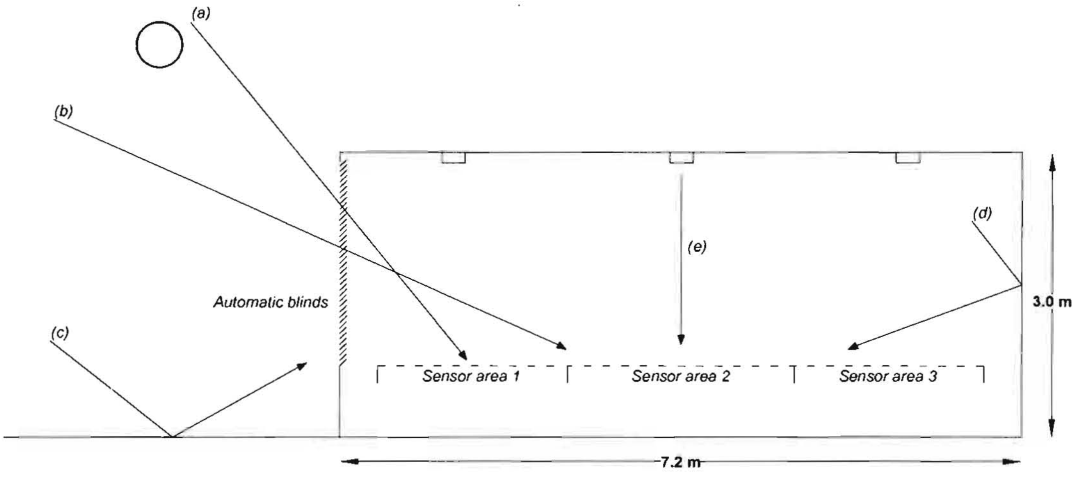


Fig. 3.3 – Sensor areas simulated in DAYSIM: (a) direct sunlight, (b) skylight, (c) ground albedo, (d) internal reflections, (e) direct component from luminaires. NB: direct sunlight is blocked for values > 50 W/m^2, component (e) was not simulated in DAYSIM

First, these restructured daylight illuminance databases for Madrid, Paris, Berlin, and Helsinki could then be easily compared to the required illuminance curves of the Dynamic Lighting system. When daylight (partly) provided the required task illuminance, the required illuminance from the lighting system could be adjusted in accordance. This resulted in four additional databases with the timestep-per-timestep required task illuminance from the luminaires. This approach is also demonstrated by a flowchart in Appendix A. Using Equation 3.1 the annual energy consumption was then determined from these databases. Second, the analysis of the daylight CCT in Lyon, which was discussed in Section 3.2, resulted in four site-specific daylight loci (North, East, South, West), and an annual frequency distribution of the daylight CCT. From this data conclusions were drawn about what range and frequency of daylight CCT's the Dynamic Lighting system should be able to mix over the course of one year.

3.3.2 Additive mixing principle

In order to make a final assessment of the Dynamic Lighting system under daylight conditions, the databases of task illuminance was combined with the range and frequency of the daylight CCT. This data was combined using the additive mixing principle for light beams [40,41]. Basically, this means that a daylight component (DC) is mixed with a luminaires component (LC) in the CIE 1931 chromaticity diagram, resulting in a mixed component (MC). For two components that have equal luminances, the MC is exactly in the middle. If one component has twice the luminance of the other component, the distance from the MC to the "strongest" component is one-third of the distance to the "weaker" one [41]. For each timestep this mixed component should ideally lie on the CCT-isotherm corresponding with the Dynamic Lighting curve.

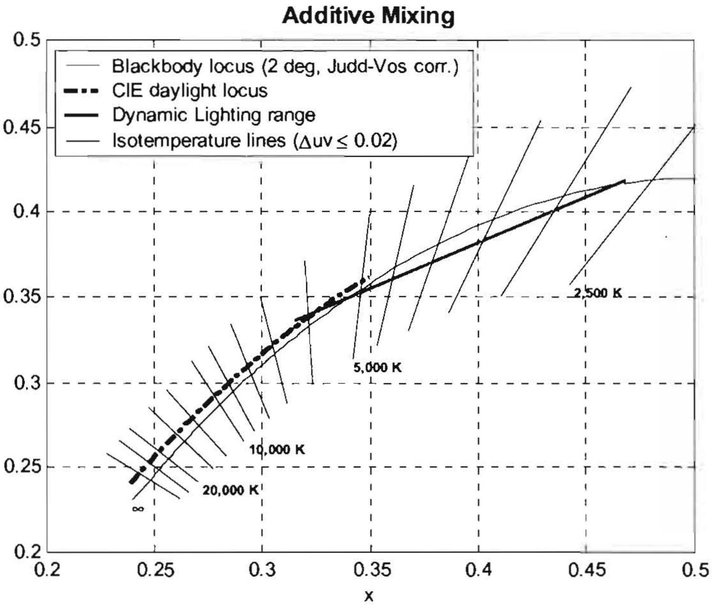


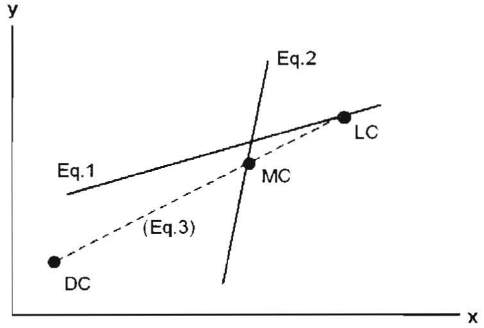
Fig. 3.4 – Mixing range of Dynamic Lighting system and the CIE daylight locus plotted in the CIE 1931 chromaticity diagram

To determine the MC of two arbitrary sources, i.e. a DC with brightness Y_{DC} and chromaticity (x_{DC},y_{DC}) and a LC with brightness Y_{LC} and chromaticity (x_{LC},y_{LC}), the simple linear procedure of Equation 3.5 can be used. This linear procedure is only valid when the two chromaticities are relatively close to each other in the CIE 1931 diagram, i.e. the distance from the blackbody locus should be no more than $\Delta uv = 0.02$. This holds true for the all the values considered here.

$$x_{MC} = \frac{Y_{DC}}{Y_{DC} + Y_{LC}} \times x_{DC} + \frac{Y_{LC}}{Y_{DC} + Y_{LC}} \times x_{LC} \tag{3.5a}$$

$$y_{MC} = \frac{Y_{DC}}{Y_{DC} + Y_{LC}} \times y_{DC} + \frac{Y_{LC}}{Y_{DC} + Y_{LC}} \times y_{LC} \tag{3.5b}$$

On the basis of the additive mixing principle, it is now possible to determine for any arbitrary combination of daylight and luminaire illuminance ($E_{daylight}$ / E_{dim}) with any arbitrary combination of chromaticity coordinates, what the resulting MC is. Analogously, it is also possible to determine for any arbitrary MC, which lies on a CCT-isotherm corresponding with the Dynamic Lighting curve, what the LC should be for any arbitrary DC. In other words, it is possible to determine what chromaticity the luminaires should provide for a realistic combination of $E_{daylight}$ / E_{dim} and corresponding values for daylight and mixed CCT. If the required luminaire chromaticity exceeds the Dynamic Lighting mixing range (Fig. 3.4), the system is not able to follow the Dynamic Lighting curve at that timestep. In order to efficiently calculate the chromaticity coordinates of the LC, the problem should first be defined as a system of linear equations.



1. Equation 1: This equation contains all the possible chromaticities that can be mixed by the Dynamic Lighting system. A line segment can be constructed from the chromaticity coordinates of the two lamps inside the luminaire (2,700 K and 6,500 K), to find the corresponding slope and y-intercept: $y = 0.542 \cdot x + 0.165$.
2. Equation 2: This equation represents the isotherm that corresponds with the CCT values of the Dynamic Lighting curve. A line segment can be constructed by connecting the blackbody temperature with a correlated colour temperature (e.g. one of the mix colours of the Dynamic Lighting system). This results in 10 different values for the slope and y-intercept: $y = a \cdot x - b$, where:

Table 3.3 – Slopes and y-intercept values

CCT [K]	a	b
3200	2.42	0.624
3400	2.57	0.662
3600	2.63	0.663
3700	2.75	0.701
4000	2.93	0.738
4400	3.00	0.729
4500	3.04	0.734
4600	3.04	0.727
4800	2.61	0.560
4900	2.32	0.453

3. Equation 3: The additive mixing line. This equation joins the chromaticity coordinates of the DC and LC so that the MC is on the line segment represented by Equation 2: $y = a \cdot x + b$, where *a* and *b* are unknown.

