HYBRID LIGHTING SYSTEMS

Performance, Application and Evaluation

A thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in philosophy by

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I ABSTRACT

Daylight was the main source of lighting in vernacular architecture, and building design accordingly responded to its strategic limitations. Needs for new types of buildings in conjunction with the great development of electric lamp led to the ascendancy of electric lighting. However, a return to the interest in natural lighting emerged with the energy crises in the 1970s. In order to meet the new requirements, new optical materials and technologies have been combined to produce innovative daylighting systems able to deliver daylight long distances into buildings. There is a need to maximize the utilization of daylight, to optimize the integration between daylighting and electric lighting systems so as to increase the potential application of daylighting system. The development of the hybrid lighting systems (HLS) aims to satisfy these desires.

HLS seek to maximize the utilization of daylight by tracking sunrays, and in most cases they are concentrated to minimize the light guidance size, which eases the installation and in turn increases the potential application of HLS. Prior to delivery of daylight, electric lighting source is added to instantly top up any possible shortage of daylight. A control system works to regulate this process to minimize the energy consumption. The one output device for both sources used in the HLS made it possible to no longer need for two distinct lighting systems to be installed in one space.

Investigations in this work have measured HLS performance in terms of light delivery, light quality, energy saving and economic performance. Potential applications of HLS in different buildings types and across a wide geographical region have been investigated. An overall evaluation of HLS has been carried out. Furthermore, methods to estimate illuminance data, where measured data is unavailable, have been developed to help investigating systems performance over different geographical locations. Illuminance data produced using the developed methods showed superiority over that produced using other available methods, with the additional advantages of simplicity and universal application.

HLS performance and potential application are influenced by many variables including system characteristics, building types, and location features. The research showed that the most important variable is the concentration ratio of the light collector. This determines HLS ability to collect daylight, and thus its applicability in different geographical locations. It also stipulates light collector and guidance size, and thus HLS applicability in different building type, influences the delivered light quality, and thus occupants' perception of daylight, and influences HLS initial and running costs. Delivered light by HLS may not be perceived as daylight due to the absence of the outside view, the likely change in daylight colour because of the mixing with electric light, the fade awareness of the seasonal and diurnal changes in daylight colour and intensity because of the instant and continuous top up. The challenges of cost, light quality and integration in building design are the most serious barriers confronting HLS ability to penetrate the market and to be used widely. This work makes suggestions to overcome these problems.

I DECLARATION

This is to certify that I am the responsible for the work submitted in this thesis, that the original work is my own except as acknowledged in references, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

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7. EXPERIMENTAL STUDY

CHAPTER

1

Introduction

1.1. INTRODUCTION

The history of architecture is synonymous with the history of daylighting. Since the very beginning of the built dwelling, daylight was the main source of light. Although oil lamps were produced thousands of years ago, and then replaced by the gas-based or petroleum-based lamps, daylight remained the primary means of lighting until the early twentieth century [1]. Early lamps suffered lack of efficiency and high-priced fuels. Both have been overcome by the invention of the electric lamp and the great development of the electricity sources. Electric lamps rapidly replaced daylight with their ability to meet the new requirements and solve the new problems associated with the great growth in building sector and the great pressure of economic demands.

For decades the building industry, as many others in that period, was engineering oriented. Environmental and human factors were largely dismissed until the economic threats of the energy crises of 1973 led to increased interest in energy conservation. Looking for ways to reduce building consumption of electricity inevitably led to return to the natural resource of lighting, which besides achieving the environmental targets, satisfied the human desire for association with nature [2, 3].

Interest in daylighting was outweighed by the convenience and cost of electric lighting. In addition a lot of difficulties were caused by the integration of conventional daylight techniques into modern buildings [4]. To counter these problems new daylighting techniques were created using combinations of new materials and technologies. These developed initially with enhanced conventional techniques, and went through innovative daylighting techniques, and ended with what is called hybrid lighting systems.

The ultimate expression of daylighting systems, hybrid lighting system (HLS), is the latest production in the daylighting field. This was developed over the last fifteen years or so, but fully developed commercial products are not yet available. HLS are introduced in this study, identified, assessed and evaluated; to explore their potential to satisfy current visual environment requirements.

1.2. BACKGROUND

1.2.1. Traditional daylighting strategies

The early openings in building walls, filled in by various means, formed the windows to let in light and air. Throughout many centuries they have been developed and openings in buildings roofs have been created to allow daylight into buildings cores. The addition of light control devices allowed daylighting to play a functional and aesthetical role in creating building form and producing an attractive interior.

Traditionally, three strategies have been used to introduce daylight into buildings. The main strategy is through vertical windows. Their ability to introduce daylight is subject to many variables such as size, number, place and arrangement of windows, in addition to space's height, surfaces' reflections and window direction. Side lighting from windows decreases rapidly with distance, and any attempts to increase daylight penetration distance risk an excessive illumination and high heat gain alongside the window zone. For bigger buildings changes in window variables were not enough, and thus the roof light strategy was developed to introduce daylight into interiors remote from the side windows. Unlike side windows, roof openings are able to provide uniform horizontal planar illuminance distribution. Roof lights were limited by the construction methods of the day, and had a limited application in multi-storey buildings, which is the dominant case in the modern architecture. The third strategy is the central courts, whether covered or not, that admit side lighting to surrounding spaces. They, in one hand, allow increasing skin-to-volume ratio, but on the other hand result in loss of rentable space that under economic constraints might be unacceptable.

1.2.2. New daylighting strategies

Needs for bigger buildings and more complicated usages and high value of city land, among many other reasons, made compact and high-rise buildings an inevitable solution. Thus, maintaining a low skin-to-volume ratio that allows daylight to reach most building spaces became inapplicable. Consequently two approaches have been developed to bring daylight deeper into new buildings forms, and to control and distribute direct sunlight [5], either by enhancing traditional techniques or transferring daylight via guidance systems. In both approaches newly developed optical materials are used.

Beam daylighting approach uses techniques such as overhangs, light shelves and louvers, either to reduce daylighting problems, to send more light to the back of the space, or to improve daylight uniformity within the space [6]. This approach helped to extend daylight delivery distance; especially with the use of highly efficient reflective and refractive materials. Further extension is obtained using the second approach techniques, by which daylight are transported via light wells or light pipes into remote spaces that may even have no connection with building skin. Daylight guidance systems (DGS) used in the second approach generally consisting of three components: collector, which collects daylight by means of passive or active mirrors and/or lenses, or simply topped with clear dome permits daylight into system guidance - the second component that transports daylight to where it is needed. The guidance is made of or lined with high reflective materials allows total internal reflections with minimum attenuation of daylight. Extractor devices may be included in the guidance to allow emittance of proportions of daylight where it is needed along the guidance rout. The guidance ends with a diffuser that spread daylight uniformly across the space [7]. The DGS significantly improved daylighting systems delivery distance, but at the expense of contact with outer view, though it might be argued that DGS mostly delivers daylight into spaces initially have no access to outside view.

1.2.3. More than daylight provision

Both traditional and new daylighting strategies have more impacts than just providing daylight. Devices used by both of them influence building design. Provision of daylight is associated with environmental and human benefits. Eventually, all impacts contribute to some extent in the building economic performance.

1.2.3.1. Influence on building design

A mutual relationship exists between building design and daylighting strategies. Daylight is known as formgiver for building. Windows reflect the nature of the building and draw its appearance. Central courts and roof openings influence building form. Interior planning, space sizing, and function zoning responded to the ability to deliver daylight. Light control devices turned into architectural elements define elevations. On the other hand, construction systems and materials determine openings size, type and location. Development of structural systems allowed the small aperture in the masonry bearing wall system to turn into full glazing walls in the skeleton systems. Innovation of structure led to a wonderful utilization of light in architecture such as the split roof levels in the Egyptian temples, the marvellous opening in the centre of the Pantheon dome, and the whole walls of window between the flying buttresses in the medieval cathedral [1] (**Fig. 1.1**).

1.2.3.2. Environmental benefits

Realization of the big impact of building on environment has been raised the environment issue above simple economics to become a moral issue [9]. Building consumption of energy not only rise running bill, but also waste finite supply of stored energy where it can be replaced with other environment friendly alternatives, in addition to the pollution produced from fossil fuel-burning plants. Lighting consumption of energy widely varies according to building usage and geographical location. Acceptable figures of 24% of building

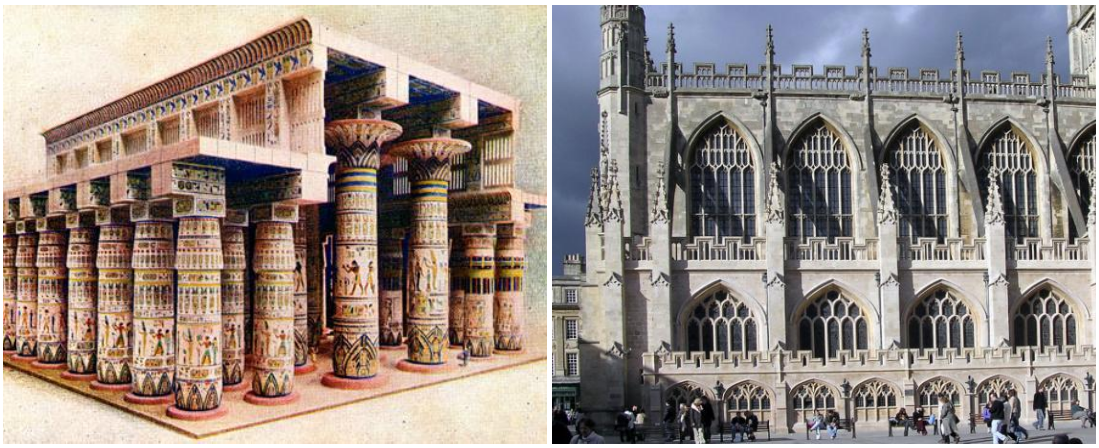

Figure 1.1: *The split roof levels in the Egyptian temples* (left); *the flying buttresses in Bath abbey, UK* (*completed in 1611*) [8] (*right*).

annual energy use, and 63% of building energy cost were suggested by Lam for lighting consumption of energy in a typical office building [9]. A cut of some 50-75% of electric lighting consumption could be achieved if daylighting techniques are used in combination with efficient artificial lighting. Additional cuts may be gained due to the reduction in the use of electricity for ventilation and cooling; because daylight provide more light for less input of thermal energy than any other artificial light source [10]. The previous figures are just examples for the massive statistics of lighting consumption of energy, and the enormous research that prove daylighting strategies ability to save energy and consequently protect environment, if not for economic reasons, then for moral reasons.