After these three equations are defined, the system can be solved with the Matlab Symbolic Math Toolbox. First, it should be noted that one point on Equation 3 is known: the x and y chromaticity coordinates of DC. Second, also the proportion of the distance DC–MC to MC–LC is known, since this is equal to the proportion of the horizontal illuminance by daylight to horizontal illuminance by luminaires. Following Pythagoras' theorem, this relationship can also be described as:

$$v = \frac{x_{LC} - x_{MC}}{x_{MC} - x_{DC}} \rightarrow x_{LC} = v \cdot (x_{MC} - x_{DC}) + x_{MC} \qquad (3.6)$$

Where:

$$v = \frac{E_{dim}}{E_{daylight}} = \text{constant}$$

$$x_{DC} = \text{constant}$$

To find x_{LC}, this system of equations should be defined as symbolic variables and solved with the Matlab Symbolic Math Toolbox. This will result in a solution for the x-coordinate of LC, which should not exceed $x = 0.469$. This is the chromaticity coordinate corresponding with a CCT of 2,700 K, which is the lowest possible CCT the Dynamic Lighting system can produce. This means that if for any combination of DC with $E_{daylight}$ / E_{dim} the LC has a chromaticity that exceeds $x = 0.469$, the system is not able to mix the required CCT and consequently the CCT-curve is distorted.

3.3.3 Final assessment

Based on the above, it was possible to make a final assessment of the two criteria that form the main focus of this report:

1. What are the annual energy savings of the lighting system?
2. On which days is the system capable of mixing the required CCT-curve?

These two questions were addressed for both the daylight responsive control strategy and the time switching strategy (Fig. 1.1). From this assessment, it followed for which location, orientation, zones, and time periods it is feasible to install Dynamic Lighting with either one of these two strategies. The results are presented in the next Chapter, and discussed in Chapter 5.

4 Results

Following the methodology explained in Chapter 3, this Chapter presents a detailed overview of the results of the study. In general, the annual energy savings and colour mixing properties are presented for all the variants that are defined in Section 3.1.2. The results are divided into the two main strategies:

1. Daylight responsive control: the artificial lighting is dimmed in response to daylight
2. Time switching: the artificial lighting is switched on and follows the Dynamic Lighting curve, or the Dynamic Lighting curve is switched "off " and the lighting system only provides a regular task illuminance of 500 lx

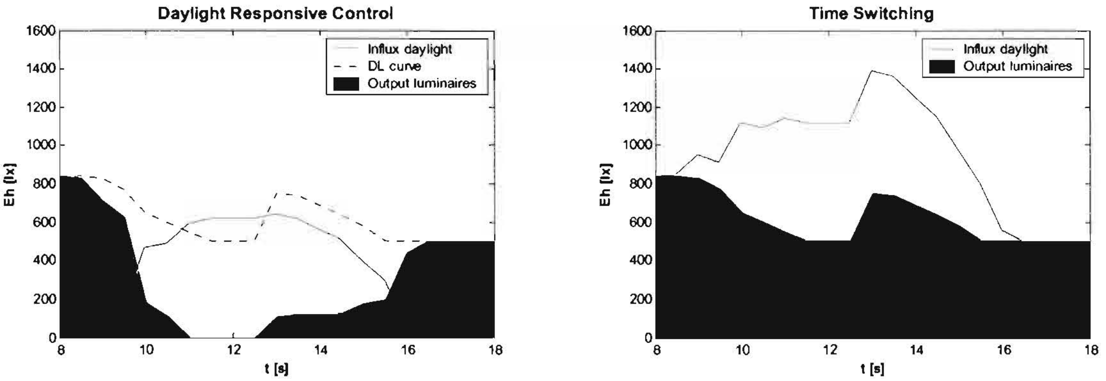


Fig. 4.1 – Energy saving strategies, simulation data plotted for: Paris, 21 Dec 2000 (North oriented façade, largest window size, back of room)

As can be seen from the two curves plotted in Fig. 4.1, daylight responsive control follows the Dynamic Lighting illuminance curve quite well, whereas with time switching the Dynamic Lighting curve is distorted much more by daylight. The purpose of this Chapter is to extend this observation over 260 workdays for all variants, and to assess the monthly and annual performance of both energy saving measures for four different locations in Europe (Table 4.1).

Table 4.1 – Comparison of site characteristics

	Madrid	Paris	Berlin	Helsinki
Latitude:	40° 45' N	48° 73' N	52° 47' N	60° 32' N
Longitude:	3° 55' W	2° 40' E	13° 40' E	24° 97' E
Elevation:	582 m	96 m	49 m	56 m

4.1 Annual energy savings

4.1.1 Daylight responsive control

This first energy saving strategy comprises a light sensor in a closed loop system with automatic blinds, in other words: it measures the resulting average task illuminance on an area of the work plane and adjusts the light output of the luminaires in response to this measurement (Fig. 4.2). Summing the resulting energy use during each time interval (Eq. 3.1), and comparing it to the annual energy use of a Dynamic Lighting system without dimming, determines the annual energy savings (Eq. 3.2).

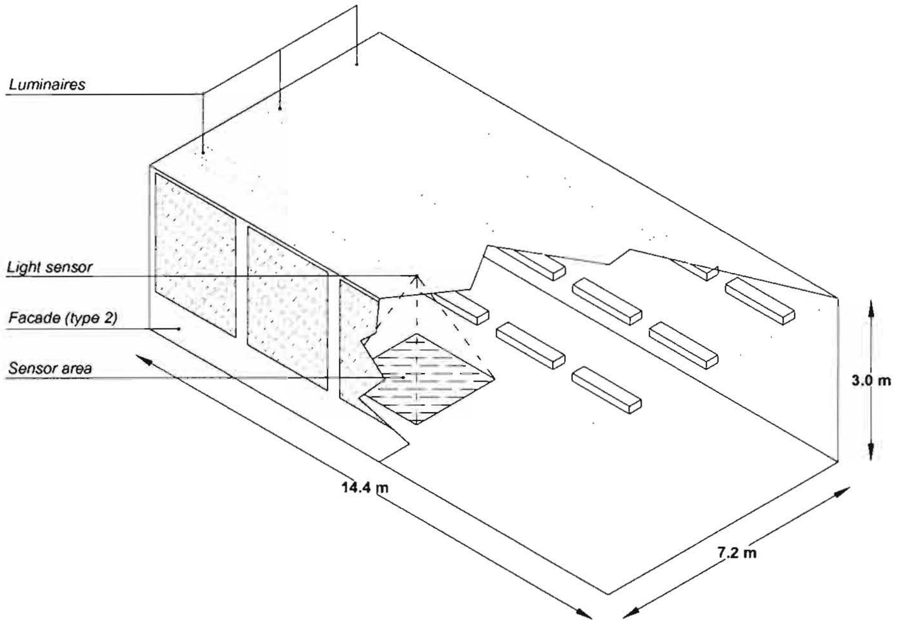


Fig. 4.2 – Calculation of average illumination of the control area of a light sensor: Façades and orientation are varied

It follows from the initial results that the annual energy savings are hardly orientation-dependent, which is due to the automatic blinds that block out any direct sunlight that hits the work plane. If direct sunlight is not taken into account, the internal daylight illuminance is determined for all orientations by the sky luminance. The sky luminance at any point in time is directly related to the sky conditions, and this causes much smaller internal orientation-related differences than does direct sunlight.

Table 4.2 – Annual energy saving with daylight responsive control

Façade:	Zone:	DF:	Location:			
			Madrid	Paris	Berlin	Helsinki
1	1	21.6	71%	68 %	67 %	62 %
	2	8.1	67%	63 %	60 %	55 %
	3	3.9	58 %	54 %	50 %	46 %
2	1	16.1	71 %	68 %	66 %	62 %
	2	6.6	64 %	61 %	58 %	56 %
	3	3.2	53 %	49 %	46 %	47 %
3	1	13.6	70 %	67 %	65 %	60 %
	2	5.0	60 %	57 %	53 %	49 %
	3	2.4	46 %	43 %	38 %	35 %
4	1	3.3	63%	61 %	57 %	53 %
	2	2.5	39 %	39 %	34 %	31 %
	3	1.1	21 %	21 %	18 %	17 %
5	1	3.1	62 %	60 %	55 %	51 %
	2	1.2	20 %	19 %	17 %	15 %
	3	0.5	9 %	8 %	7 %	6 %

As can be seen from Table 4.2, energy savings by daylight responsive control are directly related to the annual sky conditions: for Southern countries with a high frequency of clear skies, the amount of (indirect) daylight is higher than for Northern countries with a high frequency of overcast skies. If the energy savings are related to the distance to the window, it follows that the there is a sharp reduction in daylight availability and therefore in energy savings. The daylight factor (DF) might be used to make a rough estimate of the potential energy savings for an arbitrary design, although the correlation between DF and energy savings is not 100% accurate. This is due to the façade design, which is different for each variant, and this might cause that a sensor area is illuminated by a different part of the sky for a different façade design. This has of course also a direct impact on the energy savings.