1.2.3.3. Human benefits

There is an increasing interest in daylighting that moves beyond the traditional argument of energy issues. Many experts realize that daylight helps fulfil our psychological needs, and carrying out our physiological functions; through inherent and unique qualities that are not easy to imitate artificially [3]. The presence of daylight, especially if associated with a link to the outside world, provides information that allows us to experience the time of day, changes in the weather, and seasonal differences. It also improves mood, enhances morale, lowers fatigue, and reduces eyestrain [11]. Absence of daylight fosters conditions that promote disease, not least of which is the 'Sick Building Syndrome ', which is a term used to describe situations in which building occupants experience discomfort and even acute health problems such as stress, eye discomfort, aches and other symptoms. That appear to be related to time spent in the building, even when no specific illness or cause can be identified [2, 3].

Links have been established between daylit environment and occupants' performance. For example, school children and teachers who experience daylight in their schools tends to do significantly better than students who do not. Surveys reported that there is increased student and teacher attendance, increased achievement rates, reduced fatigue factors, improved student health, and enhancement of general development. Similar associations were found between daylighting and performance in workplaces, retails, or health care facilities [12].

1.2.3.4. Economic performance

Daylight itself is free, but introducing it into building requires initial costs to create apertures in the building envelope, or install devices to catch and/or control daylight. Running costs are required for cleaning and maintenance to minimize light lose. Initial costs of daylighting systems might outweigh that of the electric lighting systems, but direct and indirect economic benefits of daylighting are expected to help overcome this difference. Saving in lighting electricity consumption may be the most concerning issue because of its instant reflection on building running bills. More saving in energy may be obtained due to the reduction in heat gains, and consequently the reduction in cooling loads. Apart from energy saving, many other aspects may add to the building value such as increase in rental price or enhancement of occupants' productivity.

Numerous studies report that provision of daylight improves indoor environmental quality, which in turn improves human wellness, peoples' mood, and users' satisfaction. Under such circumstances, Wright and Cropanzano concluded that people experiencing positive emotional states tend to be more productive [13], and that positive emotional states can be reinforced by providing people with their preferred work environment. Studies show that daylight help productivity in many cases to increase between 5% and 15% in offices [14]. Also higher sales were reported in retail with daylighting, and more productions claimed in industrial workshops [12]. It is argued that since 85% or so of the cost of running an office-based business is the cost of people, any small improvement in performance would reap huge benefits. A 1% increase in worker productivity can provide a company with savings that exceed its entire energy bill, according to Romm and Browning [14], which makes a case for energy efficiency as a way to boost productivity and increase a company's bottom line.

1.3. PROBLEM FORMULATION

The need for *deep-plan buildings* meant that side windows are not the best choice as they can't deliver daylight any further than a parameter zone of some 4-6 metre depth, even with the enhancement of the beam daylighting techniques. The need for *high-rise buildings* meant that roof openings are not the proper solution as they are mostly inapplicable for other than the highest storey. The precious *value of city land* made the central spaces an uneconomic alternative in many cases. The functional need for *windowless spaces* led to the development of the DGS. The passive tubular daylight guidance system (TDGS) is believed to be the most commercially available DGS. It proved a universal acceptance and applicability over a wide range of building usages and geographical locations, though it still has some limitations. It is mostly installed in the highest storey of the building due to difficulty in guide penetration of usable working spaces, although it is technically able to deliver daylight further. In some applications when it is applicable to install sun pipe in a central space it delivered daylight up to 14 stories [15]. Commercially available DGS provide daylight only, which means in the absence of daylight, a separate electric lighting system has to be on operation. That in turn means two different lighting systems have to be installed in the space, and in order to work efficiently together, they need to be linked with a control system to regulate the supply of electric lighting system to just top up inadequacy of daylight.

From the previous, it can be seen that daylighting systems developed so far have many limitations. Developers of HLS cannot claim that their systems are able to overcome all these limitations at once, but efforts have been made to achieve the following goals:

- Maximize the utilization of available daylight, and optimize the integration with the electric lighting system to minimize energy consumption.
- Increase daylight delivery distance into building core.
- Maintain an improved indoor visual environment in order to enhance occupants'

well-being and increase users' productivity.

- Enhance the ability to penetrate building spaces with minimum influence on its elements and systems.
- Cover wide variations of applications; in terms of building usages and geographical locations.
- Ease of installation in both new and existing buildings.

1.3.1. Research objectives

This research aims to investigate new daylighting systems developed over the last fifteen years or so. These systems in common combine both daylight and electric light in order to maximize the benefit of daylight and minimize the energy consumption of the electric lighting system. Many aspects concern the performance and applications of what is so called HLS are still unrevealed. Most related publications are carried out by the HLS developers to present systems development progress. Universal utilization of the HLS requires more studies to investigate many areas such as systems performance in terms of light delivery, light quality, light distribution, relationship with the host building, integration with other building systems, compatibility with building codes, economic performance, installation applicability, suitability of use across various geographical locations, and users' response and perception of the provided light. This research, throughout attempts to answer the following questions, seeks to reveal some of the previously mentioned aspects.

1.3.2. Research questions

The development of new daylighting systems raises many questions. Based on the available resources, this research focuses on the following ones:

I. What is the HLS? What are their main features?

II. What is the relationship between HLS and building systems and elements?

III. How much daylight can a HLS deliver?

IV. What is the quality of the delivered daylight by HLS?

V. How much energy can HLS potentiality save?

VI. Is HLS economically viable as a lighting alternative?

1.3.3. Research hypothesis

Based on the published description and features of the HLS, the following hypothesis was formulated:

HLS have the potential to save energy and provide sufficient light in remote spaces by maximizing the benefits of daylight and optimizing the integration with the electric lighting systems. However, they should be available at a price comparable to alternative systems, and should be more integrable in building to be more applicable.

1.4. RESEARCH METHODOLOGY

This research focuses on identifying the concept of HLS, assessing their performance, investigating their potential applications, and carrying out an overall evaluation process. Since the research consists of different assignments, combination of different methods has been used in the study.

The first assignment of the research was to identify the HLS. A comprehensive literature review has been carried out to collect as many daylighting systems as possible, and regularly updated over the research period. Then they are analysed, classified and identified according to their characteristics. Consequently HLS has been set out and assigned a definition and common features.

The second assignment was to assess the HLS performance in terms of light delivery, light quality, light distribution, energy saving and economic performance. Real measurements of one of the HLS were carried out over a six-month period to investigate the light delivery. Numerical simulations were carried out to estimate the light delivery in a number of locations spread across different geographic and climatic regions, and thus to estimate energy savings. The light quality in terms of light spectrum was obtained from the literature, whilst in terms of light distribution it has been measured for one system and obtained from the literatures for the others. The economic performance has been analyzed using the whole life cycle costing approach to estimate the HLS payback periods.

The third assignment was to investigate the potential applications of the HLS. Analyses of HLS strategies and building design strategies have been carried out to study HLS integration in building design. HLS applications in buildings were consequently examined. Part of the building integrated design process is to select HLS that matches building needs and budget. In order to determine selection criteria and measure their importance, and to what extend each of the different HLS was preferred by the decision makers in the field of building design and operating, an online survey was conducted. Applications of HLS in terms of the geographical locations may be investigated using measurements of systems performance in case studies, computer simulations, or numerical simulations over wide range of locations. The third was used due to the difficulty of the first, and inapplicability of the second. Since HLS are newly developed, few case studies spread across different countries are available. Moreover, the researcher has got no access for any of them. Meanwhile, Computer simulation programmes such as Radiance and Ecotect are not designed to simulate HLS complicated optical process in collecting, transporting and distributing daylight.

Illuminance data are required to carry out the numerical simulations of HLS performance over a wide range of geographical locations. Since measured data are available for limited locations only, models have been developed to produce illuminance data for all points on earth's surface.

1.5. THESIS OUTLINE

In addition to this introduction and the discussion and conclusion presented in the last chapter, this thesis comprises seven chapters. Chapter two was assigned for the developed models to produce illuminance data. In order to avoid interrupting the continuity of the HLS-related studies, it is preferred to start with this chapter. Chapter three summarises existing daylighting systems. After defining the concept of HLS in this chapter, chapter four looks at the context in which HLS will work. The relationship between HLS and buildings, and the process of selecting HLS for purpose and budget were discussed. The next three chapters investigate HLS performance from different points of view. Chapter five assesses the HLS performance in terms of light delivery, light quality and energy saving, while the economic performance assessed in chapter six. The experimental study was presented in chapter seven. By which some aspects in HLS performance, such as light delivery and light distribution, have been validated, and the design methods have been discussed. An overall evaluation has been carried out in chapter eight.

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CHAPTER

2

Illuminance Data

2.1. INTRODUCTION

The development of 'daylight guidance systems' has made redirection of zenithal daylight into areas remote from the building envelope a practical possibility. Since the systems use as a source, variously, combinations of sunlight and skylight at different orientations, a detailed knowledge of illuminance conditions at potential locations is necessary in order to assess their feasibility. Unfortunately there is a general dearth of measured daylight data suitable for this task. In the UK for example there are less than ten sites measuring illuminance data in contrast to over 600 measuring meteorological data including solar irradiance. Luminous efficacy models relate direct, global and diffuse radiation components to their photopic equivalents. They enable the calculation of daylight illuminance from the more widely available irradiance data. Luminous efficacy is defined as the ratio between illuminance and irradiance. Thus, if E is the illuminance in lux and I is the irradiance in W/m^2, the luminous efficacy of the solar radiation, K, will be given by:

$$K=E/I \quad \text{(lm/W)} \qquad (2.1)$$

Although this work has its origins in a study of daylight guidance systems, the techniques described allow generation of data for design or analysis of any daylight device.

2.2. REVIEW OF LUMINOUS EFFICACY MODELS

2.2.1. Model classification

Published models of luminous efficacy can be divided into three groups according to the variables used. The first uses *solar altitude* as the only independent variable (details in **Table 2.1**). The second group uses one or more of *solar zenith angle, amount of water vapour, clearness index, brightness index, relative optical air mass and atmospheric turbidity factors* as independent variables. In addition *solar altitude* is used in some cases (see **Table 2.2**). The last group uses *constant values* without any variables.

2.2.2. Model characteristics

The majority of models listed in **Table 2.1** are based on polynomial expressions of different degrees functions of solar altitude. They thus could be considered to be one model with the addition of local climatic coefficients. The Robledo and De Souza exponential models are examples of the latter for Madrid and Florianopolis respectively [1, 2].The majority of models employing solar altitude as the only independent variable are specific to sky type and location.

The models set out in **Table 2.2** were developed from either meteorological parameters or experimental data from specific locations, but are intended to represent all sky types. A number of studies have been carried out seeking to prove their universal applicability. Muneer, commenting on the validation studies to test this claim, concluded that none were able to do this [14].

The third group advance constant values for luminous efficacy for each of direct, global and diffuse irradiance. De Rosa claims that its constants universally "behaves well and furnishes good results in spite of its simplicity in all skies" [18]. A number of authors among the first two groups have also suggested constant luminous efficacies as a secondary alternative to those produced using functions.