4.1.2 Time switching

This second energy saving strategy comprises a much simpler technical solution than daylight responsive control: it provides a constant task illuminance of 500 lx, but for certain time periods it switches on the Dynamic Lighting curve on top of it. To decide for which time periods it is feasible to provide the extra task illumination, the average daily "distortion" by daylight was assessed over the course of one year for four different locations.

Table 4.3 – Annual energy savings (SAV) and percentage of days the system is on (SYS) with time switching

Façade:	**Zone:**	**Threshold value for daylight: ▲▲**							
		Madrid		**Paris**		**Berlin**		**Helsinki**	
		SAV	**SYS**	**SAV**	**SYS**	**SAV**	**SYS**	**SAV**	**SYS**
1	1	13%	12%	12%	23%	10%	32%	9%	37%
	2	2%	82%	4%	70%	2%	83%	2%	81%
	3	0%	100%	0%	100%	0%	100%	0%	100%
2	1	9%	21%	8%	29%	8%	36%	7%	37%
	2	1%	93%	1%	90%	1%	94%	3%	78%
	3	0%	100%	0%	100%	0%	100%	2%	82%
3	1	7%	40%	7%	38%	6%	48%	6%	51%
	2	0%	100%	0%	100%	0%	100%	0%	100%
	3	0%	100%	0%	100%	0%	100%	0%	100%
4	1	1%	88%	3%	78%	1%	90%	1%	91%
	2	0%	100%	0%	100%	0%	100%	0%	100%
	3	0%	100%	0%	100%	0%	100%	0%	100%
5	1	1%	91%	2%	86%	1%	94%	1%	96%
	2	0%	100%	0%	100%	0%	100%	0%	100%
	3	0%	100%	0%	100%	0%	100%	0%	100%

In Table 4.3 the results are presented for a threshold value of 250%, which means that the system is considered to be "off" when the average daylight contribution is more than 2,5 times the average artificial lighting. Of course, the energy savings tabulated here present an idealised situation: in reality, the savings will be lower, because with time switching the lighting system is switched on and off according to a pre-set algorithm. This also means that the amount of daylight that enters the office is not known, and the system cannot be dimmed less than 500 lx. Daylight responsive control is capable of real-time measuring the task illuminance and steers the light output of the luminaires in accordance: this results in much higher energy savings.

Table 4.4 – Annual energy savings (SAV) and percentage of days the system on (SYS) with time switching

Façade:	Zone:	Threshold value for daylight: ▼▼							
		Madrid		Paris		Berlin		Helsinki	
		SAV	SYS	SAV	SYS	SAV	SYS	SAV	SYS
1	1	15%	0%	15%	0%	15%	0%	14%	7%
	2	12%	0%	11%	4%	11%	11%	9%	23%
	3	12%	3%	10%	18%	9%	25%	8%	32%
2	1	12%	0%	12%	0%	12%	0%	11%	7%
	2	12%	0%	11%	8%	10%	15%	10%	20%
	3	11%	9%	9%	25%	8%	31%	9%	27%
3	1	12%	0%	12%	0%	12%	0%	10%	15%
	2	12%	0%	10%	15%	9%	21%	8%	30%
	3	9%	25%	8%	36%	7%	45%	6%	47%
4	1	12%	0%	11%	5%	10%	16%	9%	28%
	2	7%	43%	7%	43%	6%	52%	5%	54%
	3	0%	98%	0%	97%	0%	99%	0%	99%
5	1	12%	0%	11%	8%	10%	19%	8%	30%
	2	0%	98%	0%	99%	0%	100%	0%	100%
	3	0%	100%	0%	100%	0%	100%	0%	100%

In Table 4.4 the annual energy savings are determined for a threshold value of 50%, which means the lighting system is considered to be off when the average daylight contribution is more than half of the average artificial lighting. This is a much stricter threshold than used in the former approach, and this means the lighting system will be switched "off" for a much larger period of time. Consequently, the energy savings will be higher since these are directly related to the light output of the system over time.

4.1.3 Implementation ranges

From the data presented above, it can be concluded that for some time periods the Dynamic Lighting system cannot be used. This is for different reasons: (1) for daylight responsive control, when the system is completely dimmed down during the whole workday; (2) for time switching, when curve cannot be added to the regular task illuminance of 500 lx for a workday, because the incoming daylight exceeds the threshold value of 50% or 250%.

As can be seen from Table 4.5 the daylight responsive control can be switched on for the largest part of the year. It follows that the first zone directly behind the window is a difficult area to apply Dynamic Lighting with daylight responsive control, because it will be switched off for a large part of the year except for the winter months. This finding is not influenced very much by the location: there is a difference of one or two months, depending on the distance between the two locations that are compared.

For Dynamic Lighting with time switching the threshold value is very important in assessing in which months the system only provides 500 lx, i.e. the Dynamic Lighting curve is not added to the regular task lighting. When the day average threshold value is set to 250% daylight to artificial lighting, the results for time switching are comparable to the results obtained for daylight responsive control (Table 4.6). The main differences are that: (1) not only the first zones directly behind the window for façades 1-3 are influenced, but for façades 1-5; (2) the second zone of the largest façade is also a problem area; (3) the periods for the first three façades are 2-3 months longer. In contrast, when the threshold is set to 50%, the system is switched off 50%–100% all year for all façades and zones, except for zones 2 and 3 of façades 4 and 5.

Table 4.5 – Months that Dynamic Lighting is switched off (> 50% of the time)

	Location	Façade	Zone	Start	End
Daylight Responsive Control	Madrid	1	1	Mar	Sep
		2	1	Apr	Sep
		3	1	Apr	Sep
	Paris	1	1	Apr	Sep
		2	1	Apr	Sep
		3	1	Apr	Aug
	Berlin	1	1	May	Aug
		2	1	May	Aug
		3	1	May	Aug
	Helsinki	1	1	Apr	Aug
		2	1	Apr	Aug
		3	1	Apr	Aug

Table 4.6 – Months that Dynamic Lighting is switched off (> 50% of the time)

	Location	Façade	Zone	Start	End
Time Switching – Threshold = 250%	Madrid	1	1	Feb	Oct
		1	2	Apr	Jul
		2	1	Feb	Oct
		3	1	Mar	Oct
		4	1	May	Jul
		5	1	Jun	-
	Paris	1	1	Feb	Oct
		1	2	Apr	Jul
		2	1	Feb	Oct
		3	1	Mar	Oct
		4	1	May	Jul
		5	1	Jun	-
	Berlin	1	1	Feb	Oct
		1	2	Apr	Jul
		2	1	Feb	Oct
		3	1	Mar	Oct
		4	1	May	Jul
		5	1	Jun	-
	Helsinki	1	1	Feb	Oct
		1	2	Apr	Jul
		2	1	Feb	Oct
		3	1	Mar	Oct
		4	1	May	Jul
		5	1	Jun	-

4.2 Colour mixing properties

4.2.1 Site-specific differences

Since it is very difficult to predict the exact daylight CCT at an arbitrary point in time for an arbitrary location, the daylight CCT is dealt with by the range and frequency that might be expected in Europe. To make a realistic estimate, one-year chromaticity measurements were analysed and compared to similar data derived from literature [42].