Table 2.1: Direct, global and diffused luminous efficacy models using solar altitude as the only independent variable

Model	Sky type	Light type
Aydinli (1983) [3]	Clear	Direct - Global
Littlefair (1988) [4]	Clear	Direct - Global - Diffuse
	Overcast	Global
	Intermediate	Global
Olseth (1989) [5]	Clear	Diffuse
Chung (1992) [6]	Clear	Direct - Global - Diffuse
	Overcast	Global
	Intermediate	Global
Ullah (1996) [7]	Clear	Direct - Global - Diffuse
	Overcast	Global
	Intermediate	Global - Diffuse
Robledo (2000) [1]	Clear	Direct
Robledo (2000) [8]	Clear	Global
Robledo (2001) [9]	Clear	Diffuse
Souza (2004) [10]	Clear	Diffuse
De Souza (2005) [2]	Clear	Direct

Table 2.2: Direct, global and diffused luminous efficacy models using independent variables other than solar altitude

Model	Sky type	Light type	Input parameters
Olseth (1989) [5]	Overcast	Diffuse	k_t, α
Perez (1990) [11]	All	Direct - Global - Diffuse	*w, z,* Δ (*)
Molineaux (1995) [12]	All	Direct	*m, β, w*
Palz (1996) [13]		Global	α
		Diffuse	cc
Muneer (1997) [14]	All	Global - Diffuse	k_t
Ruiz (2001) [15]	All	Global - Diffuse	k_t
Robledo (2001) [16]	All	Direct	α, Δ
Robledo (2001) [17]	Overcast Intermediate	Global	α, Δ
Robledo (2001) [9]	All	Diffuse	α, Δ
De Souza (2005) [2]	All	Direct	α, Δ

$\mathbf{k_t}$: clearness index, **Δ**: brightness index, ***z***: solar zenith angle, **α**: solar altitude, ***w***: atmospheric precipiTable 2.water content, ***cc:*** cloud cover, ***β***: turbidity factor

* In addition to 4 constants depending on k_t. Air temperature and humidity needed to estimate *w*.

2.2.3. Previous methodologies

Three methodologies for estimating luminous efficacy emerge from the literature. The first makes use of either the available meteorological data, or the measured irradiance and corresponding illuminance data, in specific locations in order to develop a model. The second employs measured data to validate an established model often with the development of new local coefficients. The last uses an established model to generate illuminance values for new location.

2.3. THE PROPOSED MODELS OF LUMINOUS EFFICACY

2.3.1. Aims and advantages

The current work seeks to develop validated universal models for each of direct, global and diffused horizontal luminous efficacy, valid for all skies, using satellite-based website data. The independent variables used are available for all points on the earth's surface in free-access web servers. It is not necessary to determine local sky conditions to use the current model and no local coefficients are included.

2.3.2. Data sources

A number of websites offer satellite derived radiation and illuminance data for a limited number of locations. Data from two sites were used to develop the present models, the first being *Satel-light*, the European database of daylight and solar radiation [19]. The website provides irradiance and illuminance data in different forms, including monthly means of hourly values. Data is available for the three main radiation types: direct, global and diffused incident for any defined surface orientation. Its geographic spread covers Europe and parts of North Africa and includes data for the period 1996 to 2000. Satel-light is used in this work to provide irradiance and illuminance monthly means of hourly values, from which luminous efficacy for the selected locations is directly calculated.

The second source is NASA Surface meteorology and Solar Energy (SSE) [20]. Data is available for the entire globe at a resolution of 1° in latitude and 1° in longitude, as monthly means for the years 1983-2005. SSE is used in this work to obtain data of independent variables such as hourly solar altitudes and cloud amount ratios. The solar altitude data is available as monthly averaged hourly solar angles, but cloud amounts are as monthly averaged three hourly values. From this, hourly values of cloud amounts are derived as follows. For instance, if cloud amount at 1200 and 1500 is *C12* and *C15* respectively, cloud amount at 1300 and 1400 are calculated as (0.67 *C12* + 0.33 *C15*) and (0.33 *C12* + 0.67 *C15*) respectively.

Other independent variables such as sky clearness index, k_t, and sky brightness index, Δ, were estimated using published models. The k_t is given by the following formula [21]:

$$K_t = G_h / I_0 \, E_0 \sin \alpha \qquad (2.2)$$

Where: I_0 is the extraterrestrial radiation = 1367 W/m^2; E_0 is the eccentricity correction factor of the Earth's orbit.

E_0 is computed according to Spencer's model [22], which is chosen for the purpose of this study for its accuracy rather than Cooper's formula [23] that used in the solar literature due to its simplicity [24].

$$E_0=1.00011 + 0.034221\cdot\cos\Gamma + 0.00128\cdot\sin\Gamma + 0.000719\cdot\cos2\Gamma + 0.000077\cdot\sin2\Gamma \quad (2.3)$$

Where the day angle Γ (radians) is given by:

$$\Gamma = 2\pi\,(n-1)/365 \text{ (radians)} \quad (2.4)$$

The sky brightness is given by [25]:

$$\Delta = I_d \,.\, m / I_0 \quad (2.5)$$

Where: I_d is the diffused irradiance, I_0 is the extraterrestrial radiation, and m is relative optical air mass that can be approximated by **Eq. (2.6)** which gives satisfactory results for α angles from 30° to 90° [26].

$$m = 1/\sin\alpha \quad (2.6)$$

Instead it can be given by **Eq. (2.7)** according to Kasten and Young [27].

$$m = [\sin\alpha + 0.50572(\alpha+6.08)^{-1.6364}]^{-1} \quad (2.7)$$

2.3.3. Choice of locations

The calculations are based on data for locations which are broadly representative of conditions throughout the area covered by Satel-light. The ten locations include both maritime and continental cities; and latitudes from 55°N to 35°N at intervals of about 5°. **Table 2.3** lists the selected cities and their locations and altitudes, and the frequencies of occurrence of the characteristic sky conditions of the locations.

2.3.4. Statistical indicators

Statistical indicators used include mean bias deviations (MBD), root mean square deviations (RMS) and mean of absolute deviations (MAD). They are defined by the following equations:

$$\text{MBD}= \sum_{i=1}^{N}[(y_i - x_i)/x_i \,.\, 100]/N \quad (2.8)$$

Table 2.3: Locations and frequencies of sky conditions

CITY		Location Conditions		Sky Conditions (%)		
		Lat (°N)	Lon (°E)	Sunny	Intermediate	Overcast
Copenhagen	DK	56	13	34	38	28
Moscow	RU	56	38	35	40	25
London	UK	51	0	31	42	27
Kiev	UA	50	31	38	35	27
Bordeaux	FR	45	1	47	34	19
Bucharest	RO	44	26	49	31	20
Valencia	ES	39	0	70	20	10
Athena	GR	38	24	68	21	11
Nador	MA	35	0	67	24	9
Khania	GR	36	24	69	19	12

RMS= $\left[\sum_{i=1}^{N}[(y_i - x_i)/x_i \, . \, 100]^2/N\right]^{1/2}$ (2.9)

MAD= $\sum_{i=1}^{N}(|y_i - x_i| \, /x_i \, . \, 100)/N$ (2.10)

Where: y_i is the estimated value, x_i is the given value (selected from Satel-light in the present work) and N is the number of values. The MBD indicates a measure of the overall trend of a given model, i.e. overestimating (positive values) or underestimating (negative values). MAD and RMS offer measures of absolute deviation.

2.3.5. Luminous efficacy generation

Direct, Global and diffuse horizontal illuminance and irradiance data were obtained from Satel-light in the form of monthly means of hourly values for ten 'originating' locations. From each, the direct, global and diffused horizontal 'reference luminous efficacy' (K_b, K_g and K_d, respectively) were calculated using **Eq. (2.1)**. **Table 2.4** lists the maximum, minimum and mean reference values for each location, excluding values corresponding to solar altitude less than 1˚.

It is clear that there are very similar maximum and minimum values in the direct case, and that the mean values gradually increases from around 95lm/W for sites in the Northern locations to 103 for those further south. The average of the maximum, minimum and mean reference values are 110lm/W, 50lm/W and 99.4lm/W respectively. In the global case, it is clear that the maximum values are very similar, with a slight decrease in the Southern locations. The minimum and mean values are almost identical. The averages of the maximum, minimum and mean global reference values are 114lm/W, 101lm/W and 111.4lm/W, and of the diffused values are 132lm/W, 111lm/W and 123lm/W respectively.

2.4. DIRECT LUMINOUS EFFICACY

2.4.1. Development of the proposed direct models

2.4.1.1. Model developed from solar altitude

Polynomial function for K_b against solar altitude, α, were obtained by plotting the variation of K_b with α for all ten originating locations. **Fig. 2.1** shows the best fit polynomial curve,

Table 2.4: Maximum, minimum and mean reference luminous efficacy values

CITY	K_b (lm/W)			K_g (lm/W)			K_d (lm/W)		
	Max.	Min.	Mean	Max	Min	Mean	Max	Min	Mean
Copenhagen	109	50	96	115	100	111	150	100	120
Moscow	110	50	94	115	100	111	127	100	121
London	110	50	98	116	100	112	130	116	122
Kiev	110	50	99	115	100	111	130	118	124
Bordeaux	110	50	100	115	100	112	135	117	127
Bucharest	110	33	100	114	100	111	128	100	120
Valencia	110	50	100	114	103	111	129	100	122
Athena	110	50	102	113	100	112	130	119	124
Nador	109	50	102	114	100	111	126	118	122
Khania	109	67	103	113	105	111	139	121	127

which are as follows:

$$K_{b1} = -2E\text{-}06\ \alpha^4 + 0.0006\ \alpha^3 - 0.0672\ \alpha^2 + 3.0984\ \alpha + 54.942 \quad (2.11)$$

The relationship between K and sine α is plotted in **Fig. 2.2** and the best fit curve is expressed in **Eq. (2.12)**.

$$K_{b2} = 73.85\ (\sin\alpha)^3 - 193.5\ (\sin\alpha)^2 + 174\ (\sin\alpha) + 55 \quad (2.12)$$

2.4.1.2. Model developed from solar altitude and cloud amount

There is a direct relation between the cloud amount (C) and the amount of direct illuminance reaching the earth's surface. To investigate the relationship between the cloud amount C, solar altitude α, and luminous efficacy; values of α multiplied by (1-C) have been plotted against K_b (see **Fig. 2.3**). Inspection of **Figs. 2.1 & 2.3** show that the variation of K_b with α is less scattered when α is adjusted by (1-C).