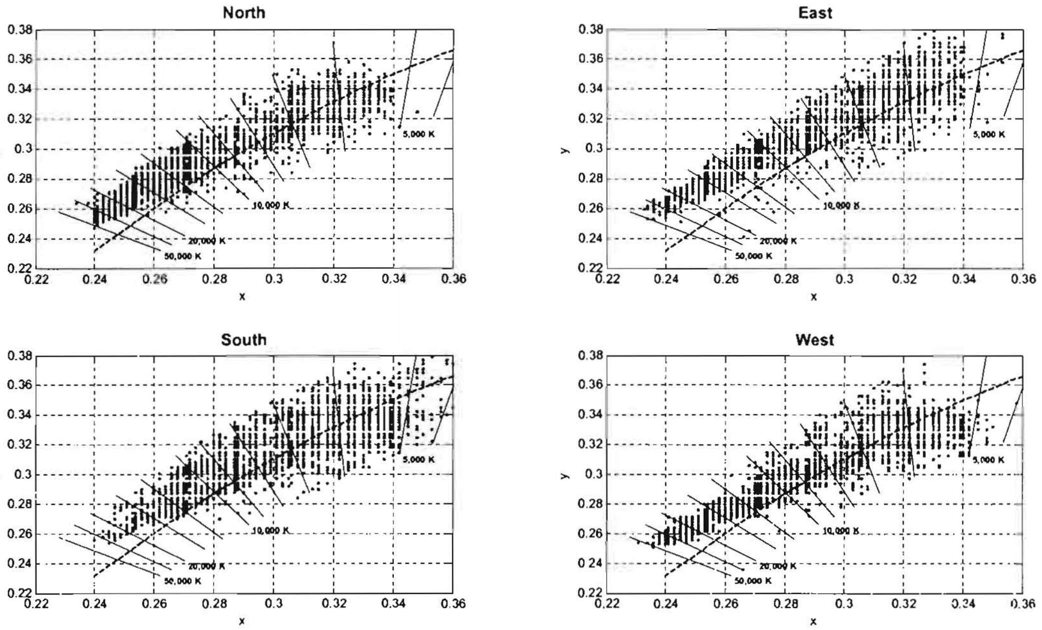


Fig. 4.3 – Range of daylight chromaticities measured in Lyon, France

As can be seen from Fig. 4.3, the distribution of daylight chromaticity coordinates across the CIE 1931 diagram varies for each orientation. When these results are compared to the CIE daylight locus [43], a line that follows the blackbody locus but is slightly above it, it should be noted that the measurements in Lyon show a much wider chromaticity distribution. Furthermore, when compared to the CIE daylight locus, the chromaticity of high CCT's tends to be more toward to blue-green part of the spectrum. This is in accordance with the measurements taken in Granada, which also display a shift "toward the greens" for CCT's > 9,000 K [42]. On the other hand, the measurements from Lyon display a stronger shift toward red chromaticities for CCT's < 6,500 K in comparison with the Granada data (Fig. 4.3). In fact, the Lyon locus is actually below the blackbody locus, whereas the Granada locus is above or on the blackbody locus.

Table 4.7 – Comparison of site characteristics

	Lyon	Granada
Latitude:	45° 47' N	37° 11' N
Longitude:	4° 56' E	3° 37' W
Height above sea level:	170 m	680 m
Number of measurements:	13,904	2,600
Start of measurements:	Dec 1999	Feb 1996
End of measurements:	Dec 2000	Feb 1998

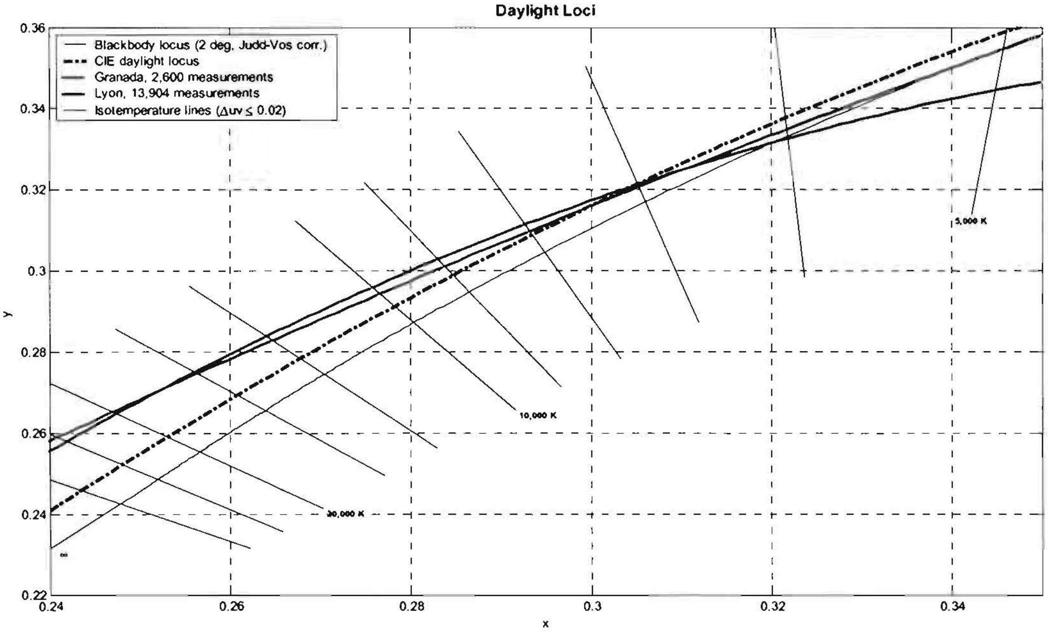


Fig. 4.4 – Blackbody locus and three daylight loci: Lyon, Granada, and CIE

Based on these observations, it is clear that the chromaticity of daylight varies per measurement site, and to determine the exact daylight CCT for any location, orientation, and time period requires real-time measurements. The daylight CCT is site-specific and strongly time-bound, and this makes it very hard to make a timestep-per-timestep prediction of the daylight CCT to compare with the Dynamic Lighting curve.

4.2.2 Range and frequency

Due to the unpredictable nature of daylight CCT, it was analysed more generally by dividing the daylight CCT in ranges and calculate the number of CCT's in range. The ranges were defined in line with the ranges published in [42], and are presented in Table 4.8.

Table 4.8 – Comparison of measurement ranges

CCT Range [K]	Lyon	Granada
3,000 – 5,000	0.8 %	0.6 %
5,000 – 9,000	69.3 %	53.2 %
9,000 – 17,000	23.4 %	37.6 %
> 17,000	7.3 %	8.6 %

As can be seen from Table 4.8, more than 90% of the measurements for both locations were in the range of 5,000 to 17,000 K. The Granada-site had a higher frequency of CCT's in the range from 9,000 to 17,000 K, which is most likely due to the differences in height and annual sky conditions. The Granada measurements were taken at a site that was 510 meters higher than the Lyon measurements, and the average frequency of clear skies was also much higher in Granada. This probably accounts for the higher frequency of 'bluish' daylight CCT's in Granada.

4.2.3 Colour mixing results

As explained in Chapter 3, to assess the colour mixing properties of the Dynamic Lighting system, it was tested for what range of daylight CCT's the system was capable of providing the required CCT to let the resulting CCT follow the Dynamic Lighting curve. For each timestep the highest possible daylight CCT was calculated, and from this data monthly datasets were constructed. From these monthly datasets the frequency of each CCT was calculated, and then it was assessed which daylight CCT is possible for 75% and 50% of the time. A percentage of 100% was not considered: due to several fast peaks in the daylight availability that cannot be mixed, the system will never be able to correctly mix all incoming daylight. Therefore, it was studied what CCT-range the system could maintain over a relatively long period of time.

The following ranges were used (in line with Table 4.8):

▪ 3,000 – 5,000 K:	Bad daylight colour mixing properties
▪ 5,000 – 9,000 K:	Average daylight colour mixing properties
▪ 9,000 – 13,000 K:	Good daylight colour mixing properties
▪ 13,000 – 17,000 K:	Excellent daylight colour mixing properties

Table 4.9 – Number of months that Dynamic Lighting can mix required CCT (> 75% of the time)

Colour mixing properties – Daylight responsive control																
Façade:		**1**			**2**			**3**			**4**			**5**		
Zone:		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Madrid	Bad	12	12	12	12	12	12	12	12	12	12	12	8	6	6	-
	Average	-	-	-	-	-	-	-	-	-	-	-	1	2	2	-
	Good	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-
	Excellent	-	-	-	-	-	-	-	-	-	-	-	3	3	3	12
Paris	Bad	12	12	12	12	12	10	12	12	9	12	9	6	5	5	-
	Average	-	-	-	-	-	2	-	-	1	-	-	1	1	1	-
	Good	-	-	-	-	-	-	-	-	-	-	1	-	1	1	-
	Excellent	-	-	-	-	-	-	-	-	2	-	2	5	5	5	12
Berlin	Bad	12	12	10	12	11	9	12	11	8	11	7	5	3	3	-
	Average	-	-	1	-	1	1	-	-	1	1	1	1	2	2	-
	Good	-	-	-	-	-	1	-	-	-	-	1	-	-	-	-
	Excellent	-	-	1	-	-	1	-	1	3	-	3	6	7	7	12
Helsinki	Bad	12	10	9	12	12	12	11	9	8	9	7	5	4	4	-
	Average	-	1	-	-	-	-	-	-	1	1	1	-	1	1	-
	Good	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Excellent	-	1	3	-	-	-	1	3	3	2	4	7	7	7	12

Table 4.9 compares the colour mixing properties obtained using Dynamic Lighting with daylight responsive control. It is apparent from this table that the annual daylight availability directly influences the quality of the colour mixing properties of the lighting system. When the annual daylight availability is lower, as is the case in the Northern cities, it becomes easier to mix daylight and artificial light due to the lower daylight component. For a lower daylight component the lighting system is fully dimmed less often, and is therefore more often capable of mixing the CCT required for maintaining the Dynamic Lighting curve. Of course it is also easier to mix a "weaker" daylight component, e.g. to mix daylight of 500 lx instead of 1,000 lx (Section 3.3.2).

Table 4.10 – Number of months that Dynamic Lighting can mix required CCT (> 75% of the time)

	Colour mixing properties – Time switching															
	Façade:	**1**			**2**			**3**			**4**			**5**		
	Zone:	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Madrid	Bad															
	Average															
	Good															
	Excellent															
Paris	Bad	12	12	9	12	10	9	12	10	7	11	7	-	-	-	-
	Average	-	-	1	-	2	1	-	-	2	1	1	5	3	3	-
	Good	-	-	-	-	-	-	-	2	-	-	1	-	2	2	-
	Excellent	-	-	2	-	-	2	-	-	3	-	3	7	7	7	12
Berlin	Bad															
	Average															
	Good															
	Excellent															
Helsinki	Bad															
	Average															
	Good															
	Excellent															

The data presented in Table 4.10 show the colour mixing properties for Dynamic Lighting with a time switching strategy. Comparing these results with Table 4.9, it can be seen that the colour mixing properties with time switching surpass the colour mixing properties with daylight responsive control. This difference is probably caused by the fact that with time switching the lighting system is never fully switched off, but always provides a minimum task illuminance of 500 lx. Hence, for moments when daylight responsive control partly of fully dims the Dynamic Lighting system, time switching will either provide the full Dynamic Lighting curve or 500 lx task illuminance. As explained in Section 3.3.2, this will make it easier to mix the "correct" resulting CCT. Additionally, Appendix C has the same data tabulated, but in these tables the threshold was reduced to 50%. For example, when in one month it is possible to mix a CCT of 13,000 K for > 50% but not for > 75% of the timesteps, it would be classified as "average" in the tables above, but as "good" in the tables of Appendix C.

4.3 Implementation strategies

4.3.1 Daylight responsive control

Saving energy with Dynamic Lighting systems by installing daylight responsive control is certainly feasible for the second and third zone behind the window (Fig. 4.2) during the whole year and for all locations and window sizes. In the first zone behind the window it is only feasible to apply this energy saving measure from (roughly) October to March for façades 1-3; for the other months the system is dimmed completely for 50%–100% of the time. On the other hand, for façades 4 and 5 it is feasible to use daylight responsive control in the first zone during the whole year.

If daylight responsive control is installed, the resulting energy savings are presented in Table 4.2. These savings are not viable for the first zone of façades 1-3, and a different lighting concept should be applied here, for instance a regular 500 lx lighting solution. This is because the Dynamic Lighting system is switched off for the largest part of year (6 to 7 months) and during this period the indoor illuminance curve follows the outdoor sky luminance. Therefore, during this time period the illuminance curve cannot be "corrected' by the lighting system, and there is no motive to use Dynamic Lighting in stead of regular lighting.

The colour mixing properties related to this first strategy should be considered bad. It is very difficult to maintain the Dynamic Lighting curve for colour temperature for more than a couple of months per year. Even in the zones in the back of the office, it is only possible to follow the CCT curve with very small windows sizes, i.e. for very low annual daylight availabilities.

4.3.2 Time switching

As an alternative to daylight responsive control, time switching could be applied with Dynamic Lighting in daylit offices. This is a much less sophisticated method of saving energy, and involves no sensors to steer the luminaires output. In stead it provides a regular 500 lx task illuminance during the whole day, except for those months in which Dynamic Lighting is considered to be feasible. For those months the Dynamic Lighting curve is provided on top of the regular task lighting. This has of course two mayor drawbacks: (1) since daylight is added to the Dynamic Lighting curve, the curve is always distorted by daylight; (2) energy savings resulting from this method are very low, since the only saving potential is the Dynamic Lighting curve minus 500 lx at moments when the system provides a constant 500 lx. On the other hand, the mayor advantage of this method is that it only requires a minor adaptation of the "normal" Dynamic Lighting system: the curve is switched to a constant 500 lx instead of alternating between 500 and 900 lx.

From Table 4.6 it can be seen that a threshold value of 250% is exceeded from (roughly) February to October in the first zone directly behind the window for façades 1-3. For façades 4 and 5 the problem is also concentrated in zone 1, but only around June. For zones 2 and 3 the threshold is hardly ever exceeded. It should therefore be considered feasible to apply Dynamic Lighting on these locations during the whole year.

The colour mixing properties related to the second strategy are only slightly better than the colour mixing properties of the first strategy. Only with façade 5 (very small window size) it is possible to mix the "right" CCT for the largest part of the year for all zones. So, also with this energy saving strategy the colour mixing properties should be considered bad.

5 Discussion

The mayor finding of this study is that it was possible to maintain an illuminance pattern during the workday with algorithmic lighting systems, such as Dynamic Lighting, in offices that are also (partly) illuminated by daylight. However, it was not possible to simultaneously maintain a pattern of correlated colour temperature by mixing daylight with the artificial light. Another important finding was that the orientation of the offices did not have a significant impact on the energy savings or colour mixing properties. Finally, it has also been demonstrated that the colour mixing results for time switching are only slightly better than the results for daylight responsive control.

First, it should be noted that the location has a very straightforward impact on these findings: the further to the north, the lower the daylight availability, resulting in lower energy savings and better colour mixing properties. The location has no impact on the feasibility of applying Dynamic Lighting in the first zone behind the window: the illuminance levels are too high, regardless of the location.

Second, the energy savings, colour mixing properties, and time periods the system is fully dimmed (strategy 1) or switched to 500 lx (strategy 2), are all correlated to the daylight availability. For that reason the results are also correlated to the daylight factor (DF), which might be used as a design parameter. It is however not possible to determine this value exactly, since the correlation between DF and energy savings is not 100% accurate. This is due to the façade design, which is different for each variant, and this might cause the sensor area to be illuminated by a different part of the sky for a different façade design. This has of course a direct impact on the resulting energy savings and other dependent variables. The DF can therefore only be used to make a (very) rough estimate of these parameters for a different design. In this report the relationship between DF and energy savings is not explicitly presented, but might be derived from the tables in the results Section.

Third, the second strategy, time switching with Dynamic Lighting systems, was evaluated with a threshold value of 2,5 times the daylight illuminance to artificial illuminance. This value was chosen based on a very rough estimate of what amount of daylight could be added to the Dynamic Lighting curve to still induce a (small) biological effect on office workers. Whereas for a threshold of 250% it is possible to use time switching with Dynamic Lighting, it can be seen from the results that for a threshold of 50%, it is not possible to use Dynamic Lighting. Further research is therefore needed to determine the exact threshold value. The corresponding results for thresholds of 100%, 150%, and 200% can be found in the appendices of this report.

Finally, it should be noted that the present study was designed to determine the feasibility of using a Dynamic Lighting system in an open plan office with a certain selection of window sizes, clear glazing, and for four different locations. This office design represents a very common application area for Dynamic Lighting systems. However, for office designs that are very different from the design used in this report, the results might also diverge from the figures presented here.

6 Conclusions and recommendations

This report has given a detailed account of two energy saving strategies for Dynamic Lighting systems in open plan, daylit offices: daylight responsive control and time switching. Returning to the main issue put forward at the beginning of this study, it is now possible to state that, with simple or more sophisticated technical measures, it is certainly feasible to use Dynamic Lighting under daylight conditions.

First, it was found that with daylight responsive control the Dynamic Lighting illuminance curve could be maintained very well in the second and third zone behind the window over a long period of time. Energy savings up to 67% are achievable in these zones. However, in the first zone behind the window it was found to be much more difficult to maintain the illuminance curve. This is because the system is dimmed completely over long periods of time, resulting in an illuminance curve that follows the colour and luminance of the sky. It is therefore better to use a different lighting concept for this zone, for instance a regular 500 lx lighting solution. The colour mixing properties should, however, be considered bad: it is not possible to maintain the correlated colour temperature curve by mixing daylight with the artificial light. This curve is disrupted too much by daylight to maintain over long periods of time.

Second, the results of this study indicate that with time switching, comprising a much simpler modification of the original lighting system, it is also possible to use Dynamic Lighting in daylit offices. This method does not use real-time measurements but uses a pre-set condition for each month: the lighting system either provides the Dynamic Lighting curve for the whole month, or it provides a constant output of 500 lx. This resulted in far lower annual energy savings (up to 12%) for the second and third zone behind the window. Similarly to the first strategy, it is also better to use a regular lighting solution for the zone directly behind the window since this the Dynamic Lighting curve cannot be realised for the larger part of the year. Also, even though the colour mixing properties of this approach are slightly better than of the former, it is not possible to maintain the required CCT curve.