It can also be seen in **Fig. 2.3** that for values of α(1-C) greater than approximately 2000, the

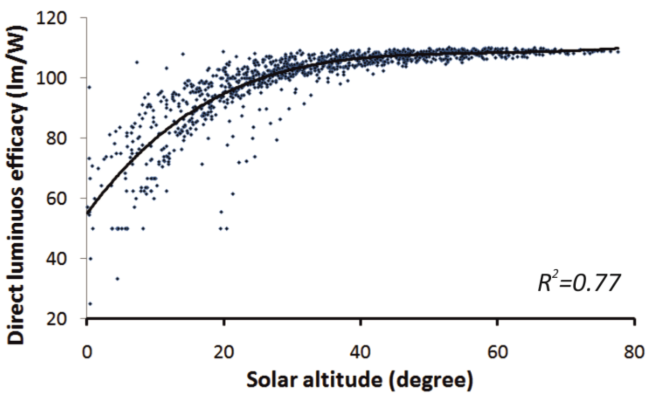

Figure 2.1: *Direct luminous efficacy plotted against solar altitude.*

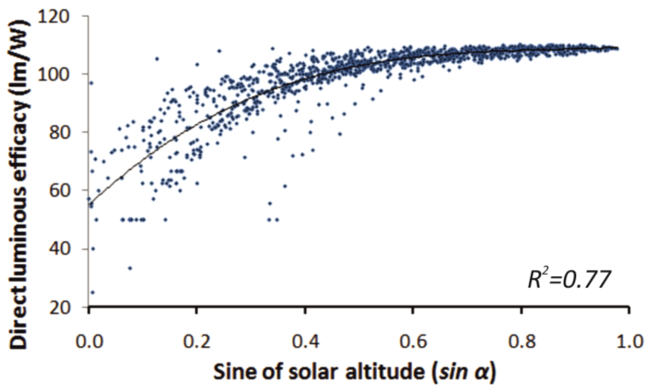

Figure 2.2: *Direct luminous efficacy plotted against sinus of solar altitude.*

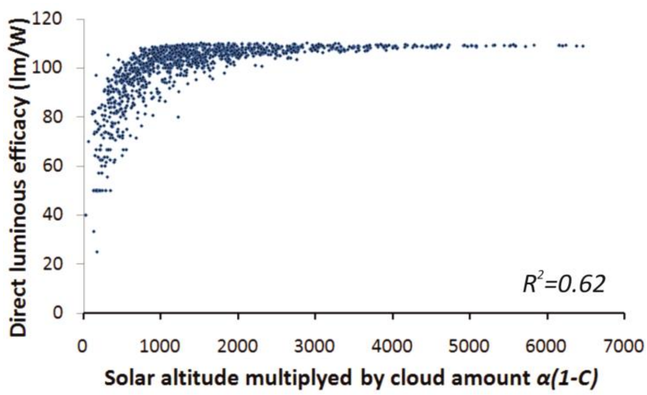

Figure 2.3: *Direct luminous efficacy plotted against solar altitude and cloud amount [α (1-C)].*

relationship becomes almost linear and horizontal. Therefore, two split curves are proposed to represent the relationship; polynomial curve if $\alpha(1\text{-}C) \leq 2000$, and a linear curve if $\alpha(1\text{-}C) > 2000$. The best fit curves, shown in **Fig. 2.4**, are obtained as follows:

$$K_{b3} \text{ if } \alpha(1\text{-}C) \leq 2000 = \text{-}2\text{E-}05\ [\alpha(1\text{-}C)]^2 + 0.062\ \alpha(1\text{-}C) + 61.62,$$

$$\text{Otherwise} = 0.0009\ \alpha(1\text{-}C) + 104.6 \qquad (2.13)$$

To further refine the model, cloud amount was investigated as a weighting parameter. In **Fig. 2.5**, the values obtained for α/C was plotted against K_b for the ten originating locations giving an almost linear relationship. The best fit polynomial curve was as follows:

$$K_{b4} = -0.004\ (C/\alpha)^4 + 0.136\ (C/\alpha)^3 - 1.28\ (C/\alpha)^2 - 1.21\ (C/\alpha) + 109.76 \qquad (2.14)$$

In **Eq. (2.14)**, the lower threshold of luminous efficacy for values corresponding to $(C/\alpha) \geq 12$ (applicable to $\alpha \leq 1^{\circ}$) are assumed to be equal to the minimum K_b of 50 lm/W.

2.4.2. Statistical performance of the proposed direct models

The proposed models have been used to generate illuminance values for the ten 'originating locations'. The generated values were compared with the actual values for the corresponding location. In addition four more cities, not used to develop the models, were added as 'validation locations'. These were:

- Oslo (NO) Lat. 60˚N, Long. 11˚E
- Berlin (DE) Lat. 52˚N, Long. 13˚E
- Parma (IT) Lat. 45˚N, Long. 10˚E
- Alger (DZ) Lat. 37˚N, Long. 3˚E

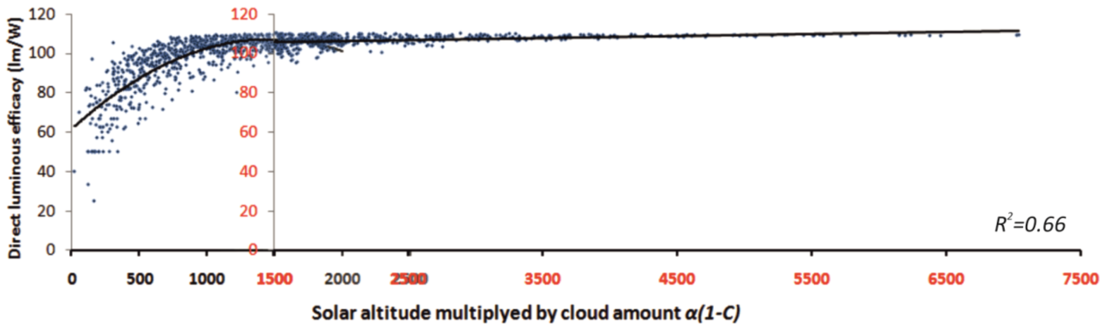

***Figure 2.4:** The split curves represent direct luminous efficacy plotted against solar altitude and cloud amount [α (1-C)].*

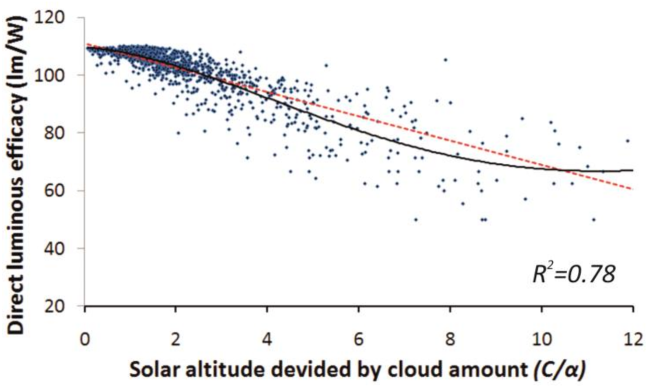

***Figure 2.5:** Direct luminous efficacy plotted against solar altitude and cloud amount (C/α).*

Fig. 2.6 shows the statistical performance of the models described by **Eqs. (2.11) - (2.14)**, named *Mb-1, Mb-2, Mb-3* and *Mb-4* respectively. Good agreement between the statistical performance of the originating and validation locations can be seen in **Fig. 2.6**. The results show the superiority of *Mb-2* over the other models in terms of MAD and RMS, and very close results in terms of MBD for either location. Over the fourteen locations, *Mb-2* obtained averages of 2.9%, 4.7%, and -0.7% for MAD, RMS and MBD respectively (see **Table 2.5**). *Mb-1* showed more stability than the other models, which is derived from the variations of the statistical indicators over the fourteen locations. The differences for *Mb-1* between minimum and maximum values of MAD, RMS and MBD are 1.1%, 1.4% and 3.8% respectively, compared with 1.3%, 4% and 3.3% for *Mb-2*.

The variations between the average reference maximum efficacy value; and the average maximum values estimated using *Mb-1*, *Mb-2*, *Mb-3* and *Mb-4* are -5, -1, 0.3 and -2 lm/W

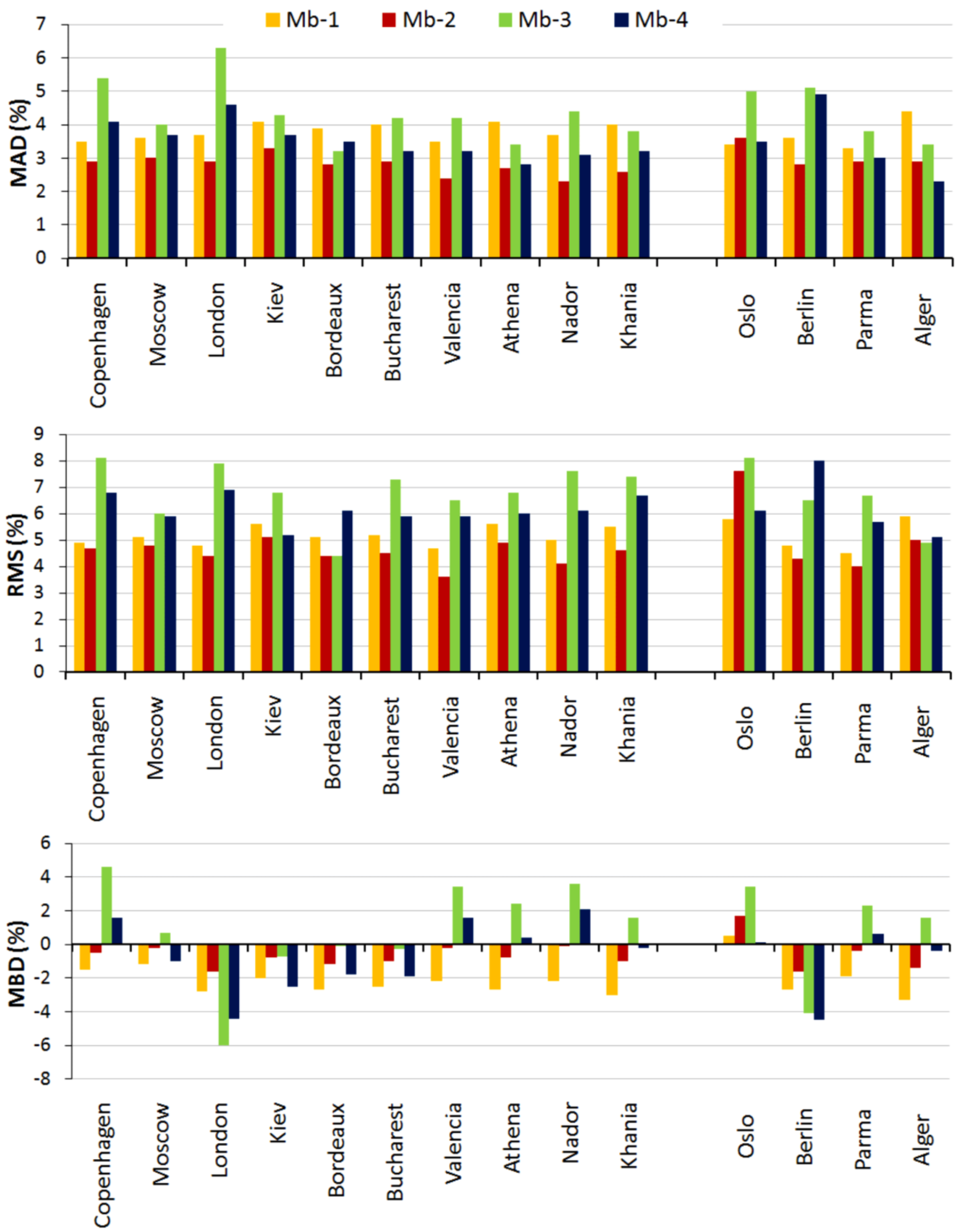

Figure 2.6: *Statistical assessment of developed direct models.*

respectively (see **Table 2.5**). For the corresponding mean values, the differences are -2.4, 0.8, 0.8 and -0.5 lm/W. Meanwhile, the minimum difference is zero for *Mb-4*, and between 6 and 14 lm/W for the others. This suggests that *M-1.4* offers the most accurate representation in terms of luminous efficacy values. Taking into account the statistical performance and stability, and the estimated luminous efficacy values, *Mb-2* can be considered the best performing model.

2.4.3. Published direct models

The models indicated in **Tables 2.1 & 2.2** are those commonly cited in the literature. All of the direct models mentioned in those Tables were evaluated using satellite data and those that gave the best results used for comparison with the proposed models. Some of the published models with many variables were excluded for this purpose since as one of the aims of this work was to generate simple models using widely available parameters only. The models considered for estimation of the direct luminous efficacy on horizontal surface were:

2.4.3.1. Aydinli et al. [3]

This is often referred to as a pioneering model based on spectral data. The relation between K_b and α is represented by the following polynomial function:

$$K_{b5} = -8.41 \times 10^{-10}\,\alpha^{-5} - 2.17 \times 10^{-6}\,\alpha^{4} + 0.00074\,\alpha^{3} - 0.0876\,\alpha^{2} + 4.459\,\alpha + 17.72 \quad (2.15)$$

2.4.3.2. Molineaux et al. [12]

This used the parameters of relative optical air mass (hereafter simply called air mass, m), atmospheric turbidity and water vapour content to develop three models. The model is based on the air mass expressed in the form of exponential function:

$$K_{b6} = 119 \exp(-0.1\, m) \quad (2.16)$$

2.4.3.3. Robledo et al. [16]

This model was developed using the brightness index, Δ, as an attenuation factor. The model was expressed in many forms; the simplest one is as following:

$$K_{b7} = 134.27\,(\sin\alpha)^{0.269}\, e^{-0.0045\alpha}\,(1.045 - 0.427\Delta) \quad (2.17)$$

2.4.4. Statistical performance of the published direct models

Similar statistical assessment to that used with the developed models, in **Section 4.2**, were

Table 2.5: Average statistical performance and estimated luminous efficacy differences for all direct models; over the originating and validation locations

Models		Statistical performance			K_b differences		
		MAD (%)	RMS (%)	MBD (%)	Max.	Min.	Mean
Mb-1	[Eq. 2.11]	3.8	5.2	-2.2	-5	6	-2.4
Mb-2	[Eq. 2.12]	**2.9**	**4.7**	-0.7	-1	7	0.8
Mb-3	[Eq. 2.13]	4.3	6.8	**0.9**	**0.3**	14	0.8
Mb-4	[Eq. 2.14]	3.5	6.2	-0.7	-2	**0**	**-0.5**
Aydinli	[Eq. 2.15]	15.1	18.5	-15.1	9	29	14.9
Molineaux	[Eq. 2.16]	10.0	14.3	-10.3	6	43	10.3
Robledo	[Eq. 2.17]	11.1	12.5	-10.2	13	17	10.4

used with the published models, in which they were used to generate illuminance values for the originating and validation locations and compared with the actual values for the corresponding locations. **Table 2.5** reports the average statistical performance of the estimated values. The MAD and RMS ranges are 10% : 15% and 12.5% : 18.5% respectively. The predicted value is underestimated by 10% : 15%.

The difference between the average estimated maximum and reference efficacy is within the range 6-13 lm/W with the difference between the mean values being between 10.3 and 14.9 lm/W. On this evidence the model developed by Molineaux appears to be the best of the published models investigated.

2.4.5. Comparison of the direct models

It is clear that no one of the proposed models performs best over all the fourteen locations in terms of all statistical indicators, although *Mb-2* is superior in 12 out of 14 locations in terms of MAD and RMS. However, that with the best overall performance can be selected by reference to the statistical indicators and the average difference between the luminous efficacy values of the reference values and those generated by the models. These may also be compared with the performance of the best published models.

Inspection of the statistical indicators and K_b differences in **Table 2.5** suggests that model *Mb-1*, the polynomial function for K_b against α, can be rapidly dismissed. Of the remaining models the best performers emerge as *Mb-2* and *Mb-4.* These are, respectively, K_b against sin α and K_b against *C*/α. Their statistical indicators for average MAD, RMS and MBD for *Mb-2* are 2.9%, 4.7% and -0.7% respectively; and for *Mb-4* are 3.5%, 6.2% and -0.7%. In terms of maximum average difference in luminous efficacy values their respective values are -1 and -2. The mean values have variation of -0.8 for *Mb-2* and -0.5 for *Mb-4*. Taking the statistical indicators and K_b differences together these models emerge as best. They are more than 3 times better, according to the statistical indicators, than the best published model, and have the least variation over the different geographical locations **(see Fig. 2.7)**.

Table 2.5 presents the maximum, minimum and mean differences between average luminous efficacy values estimated by the models and the reference values. The differences

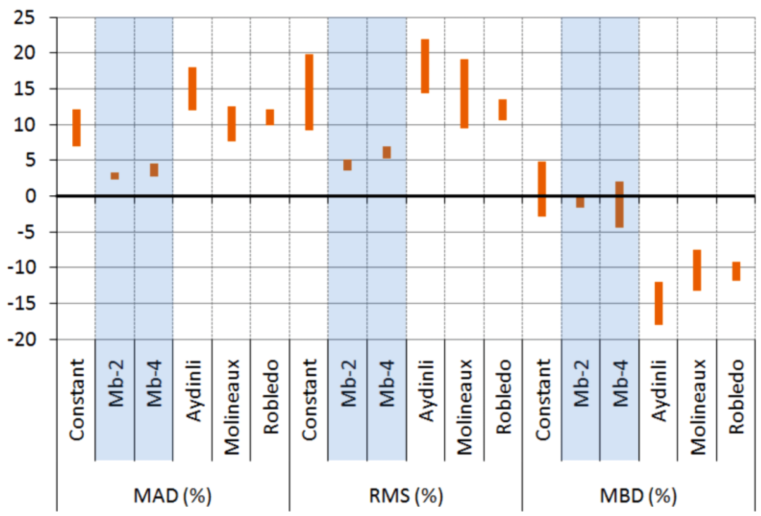

Figure 2.7: *Ranges of MAD, RMS and MBD values between the estimated and given direct luminous efficacy.*

for *Mb-2* and *Mb-4* are between zero and 7lm/W for maximum, minimum and mean, which are clearly superior to the published models. Of these Molineaux's model performs best in terms of the maximum and means, and Robeldo's for minimum. However the magnitudes of the differences are high – for example mean values vary by some 5 to 10 lm/W from those of the reference values.

2.4.6. Application of the proposed and published direct models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data gathered during International Daylight Measurement Year from the following locations [18]:

- Edinburgh (UK) Lat. 55.93˚N, Long. 3.30˚W
- Bratislava (SK) Lat. 48.17˚N, Long. 17.08˚E
- Arcavacata (IT) Lat. 39.36˚N, Long. 16.22˚E
- Fukuoka (JP) Lat. 33.52˚N, Long. 130.48˚E
- Hong Kong (CN) Lat. 22.40˚N, Long. 114.11˚E

The proposed models that included cloud amount, *Mb-3* and *Mb-4*, could not be tested since the measured data did not include simultaneous cloud amounts.

The average statistical performance of all models presented in **Table 2.6** shows no single model best performing over all locations. Performance of both developed models is very close in general, with slight superiority for *Mb-1* in terms of average performance over the five locations. They best perform in Edinburgh, Arcavacata and Fukuoka, Robledo's model is best in Edinburgh and Hong Kong, meanwhile, Molineaux's model is best in Bratislava. The average performance of all models, in terms of MAD and RMS, is of the range of 25.5-26%, and 34-37% respectively. Meanwhile in terms of MBD, the proposed models overestimate by 1.7-3.7%, and the published models underestimate by 5-10%. Apart from Aydinli's model, the other published and proposed models showed comparable performances. Thus, simplicity of proposed models tends to favour *Mb-1*.

2.5. GLOBAL LUMINOUS EFFICACY

2.5.1. Development of the proposed global models

2.5.1.1. Model developed from solar altitude

Using solar altitude, α, as the only independent variable, polynomial function for K_g against α was obtained by plotting the variation of K_g with α for all ten originating locations. **Fig. 2.8**

Table 2.6: Average statistical performance of proposed and published direct models

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Hong Kong		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
Mb-1	**39.8**	53.7	-15.5	13.6	22.3	6.6	**11.4**	20.6	**-0.7**	20.1	29.4	-6.6	44.1	55.5	24.5
Mb-2	40.1	54.1	**-14.3**	13.6	22.5	8.1	11.6	20.8	1.4	**18.9**	29.3	**-4.6**	46.5	57.9	28.0
Aydinli	42.6	54.4	-26.8	12.7	17.3	-7.6	15.6	21.5	-12.6	23.8	29.9	-17.3	37.7	47.9	14.5
Molinx	41.3	54.0	-22.6	**11.6**	**17.8**	**-1.3**	12.7	**19.1**	-7.3	21.5	**28.7**	-12.4	40.5	51.1	19.4
Robledo	**39.7**	**50.8**	-25.4	14.6	20.7	-3.1	14.6	21.4	-8.4	24.1	30.6	-14.4	**36.0**	**46.0**	**11.8**

shows the best fit curve, which is as follows:

$$K_{g1} = -0.0032\ \alpha^2 + 0.34\ \alpha + 104.46 \qquad (2.18)$$

In **Eq. (2.18)**, the lower threshold of luminous efficacy for values corresponding to α ≥ 55 may be assumed equal to the average maximum K_g of 114 lm/W. This assumption can be properly, but not necessarily, taken into account as the difference it makes was found to be insignificant.