In general, therefore, it can be concluded that Dynamic Lighting can be successfully implemented in daylit offices bearing in mind that: (1) it cannot be used in zones directly behind the window, and (2) the correlated colour temperature cannot be controlled. With a simple modification of the original system, i.e. time switching, it is possible to achieve small energy savings (up to 12%). A drawback of this method is that the illuminance curve is always distorted by daylight. With a more complex modification of the original system, i.e. daylight responsive control, it is possible to achieve large energy savings (up to 67%), while maintaining the illuminance curve very accurately.

This report has thrown up several questions in need of further investigation. Primarily, it would be interesting to know more about how to control the lighting system in response to daylight using a time switching strategy, and how to enhance the colour mixing properties of the Dynamic Lighting system. Future research might therefore explore:

- Threshold aspects of the time switching strategy. Further research in the field of direct biological effects of lighting might result in accurate threshold values for the combination of daylight to artificial light. In particular the effect of changes in illuminance at higher lighting levels should be investigated, to see if a raise from 500 lx to 900 lx, results in a comparable biological effect as a raise, for example, from 2000 lx to 2400 lx. Such information would help greatly to define the exact threshold values for the time switching strategy.

- User behaviour. In assessing the annual energy savings, the user behaviour could also be taken into account. When people go for lunch, leave for meetings, etc. it is not necessary to provide task lighting and additional energy savings are possible. This report is therefore a "worst case scenario", because it assumes the office worker to be in the office during the whole workday.

- Glass properties. It would be interesting to assess the effects of coated or coloured glazing on the correlated colour temperature of daylight entering an office. If the glass properties reduce the transmission and colour temperature of daylight entering the office, this will have a positive effect on both the energy savings and colour mixing properties. Again, using clear glazing, this report represents a "worst case".

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Appendix A: Flowcharts

Chart A1:

To calculate the dimmed value of the luminaires (E_{dim}) when daylight provides all or part of the required task illuminance, the following procedure is used in Matlab:

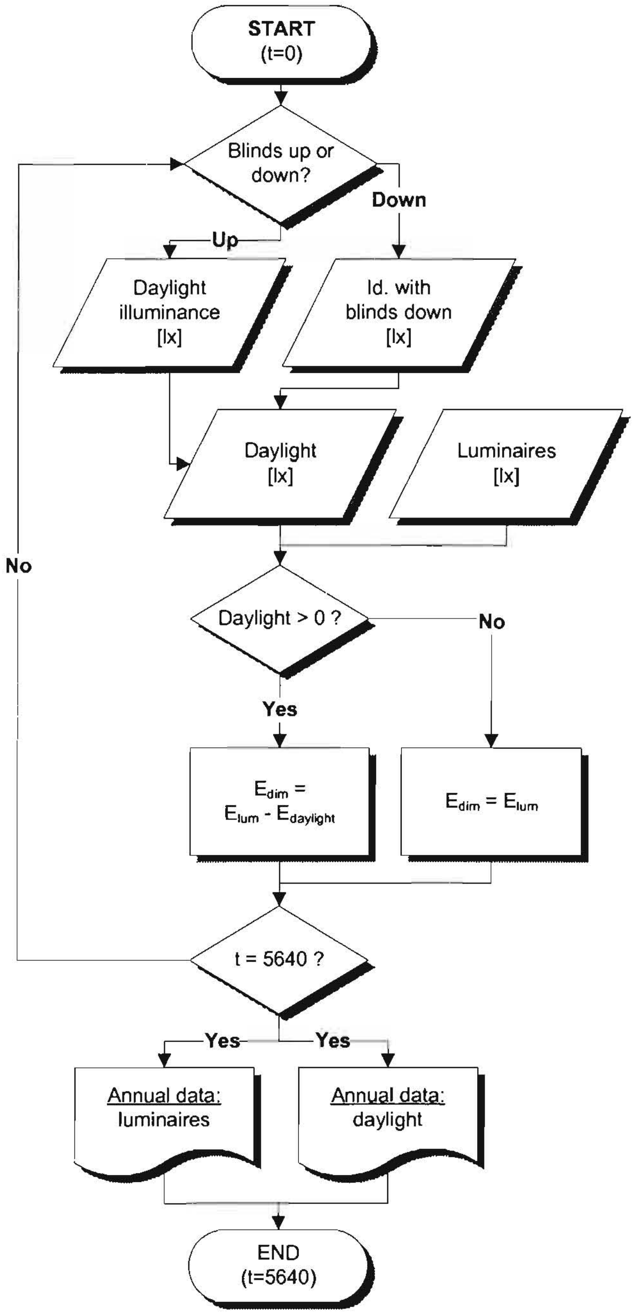
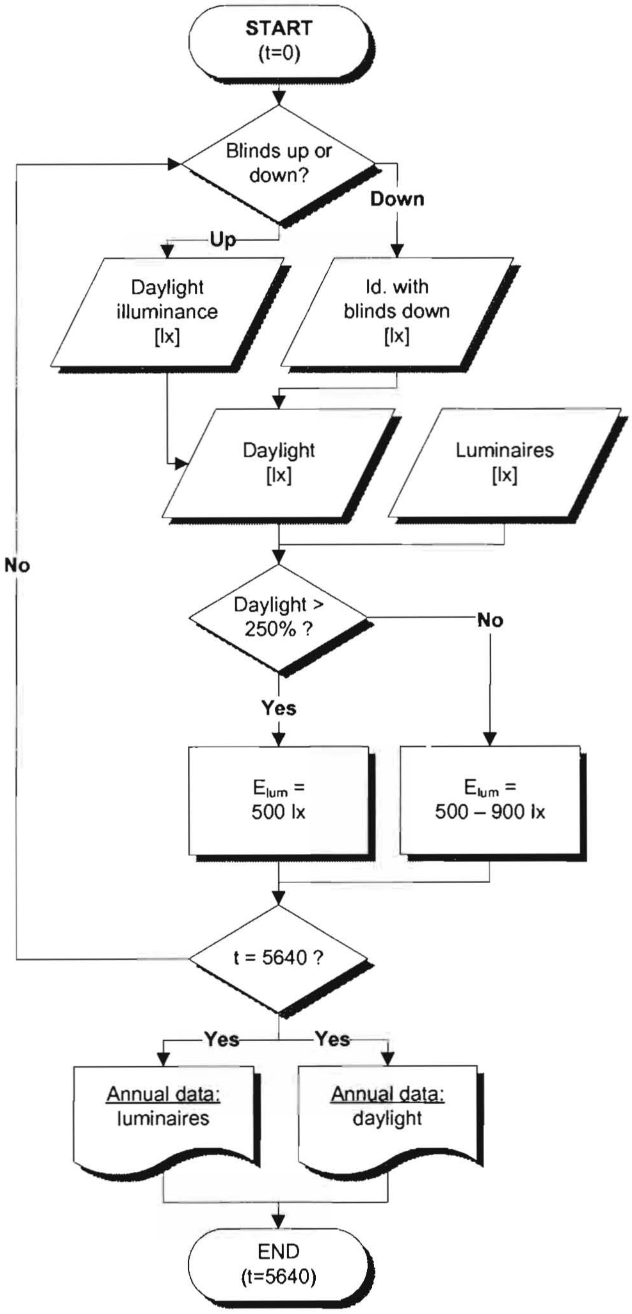


Chart A2:

To calculate the output of the luminaires (E_{dim}) with the time switching strategy, the following procedure is used in Matlab:



Appendix B: Matlab scripts

This appendix contains the most important Matlab scripts used to calculate the data, which is tabulated in this report. The nine scripts represent the following calculations:

- Script B1: this script is used to calculate whether or not it is possible to mix daylight with artificial light, while maintaining the desired CCT value.
- Script B2: calculates the correlated colour temperature from its chromaticity coordinates for any chromaticity in the CIE 1931 diagram.
- Script B3: determines the annual energy use and energy savings for Dynamic Lighting with daylight responsive control.
- Script B4: calculates for each month the percentage of time the Dynamic Lighting system cannot mix the required CCT.
- Script B5: determines the chromaticity coordinates for one day (in Lyon, France).
- Script B6: cleans up the measurement data for one day.
- Script B7: saves the annual CCT data for Lyon.
- Script B8: calculates the chromaticity from spectral data, with or without taking into account the spectral filtering by glass.
- Script B9: calculates the spectral data from chromaticity coordinates.