2.5.1.2. Model developed from solar altitude and cloud amount

Cloud amount, *C*, used as a weighting parameter to investigate its effect over the luminous efficacy-solar altitude relationship. In **Fig. 2.9**, the values obtained for *C/α* was plotted against K_g for the ten originating locations giving an almost linear relationship. The best fit curve expressed as follows:

$$K_{g2} \text{ if } (C/\alpha) \geq 13.5 = 0.0513\ C/\alpha^2 - 1.3843\ C/\alpha + 114.28, \text{ otherwise} = 101 \qquad (2.19)$$

In **Eq. (2.19)** the lower threshold of luminous efficacy for values corresponding to (C/α) ≥

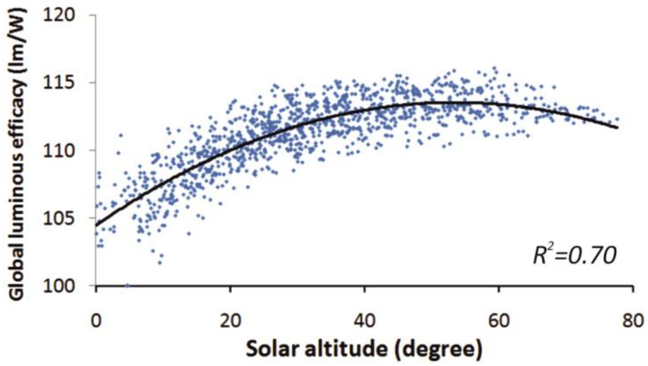

Figure 2.8: *Global luminous efficacy plotted against solar altitude.*

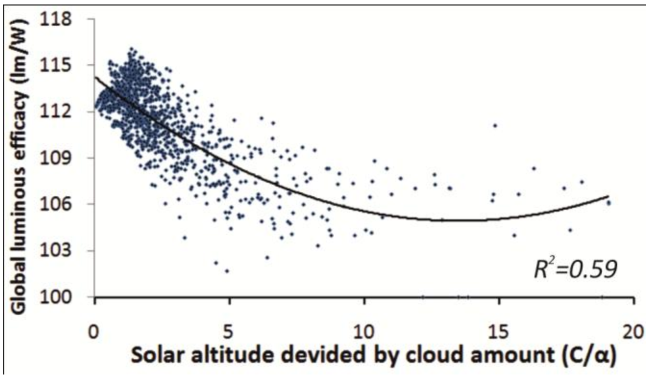

Figure 2.9: *Global luminous efficacy plotted against solar altitude and cloud amount* (C/α).

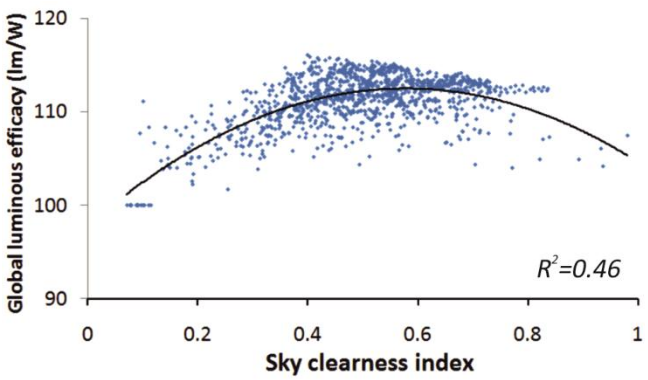

Figure 2.10: *Global luminous efficacy plotted against solar altitude and clearness index.*

13.5 (applicable to α ≤ 5˚) is assumed to be equal to the average minimum K_g of 101 lm/W.

2.5.1.3. Model developed from sky clearness index

The clearness index, k_t, is defined as the ratio of the global radiation at ground level on a horizontal surface and the extraterrestrial global solar irradiation. Muneer [14] concluded that the clearness index is the key parameter in the prediction of luminous efficacy since it appears to cause the greatest variation in global efficacy, and thus it was investigated in this study. The k_t values were estimated using **Eq. (2.2)**. The variation of K_g plotted against the k_t for all ten originating locations. **Fig. 2.10** shows the best fit polynomial curve, which is as follows:

$$K_{g3} = -44.008\, k_t^2 + 50.826\, k_t + 97.82 \qquad (2.20)$$

2.5.2. Statistical performance of the proposed global models

Statistical assessment similar to that carried out with the direct case has been carried out with the global case to identify the best performing proposed model.

Fig. 2.11 shows the statistical performance of the models described by **Eqs. (2.18) – (2.20)**, named *Mg-1*, *Mg-2* and *Mg-3* respectively. The statistical performance of the developed models showed good agreement between originating and validation locations. The results show a slight superiority of *Mg-1* over both *Mg-2* and *Mg-3* in terms of MAD and RMS, and very similar results in terms of MBD for either location. *Mg-1* had the statistical performance averages MAD = 1.1%, RMS = 1.5% and MBD = 0%, for the originating locations and MAD = 1.1%, RMS = 1.4% and MBD = 0% for the validation locations. Originating and validation location performances thus showed good agreement**.** *Mg-1* is more stable than the other two models. The differences for *Mg-1* between minimum and maximum values of MAD, RMS and MBD are 0.7%, 0.9% and 2.3% respectively, compared with 1.4%, 1.1% and 3.4% for *Mg-2*, and 1.5%, 1.8% and 2.5% for *Mg-3*. It is worth noting that underestimation of luminous efficacy tends to occur in the Northern locations.

Comparison between the averages of the reference efficacy value and the estimated values; shows differences between the maximum values of 1.4, 0.9 and 2.4lm/W for *Mg-1*, *Mg-2* and *Mg-3* respectively. The average minimum of *Mg-1* is 4lm/W more than the reference, while it is -/+ 0.8lm/W for *Mg-2* and *Mg-3*. The differences between the average mean values for all models are negligible at 0.1-0.2lm/W. The differences between the models in terms of maximum and mean values are insignificant (see **Table 2.7**).

The differences between the ‘estimated efficacies values’ suggest that all models could potentially be used for estimation purposes. However the statistical performance tends to favour model *Mg-1* which also has the additional benefit of simplicity.

2.5.3. Published global models

All models mentioned in **Tables 2.1 & 2.2** were evaluated using satellite data and those that gave the best results used for comparison with the proposed models. The models considered for estimation of the global luminous efficacy on horizontal surface were:

2.5.3.1. Ullah [7]

The author expresses the correlated global luminous efficacy solely to the solar altitude for clear skies as a fourth degree polynomial of α. The following formula based on a measured data from Singapore:

$$K_{g4} = 107.33 + 1.1416\alpha - 0.042288\alpha^2 + 0.53949 \times 10^{-3}\alpha^3 - 0.2347 \times 10^{-5}\alpha^4 \qquad (2.21)$$

2.5.3.2. Muneer et al. [14]

This model is for all sky types. The authors express the correlated global luminous efficacy solely to the clearness index as a second degree polynomial of k_t. The following formula

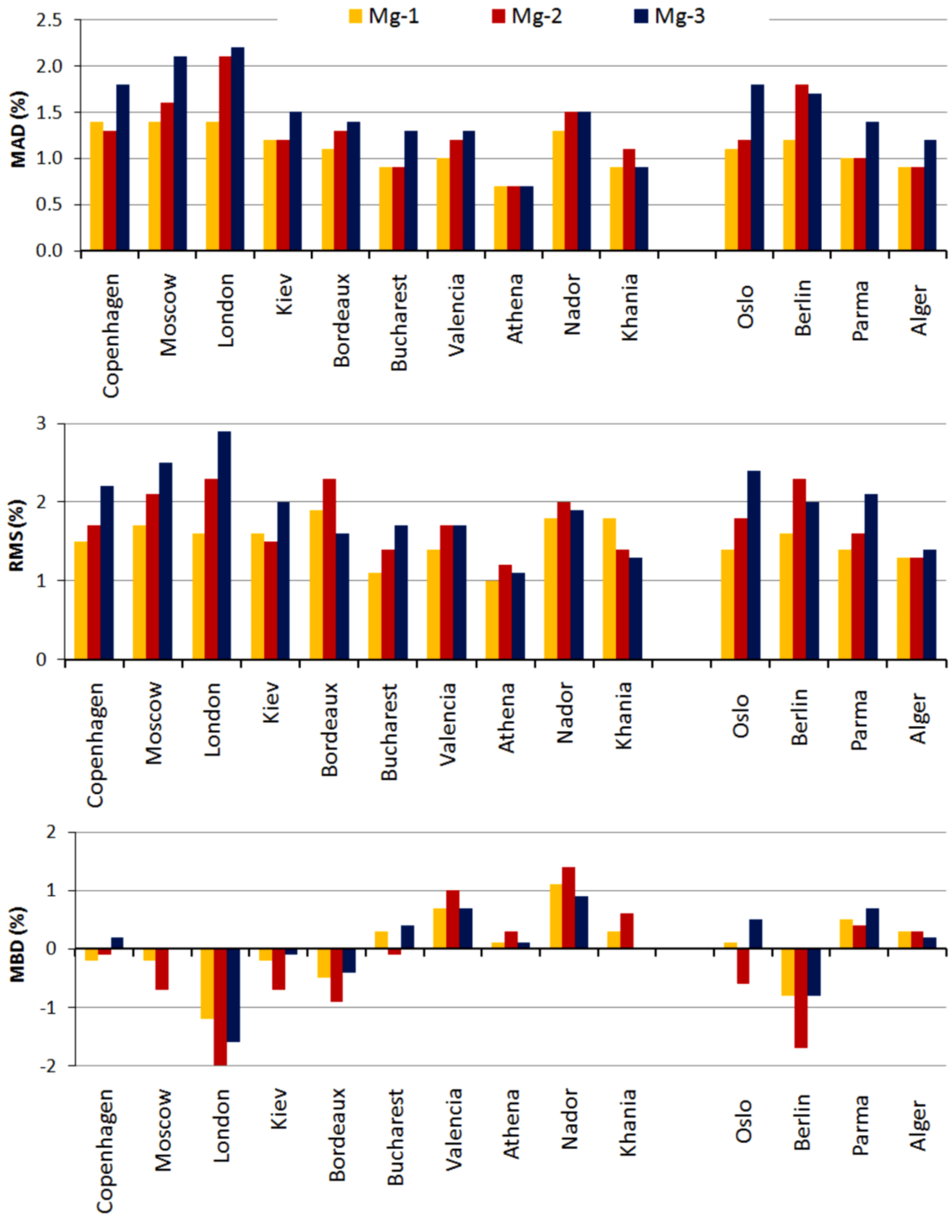

Figure 2.11: *Statistical assessment of developed global models.*

based on a measured data from five sites in the UK:

$$K_{g5} = 136.6 - 74.541\, k_t + 57.3421\, k_t^{2} \quad (2.22)$$

2.5.3.3. Ruiz et al. [15]

This model is for all skies types. The authors correlated the global luminous efficacy to the sine of solar altitude and to clearness index. The following formula based on a measured data from Madrid:

$$K_{g6} = 104.83(\sin \alpha)^{0.026}\, k_t^{-0.108} \quad (2.23)$$

2.5.4. Statistical performance of the published global models

Similar statistical assessment to that used with the developed models were used with the published models, in which they were used to generate illuminance values for the originating and validation locations and compared with the actual values for the corresponding locations.

Table 2.7 reports the average statistical performance of the estimated values from the published models. In terms of MAD indicator, Ruiz's model is the best performer with average of 3.4% against 4.1% for each of the other models. Both Ruiz's and Ullah's had a similar stability at around 1%, against 3.4% for Muneer's. The RMS indicator illustrates that the average performance of both Ruiz's and Ullah's is around 5%, against 6.5% for Muneer's. Ruiz's and Ullah's showed a similar stability around 1.5% against 3.4% for Muneer's. Since the MBD indicator has positive and negative values, the average performance may be misleading, and thus the stability value is considered to be best described in terms of MBD. Ullah's comes first with stability of 2.1%, then Ruiz's with 3.8% and Muneer's with 4.7%.

Comparison between the averages of each of the reference and estimated efficacies values, estimated using the published models, shows the following. The maximum value for Ullah's model is 2.7lm/W more than the reference, which is much better than the 17.8lm/W and 13.3lm/W achieved respectively by Muneer's and Ruiz's models. Ruiz's minimum and mean differences are best with values of 0lm/W and 0.4lm/W respectively; if compared with the 7lm/W and 2.8lm/W achieved by Ullah's, or 11.4lm/W and 3.8lm/W achieved by Muneer's.

The above suggests that Ruiz's model is the best in estimating illuminance data from satellite irradiance data.

Table 2.7: Average statistical performance and estimated luminous efficacy differences for all global models; over the originating and validation locations

Models		Statistical performance			K_g differences		
		MAD (%)	RMS (%)	MBD (%)	Max.	Min.	Mean
Mg-1	[Eq. 2.18]	**1.1**	**1.5**	**0.0**	**-1**	4	**-0.2**
Mg-2	[Eq. 2.19]	1.3	1.8	-0.2	**-1**	**-1**	-0.4
Mg-3	[Eq. 2.20]	1.5	1.9	0.1	-2	**1**	**-0.1**
Constant	111.4	2.0	2.7	0.3	-	-	-
Ullah	[Eq. 2.21]	4.1	4.8	2.7	3	7	2.8
Muneer	[Eq. 2.22]	4.1	6.5	3.5	18	11	3.8
Ruiz	[Eq. 2.23]	3.4	5.1	0.5	13	0	0.4

2.5.5. Comparison of the global models

Statistical performances and differences between reference and estimated luminous efficacies over the fourteen locations were used to compare developed and published models, and a constant luminous efficacy of 111.4lm/W representing the average of the mean efficacies values for the originating locations. This derived constant value compares with the value of 110lm/W suggested by De Rosa [18].

Table 2.7 shows that *Mg-1* has the best statistical performance among the developed models, that of Ruiz among those published, and the constant value somewhere between the two. The statistical indicators suggest that *Mg-1* performs more than three times better than Ruiz's model, the best published one, and around twice that of the constant value**.** The MAD indicator shows that *Mg-1* ranges around 1.1% with stability of 0.7%, whilst the constant value ranges around 2% with stability of 1.5%, and Ruiz's ranges around 3.4% with stability of 1%. In terms of RMS, 1.5%, 2.8% and 5.1% are the ranges of Mg-1, constant value and Ruiz's respectively, with stabilities of 0.9%, 1.4% and 1.4%. The MBD indicator tells that the constant value is the most stable one with a difference of 1.6% compared with 2.3% and 2.9% for *Mg-1* and Ruiz's respectively (see **Fig. 2.12**).

2.5.6. Application of the proposed and published global models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data from the locations previously mentioned in **Section 2.4.6**.The proposed model that included cloud amount (*Mg-2*) could not be tested since the measured data did not include simultaneous cloud amounts.

The statistical performance of *Mg-1*, all published models and the constant value, presented in **Table 2.8**, shows that no single model performs best over all locations. The constant value is best for Bratislava and Hong Kong, closely followed by *Mg-1* (less than 0.5%). Muneer's model is best for Edinburgh and Fukuoka, and Ruiz's for Arcavacata. Although Ullah's model did not perform best in any location, its average performance over the five locations compares well with the constant value. Both have the following averages ; MAD = 9.9%, RMS = 13.8%, with MBD = -1.1% for the constant value and 1% for Ullah's.

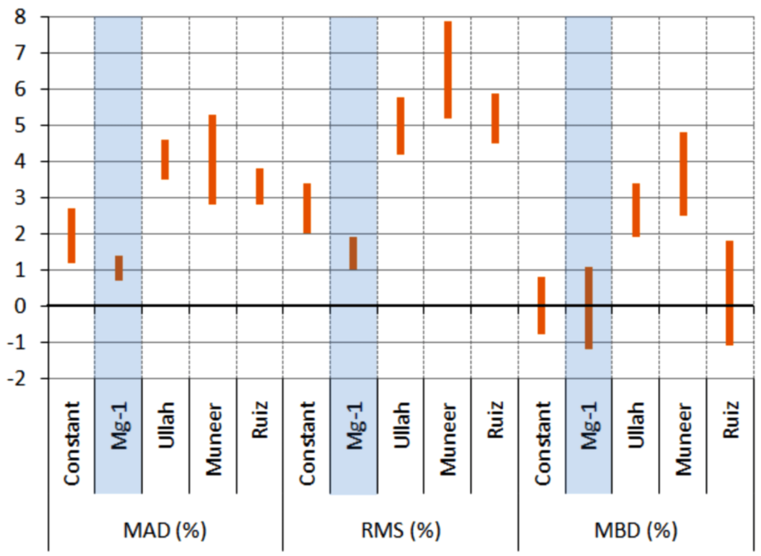

Figure 2.12: *Ranges of MAD, RMS and MBD values between the estimated and given global luminous efficacy.*

Mg-1 came next with not more than 0.2-0.3% difference for each of the statistical indicators. Muneer's model was next with 10.4%, 14.4% and 5.2% for the MAD, RMS and MBD respectively, and finally Ruiz with 1-2% difference between its averages and the best performance over all the statistical indicators.

Though the differences between the statistical performance of *Mg-1*, the constant value and Ullah's model are insignificant, *Mg-1* and the constant value show more stability than Ullah's; with values of 8.7% and 11% for the MAD and RMS respectively compared with 11.1% and 13.3% for Ullah. *Mg-1*, the constant value and Ullah's exhibit similar stability in terms of MBD at around 21.7%. Muneer's and Ruiz's stabilities are 2-6.5% more than *Mg-1* for all the indicators.

The previous comparison shows that constant value of 111.4lm/W gives the best performance along with model *Mg-1*, the second degree polynomial formula of solar altitude solely, followed by Ullah's model. Muneer's and Ruiz's models have been developed to predict global luminous efficacy under all skies types, the former is a second degree polynomial formula derived solely from the clearness index, and the later is a power formula using the sine of solar altitude and clearness index. They are both more complicated than the alternatives, tend to overestimates luminous efficacies values, and are much less stable than *Mg-1*.

2.6. DIFFUSE LUMINOUS EFFICACY

2.6.1. Development of the proposed diffuse models

2.6.1.1. Model developed from solar altitude

Using solar altitude as the only independent variable, linear function for K_d against α was obtained by plotting the variation of K_d with α for all ten originating locations. **Fig. 2.13** shows the best fit curve, which is as follows:

$$K_{d1} = 0.0215\,\alpha + 122.52 \quad (2.24)$$

2.6.1.2. Model developed from solar altitude and cloud amount

Cloud amount used as a weighting parameter to investigate its effect over luminous efficacy-solar altitude relationship. In **Fig. 2.14**, the values obtained for $\alpha\,(1\text{-}C)$ was plotted against K_d for the ten originating locations. The best fit curve expressed as follows:

$$K_{d2} = 114.1\,(\alpha\,(1\text{-}C))^{0.109} \quad (2.25)$$

Table 2.8: Average statistical performance of proposed and published global models

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Hong Kong		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
Mg-1	6.6	9.0	-5.1	8.5	12.4	**0.4**	8.9	15.0	-2.6	11.6	13.9	-10.5	15.3	19.8	11.5
111.4	6.3	8.4	-4.8	**8.1**	**12.1**	0.7	8.7	14.8	-2.1	11.6	13.6	-10.6	**15.0**	**19.5**	**11.1**
Ullah	5.4	7.8	-2.5	9.0	13.0	3.3	8.2	15.1	0.6	9.9	12.0	-8.8	16.4	21.1	12.7
Muneer	**4.1**	**6.1**	**0.6**	12.8	17.7	11.0	**8.0**	15.0	3.0	**7.9**	**9.8**	**-6.2**	19.1	23.6	17.6
Ruiz	5.0	6.9	-2.6	15.2	22.3	12.6	8.4	**14.3**	**-0.5**	9.6	11.5	-8.6	17.2	22.0	15.6

2.6.1.3. Model developed from sky clearness index

The variation of K_d plotted against the k_t for all ten originating locations. **Fig. 2.15** shows the best fit curve, which is as follows:

$$K_{d3} = 29.492\, k_t^{\,3} - 18.305\, k_t^{\,2} + 3.5567\, k_t + 121.83 \qquad (2.26)$$

2.6.2. Statistical performance of the proposed diffused models

Statistical assessment similar to that carried out with the direct case has been carried out with the diffused case to identify the best performing proposed model.

Fig. 2.16 shows the statistical performance of the models described by **Eqs. (2.24) – (2.26)**; namely *Md-1*, *Md-2* and *Md-3*. The statistical performance of the developed models shows agreement between the originating and validation locations. The results show slight superiority of *Md-3* over both *Md-1* and *Md-2* in terms of MAD and RMS, and very similar results in terms of MBD for both originating and validation locations (see **Table 2.9**). *Md-3* has the following statistical performance averages: MAD = 1.6%, RMS = 2.2% and MBD = 0%, from the originating locations and the MAD = 1.4%, RMS = 1.9% and MBD = 0.3% from the validation locations. Originating and validation location performances show good

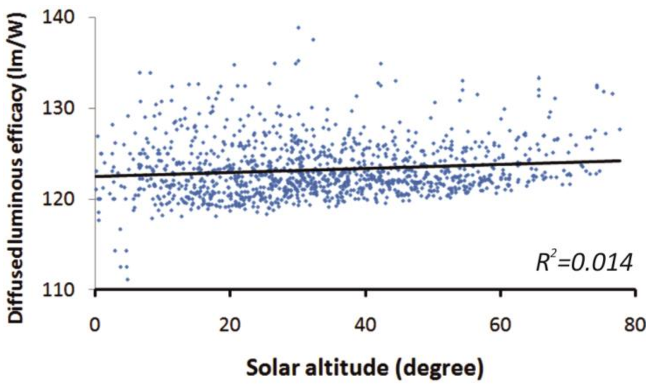

Figure 2.13: *Diffused luminous efficacy plotted against solar altitude.*

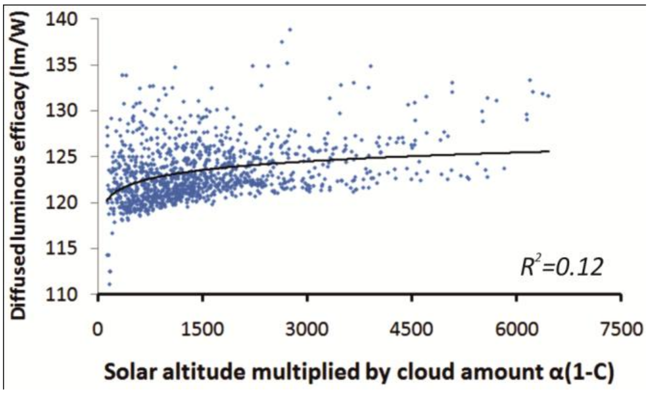

Figure 2.14: *Diffused luminous efficacy plotted against solar altitude and cloud amount* [*α(1-c)*].