Script B1:

```
function [res] = mix(coltem1,coltem2,vi)

% Usage:    Determines whether or not it is possible to mix
%           the required CCT for a given combination of daylight
%           and artificial light.
%
% Input:    [coltem1] = Dynamic Lighting curve [K]
%           [coltem2] = testvalue for daylight [K]
%           [v]       = Eh_daylight / Eh_luminaires [-]
%
% Output:   [res] = system can (=1) or cannot (=0) mix required CCT [-]
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

% Structure data
load mixdata.mat;
n = length(vi);
k = find(coltem2 == xD(:,1));

% Calculation
for i = 1:n
    a = ref(find(ref(:,1) == coltem1(i,1)),2);
    b = ref(find(ref(:,1) == coltem1(i,1)),3);
    v = vi(i);
    var = double(subs(daylight(k)));
    xL3_num(i,1) = v*(var-xD(k,2))+var;
end

% Output
res = zeros(n,1);
res(find(xL3_num <= 0.469),1) = 1;
```

Script B2:

```
function [CCT] = coltem(x,y)

% Usage:    This function calculates the Correlated Colour
%           Temperature (CCT) from CIE 1931 chromaticities.
%
% Input:    [x] = chromaticity x-coordinate [-]
%           [y] = chromaticity y-coordinate [-]
%
% Output:   [CCT] = correlated colour temperature [K]
%
% By M.H.J.Schriek and Prof. M.H. de Wit (2007)
% Eindhoven University of Technology
% The Netherlands

% Variables
p =      [6.157712e-4,    -5.688566e-3,    1.818095e-2,     -2.522991e-2,
          7.307788e-3,     4.000925e-2];
rd =     [7.686733e-5,    -2.425969e-4,    -4.285969e-4,    -2.648359e-3,
          1.006160e-2,     1.158546e-2];
pu =     [0, 0, 0,        -3*1.0474e-2,    2*4.7305e-2,     1.8745e-2];
pv =     [0, 0, 0,        3*9.7756e-3,     -2*6.5701e-2,    1.4980e-1];
rdu =    [0, 0, 0,        -3*2.2174e-5,    2*9.7688e-3,     6.9830e-3];
rdv =    [0, 0, 0,        -3*5.0618e-3,    2*9.5414e-3,     3.9557e-2];
xe =     [0.3366,         0.3356];
ye =     [0.1735,         0.1691];
A0 =     [-949.86315,     36284.48953];
A1 =     [6253.80338,     0.00228];
t1 =     [0.92159,        0.07861];
A2 =     [28.70599,       5.4535e-36];
t2 =     [0.20039,        0.01543];
A3 =     0.00004;
t3 =     0.07125;

% Estimate
n = (x-xe(1))/(y-ye(1));
var = A0(1)+A1(1)*exp(-n/t1(1))+A2(1)*exp(-n/t2(1))+A3*exp(-n/t3);

% Exact value
if (var < 1e4) % less than 10,000 K
    u = (4*x)/(-2*x+12*y+3);
    v = (6*y)/(-2*x+12*y+3);
    if (u+v < 0.5356)&(u+2.4525*v > 0.89)
        pol = rd-rdu*u-rdv*v;
        t0 = 3.27-2.27*atan((0.288-u)/(v-0.245));
        f = inline('polyval(pol,x)','x','pol');
        z = fzero(f,t0,optimset('fzero'),pol);
        CCT = 7500/z;
        ...
```

(Continued...)

```
    elseif (u+0.1648*v < 0.343)
        pol = p-pu*u-pv*v;
        t0 = 1.831-1.411*atan((0.306-u)/(v-0.277));
        f = inline('polyval(pol,x)','x','pol');
        z = fzero(f,t0,optimset('fzero'),pol);
        CCT = 3650/z;
    else CCT = 0; % error
    end
elseif (var > 5e4) % greater than 50,000 K
    n = (x-xe(2))/(y-ye(2));
    CCT = A0(2)+A1(2)*exp(-n/t1(2))+A2(2)*exp(-n/t2(2));
else CCT = var; % 10,000-50,000 K
end
```

Script B3:

```
function [Q, Qsav] = calcsav(plc,facade,or,zone)

% Usage:    Calculates annual energy use and savings for daylight resp. control
%
% Input:    [plc]    = location (Berlin,Helsinki,Paris,Madrid)
%           [facade] = window size (1-5)
%           [or]     = orientation (North,East,South,West)
%           [zone]   = distance to window (Front,Middle,Back)
%
% Output:   [Q]      = annual energy use [kWh]
%           [Qsav]   = annual energy savings [%]
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

% Input
load calcfail;
eval(['load ',char(loc(plc)),'_dev']);

% Structure data
col = (facade*12-12)+(or*3-2)+(zone-1);
data = dev(:,col); % select data from simulation database

% Calculate mean deviation [%]
for i = 1:260
    dev_avg(i,1) = mean(data(i*21-20:i*21));
end
sys = zeros(260,1);
sys(find(dev_avg <= 250)) = 1; % NIF ~= 1/4
sys_off = 0.5*ones(21,1);
sys_on = curve2/1e3;
energy = [];
for i = 1:260
    if (sys(i) == 0)
        energy = [energy; sys_off];
    else energy = [energy; sys_on];
    end
end
...
```

(Continued...)

```
% Convert to time periods
c1 = 1:21:5460;
c2 = 20:21:5460;
c3 = 1:20:5200;
c4 = 20:20:5200;
for i = 1:260
    energy_out(c3(i):c4(i),1) = energy(c1(i):c2(i),1);
end

% Energy use (6 luminaires)
A = (6*0.081)*ones(5200,1); % luminaire consumption (30m x 60s x 162W / 3.6MJ)
B = (6*0.0105)*ones(5200,1); % parasitic consumption (30m x 60s x 21W / 3.6MJ)

% Output
Q = sum(energy_out .* A + B); % absolute values [kWh]
Qsav = (1-Q/1905.8)*100*0.9; % relative values [%] * 'system potential' [-]
```

Script B4:

```
function [CCT25, CCT50] = calcfail(plc,facade,or,zone,month)

% Usage:    Calculates the percentage of timesteps per month when
%           the lighting system cannot mix the required CCT.
%
% Input:    [plc]     = location (Berlin,Helsinki,Paris,Madrid)
%           [facade]  = window size (1-5)
%           [or]      = orientation (North,East,South,West)
%           [zone]    = distance to window (Front,Middle,Back)
%           [month]   = month of year (1-12)
%
% Output:   [CCT25]   = 25% failures
%           [CCT50]   = 50% failures
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

% Input
load calcfail;
eval(['load ',char(loc(plc)),'_daylight']);
eval(['load ',char(loc(plc)),'_luminaires']);

% Structure data
col = (facade*12-12)+(or*3-2)+(zone-1);
var(:,1) = daylight(rows(month,1):rows(month,2),col);
var(:,2) = luminaires(rows(month,1):rows(month,2),col); % dimmed
n = length(var);
refdata = repmat(curve,n/21,1);

% Calculation
v = zeros(n,1);
v = var(:,1) ./ var(:,2); % ignore warning
v(find(var(:,2) == 0),1) = 100;
fail(:,1) = ccttest;
for i = 1:4
    res = mix(refdata,ccttest(i),v);
    fail(i,2) = (length(res(find(res == 0)))/n)*100; % failures [%]
end
...
```

(Continued…)

```
% Output
CCT25 = fail(findnearest(25,fail(:,2),0),1); CCT25 = CCT25(1,1);
if (max(fail(:,2)) < 25)
    CCT25 = 17000;
end
CCT50 = fail(findnearest(50,fail(:,2),0),1); CCT50 = CCT50(1,1);
if (max(fail(:,2)) < 50)
    CCT50 = 17000;
end
```

Script B5:

```
function [xy, error] = calcday(day)

% Usage:    This function finds the actual (or nearest) time values in
%           ENTPE measurements.
%
% Input:    [day]   = workday of year + 1000
%
% Output:   [xy]    = xy-chromaticities (North, East, South, West)
%           [error] = error time, orientation, day
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

data = xlsread([num2str(day),'.xls']);
n = 1:length(data);
worktimes = [16:36]/48;
for i = 1:21
    row = findnearest(worktimes(i),data(:,1),-1);
    xy(i,1:8) = data(row,[8,9,13,14,18,19,23,24]);
    for k = 1:2:7
        [up,lo] = boundaries(xy(i,k));
        if (xy(i,k+1) > up | xy(i,k+1) < lo) % out-of-range
            xy(i,k) = interp1(n,data(:,k),row);
            xy(i,k+1) = interp1(n,data(:,k+1),row);
        end
    end
end
[xy,error] = clean(xy,day);
```

Script B6:

```
function [xy, error] = clean(xy,day)

% Usage:    This function:
%           (1) Sets the range to 0.2278 < (x,y) < 0.4000
%           (2) Removes single x or y values
%           (3) Filters any chromaticities that are more than delta_uv =
%               0.02 from the blackbody locus (errors are part of the
%               output)
%           (4) Replaces missing values in first/last row
%           (5) Interpolates all other missing values
%           (6) Replaces bad interpolations
%
% Input:    [xy]    = xy-chromaticities (North, East, South, West)
%           [day]   = workday of year + 1000
%
% Output:   [xy]    = xy-chromaticities (North, East, South, West)
%           [error] = error time, orientation, day
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

% (1) replace out-of-range values
xy(find(xy < 0.2278 | xy > 0.4000)) = 0;

% (2) remove single x or y values
xy(find(xy(:,1).*xy(:,2) == 0),1:2) = 0;
xy(find(xy(:,3).*xy(:,4) == 0),3:4) = 0;
xy(find(xy(:,5).*xy(:,6) == 0),5:6) = 0;
xy(find(xy(:,7).*xy(:,8) == 0),7:8) = 0;

% (3) remove erroneous daylight chromaticities
error = [];
for m = 1:length(xy)
    for n = 1:2:7
        [up,lo] = boundaries(xy(m,n));
        iso50 = -0.76453*xy(m,n)+0.43206;
        iso35 = 2.6419*xy(m,n)+0.68015;
        if xy(m,n+1) > 1.01 * up % delta-uv > +0.02
            xy(m,n) = 0;
            xy(m,n+1) = 0;
```

(Continued...)

```
            error = [error;[8+(m-1)*0.5,n,day]];
        end
        if xy(m,n+1) < 0.99 * lo % delta-uv > -0.02
            xy(m,n) = 0;
            xy(m,n+1) = 0;
            error = [error;[8+(m-1)*0.5,n,day]];
        end
        if ((xy(m,n) > 0.2278) & (xy(m,n) < 0.2622))
            if xy(m,n+1) < iso50 * 0.99 % isotemp: 50,000 K
                xy(m,n) = 0;
                xy(m,n+1) = 0;
                error = [error;[8+(m-1)*0.5,n,day]];
            end
        end
        if ((xy(m,n) > 0.3863) & (xy(m,n) < 0.4))
            if xy(m,n+1) < iso35 * 0.99 % isotemp: 3,500 K
                xy(m,n) = 0;
                xy(m,n+1) = 0;
                error = [error;[8+(m-1)*0.5,n,day]];
            end
        end
    end
end

% (4) replace missing values in first/last row (cannot be interpolated)
for i = [1,3,5,7] % x-values
    if (xy(1,i) == 0)
        xy(1,i) = 0.313;
    end
    if (xy(21,i) == 0)
        xy(21,i) = 0.313;
    end
end
for i = [2,4,6,8] % y-values
    if (xy(1,i) == 0)
        xy(1,i) = 0.329;
    end
    if (xy(21,i) == 0)
        xy(21,i) = 0.329;
    end
end
```

(Continued...)

```
% (5) interpolate missing values
var = find(xy == 0);
n = 1:(length(xy)*8);
for i = var(1:end)
    xy(i) = interp1(n,xy(:),i);
end

% (6) replace bad interpolations
[r,c] = find(xy < 0.2278 | xy > 0.4000);
for i = r
    for c = 1:2:7
        xy(i,c) = 0.313;
    end
    for c = 2:2:8
        xy(i,c) = 0.329;
    end
end
```

Script B7:

```
% Construct annual CCT time series
% ================================

clear all;

% Luminaires chromaticities
load xydynamic.mat;
xy_luminaires = repmat(xydynamic,260,4);
save xy_luminaires xy_luminaires;

% Daylight chromaticities
days = [(3:18),(22:75),(105:226),(229:244)]+1e3; % 208/260 available workdays
M = [0.313,0.329];
xy_daylight = repmat(M,5460,4);
xy_errors = [];
for i = 1:208
    r = (days(i)-1e3)*21;
    [xy_daylight(r-20:r,1:8),error] = calcday(days(i));
    xy_errors = [xy_errors;error];
end
save xy_daylight xy_daylight;
save xy_errors xy_errors;
```

Script B8:

```
function [x, y] = spec2xy(SPD,glasstype)

% Usage:    This function calculates the CIE 1931 chromaticities
%           from relative spectral power distributions (SPD).
%
% Input:    [SPD] = spectral power distribution between 380-780 nm
%
%           [glasstype] =   spectral transmittance curve:
%                           1.) No filtering
%                           2.) Pilkington Optifloat Clear (4 mm)
%                           3.) Pilkington Energy Advantage Low-E (4 mm)
%
% Output:   [x,y] = CIE 1931 chromaticity coordinates
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

load taudata; % spectral transmittance curves (5 nm interval)
load xyz; % colour-matching functions (5 nm interval)

% Calculate k-value
var = zeros(1,81);
var = SPD.*xyz(:,2).*5;
k = 100/sum(var);

% Calculate spectral flux values
flux = zeros(1,81);
flux = taudata(:,glasstype).*SPD;

% Calculate tristimulus values
XYZ(:,1) = flux.*xyz(:,1).*5;
XYZ(:,2) = flux.*xyz(:,2).*5;
XYZ(:,3) = flux.*xyz(:,3).*5;
XYZ = k*sum(XYZ);

% Calculate CIE 1931 chromaticity coordinates
x = XYZ(1)/(sum(XYZ));
y = XYZ(2)/(sum(XYZ));
```

Script B9:

```
function [SPD, lamba] = xy2spec(x,y)

% Usage:    This function calculates the relative spectral
%           power distributions (SPD) from CIE 1931 chromaticities.
%
% Input:    [x]     = chromaticity x-coordinate (-)
%           [y]     = chromaticity y-coordinate (-)
%
% Output:   [SPD]   = spectral power distribution between 380-780 nm (-)
%           [lamba] = corresponding wavelengths (nm)
%
% By M.H.J.Schriek (2007)
% Eindhoven University of Technology
% The Netherlands

load sdata;

% Constants
M1 = (-1.3515 - 1.7703*x + 5.9114*y)/(0.0241 + 0.2562*x - 0.7341*y);
M2 = (0.0300 - 31.4424*x + 30.0717*y)/(0.0241 + 0.2562*x - 0.7341*y);

% Calculate SPD
SPD = S(:,1) + M1.*S(:,2) + M2.*S(:,3);

% Format output
SPD = SPD(17:97);
lamba = (380:5:780)';
```

Appendix C: Colour mixing results

Table C.1 – Number of months that Dynamic Lighting can mix required CCT (> 50% of the time)

Colour mixing properties – Daylight responsive control																
	Façade:	1			2			3			4			5		
	Zone:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Madrid	Bad	12	12	12	12	12	11	12	12	9	12	8	-	-	-	-
	Average	-	-	-	-	-	1	-	-	2	-	-	-	-	-	-
	Good	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-
	Excellent	-	-	-	-	-	-	-	-	1	-	3	11	12	12	12
Paris	Bad	12	11	9	12	10	8	12	9	7	10	6	-	-	-	-
	Average	-	-	-	-	-	1	-	1	1	1	1	1	-	-	-
	Good	-	-	-	-	1	-	-	-	-	-	-	2	1	1	-
	Excellent	-	1	3	-	1	3	-	2	4	1	5	9	11	11	12
Berlin	Bad	12	9	8	11	9	7	11	8	6	9	5	-	-	-	-
	Average	-	-	-	1	-	1	-	1	1	-	1	-	-	-	-
	Good	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
	Excellent	-	2	4	-	3	4	1	3	5	3	6	12	12	12	12
Helsinki	Bad	9	9	7	11	11	11	9	7	5	8	5	-	-	-	-
	Average	1	-	-	-	-	-	-	1	2	1	-	-	-	-	-
	Good	-	-	-	-	-	-	-	-	-	-	1	2	-	-	-
	Excellent	2	3	5	1	1	1	3	4	5	3	6	10	12	12	12

Table C.2 – Number of months that Dynamic Lighting can mix required CCT (> 50% of the time)

Colour mixing properties – Time switching																
	Façade:	1			2			3			4			5		
	Zone:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Madrid	Bad															
	Average															
	Good															
	Excellent															
Paris	Bad	11	8	6	11	7	5	10	8	-	7	-	-	-	-	-
	Average	1	2	2	1	2	2	2	1	2	2	5	-	-	-	-
	Good	-	-	-	-	-	-	-	-	4	-	-	-	-	-	-
	Excellent	-	2	4	-	3	5	-	3	6	3	7	12	12	12	12
Berlin	Bad															
	Average															
	Good															
	Excellent															
Helsinki	Bad															
	Average															
	Good															
	Excellent															