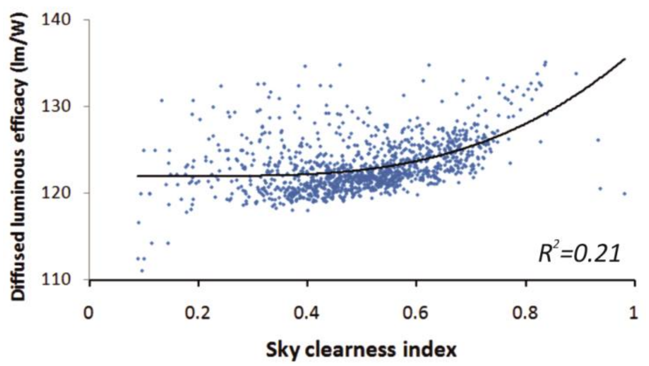

Figure 2.15: *Diffused luminous efficacy plotted against solar altitude and clearness index.*

agreement. *Md-3* performance is more stable than the other two models in terms of MBD, but very similar to them in terms of MAD and RMS. This is apparent from the variations of the statistical indicators over the fourteen locations. The differences between minimum and maximum values of MAD, RMS and MBD for *Md-3* are 1.4%, 2% and 3.5% respectively, compared with 1.9%, 2.6% and 5% for *Md-1*, and 1.3%, 1.7% and 4.5% for *Md-2*. It is worth mentioning that underestimation of luminous efficacy tends to occur in the Southern locations.

Comparison between the averages of the reference efficacy value and the estimated values; shows that the differences between the maximum values are 8, 8 and 4 lm/W for *Md-1*, *Md-2* and *Md-3* respectively, and between the minimum values are-12, -7, -11lm/W. Negligible difference of 0.1-0.2lm/W are noted between the average mean values for all models. The differences between the models in terms of maximum and minimum values

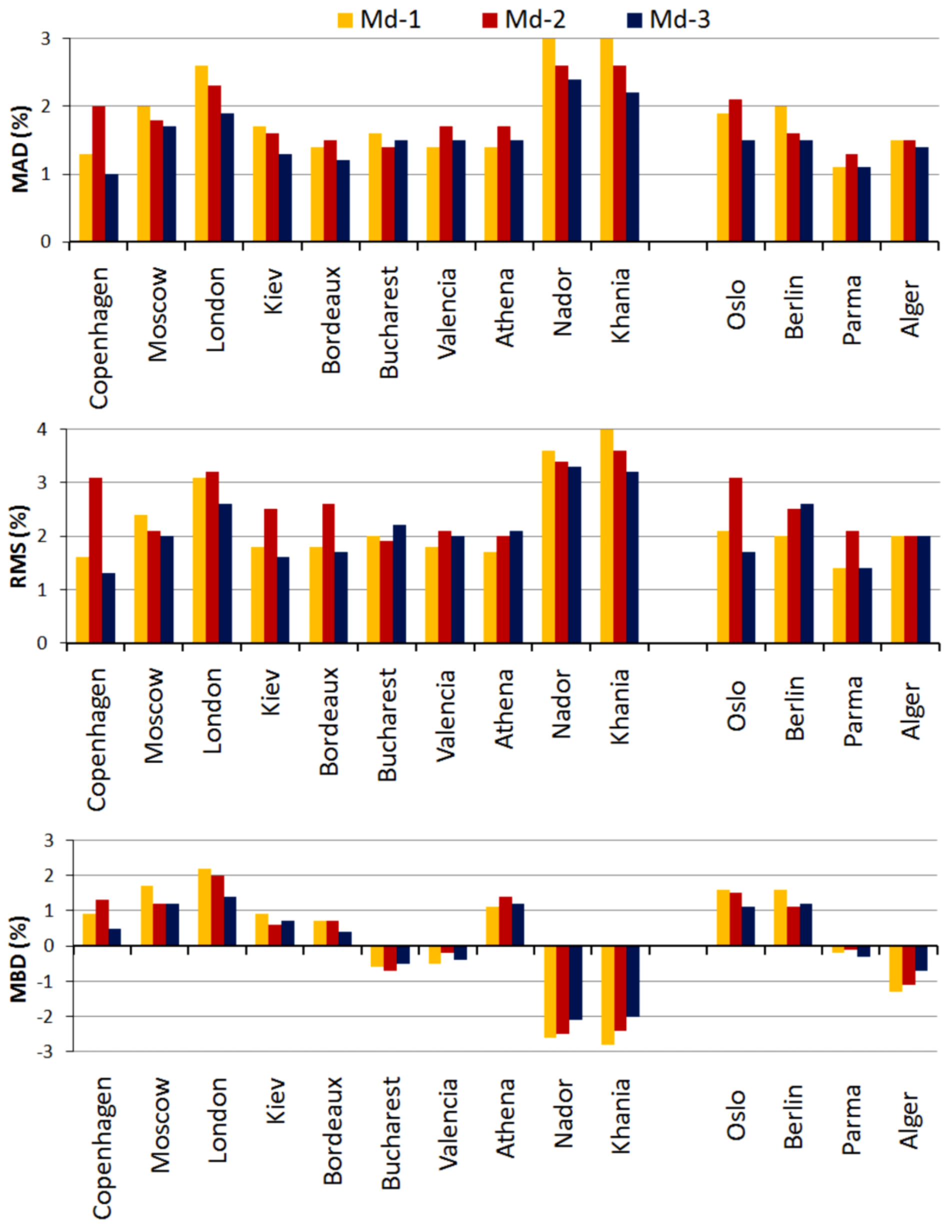

Figure 2.16: *Statistical assessment of developed diffused models.*

are significant, whilst those in terms of mean values are negligible.

Although the statistical performance tends to favour *Md-3* model, the simplicity of *Md-1* makes it a practically useful since the differences are small. In terms of 'estimated efficacy values' no one model stands out.

2.6.3. Published diffused models

All of the models mentioned in **Tables 2.1 & 2.2** were evaluated using satellite data and those that gave the best results used for comparison with the proposed models. Some of the published models with many variables were excluded for this purpose since as one of the aims of this work was to generate simple models using widely available parameters only. The models considered for estimation of the diffused luminous efficacy on horizontal surface were:

2.6.3.1. Muneer et al. [14]

This model is for all skies types. The authors express the correlation of K_d solely to the clearness index as a second degree polynomial of k_t. The following formula based on a measured data from five sites in the UK:

$$K_{d4} = 130.2 - 39.828\, k_t + 49.9797\, k_t^{2} \qquad (2.27)$$

2.6.3.2. Robledo et al. [9]

The authors correlated the K_d to the sinus of solar altitude and to sky brightness index Δ. A model developed with different coefficients for clear, intermediate and overcast skies, in addition to coefficient for all skies. The following formula for all skies based on a measured data from Madrid, and thus coefficients may change somewhat for other locations; as stated by the authors [9]:

$$K_{d6} = 82.24(\sin\alpha)^{-0.034}\, \Delta^{-0.266} \qquad (2.28)$$

2.6.3.3. Ruiz et al. [15]

This model is for all skies types. The authors correlated the K_d to the sinus of solar altitude and to diffused clearness index k_d. The authors suggest that for diffuse illuminance estimation the ratio of diffuse to extraterrestrial irradiance is to be preferred as independent variable to the ratio of global to extraterrestrial irradiance used in Muneer's Model [14]. The following formula based on a measured data from Madrid:

$$K_{d6} = 86.97(\sin\alpha)^{-0.143}\, k_d^{-0.218} \qquad (2.29)$$

2.6.4. Statistical performance of the published diffused models

The published models have been used, as well as the developed models, to generate illuminance values for all the originating and validation locations. Thus the generated values were compared with the actual values for the corresponding locations.

Comparison between Ruiz's model and the other two lead to it being rapidly dismissed. Its MAD, RMS and MBD are much inferior to the other two models. Muneer's model obtained averages of 1.9%, 3.3% and 0.7% for MAD, RMS and MBD respectively compared with 5.6%, 7.6% and 4.9% for Robledo's (see **Table 2.9**). Both showed a similar stability at around 1.4% and 2.2% for MAD and RMS respectively, whilst in terms of MBD Robledo's achieved stability of 1.9% against 3.6% for Muneer**.**

Comparison between the averages of each of the reference and estimated efficacies values, estimated using the published models, shows differences between the maximum values are 2 and -24 lm/W for Muneer's and Robledo's respectively, between the minimum values are-11 and 0 lm/W, and between the mean values of 0.7 and -5.9 lm/W (see **Table 2.9**).

The statistical performances and estimated efficacies of the published models suggest that Muneer's model is the best in estimating illuminance data from satellite irradiance data.

2.6.5. Comparison of the diffuse models

Statistical performances and differences between reference and estimated luminous efficacies over the fourteen locations were used to compare between developed and published models, in addition to constant luminous efficacy value of 123lm/W. The derived constant value is equal to that suggested by De Rosa [18].

From **Table 2.9** it can be noticed that among the developed models *Md-3* shows the best statistical performance by a very slight margin. The best performing published models is clearly Muneer's. The constant value gave the same average performance as the developed models. Taking the statistical performance into account, the MAD indicator for any of Muneer's model, the constant value and the developed models is about the same. Muneer's RMS is 1% more than them, and its MBD is only 0.5% ahead. **Figure 2.17** illustrates the similarity of the constant value, *Md-1*, *Md-3* and Muneer's model, and the difference between them and Robledo's model, though it looks more stable. The MAD indicator shows values of around 1.9% for all of them apart from Robledo's is around 5.6% with best stability of 1% for Muneer's. In terms of RMS, 2.3% is the range for the constant value and the developed models, whilst 3.4% and 7.6% are the ranges of Muneer's and Robledo's models respectively; with best stability of 1.6% for Robledo's. The MBD indicator as well indicates that Robledo's model is the most stable one with difference of 1.6% though gained the highest range around 4.9%; in compare with 0% for the constant value and developed models, and 0.7% for Muneer's.

Table 2.9: Average statistical performance and estimated luminous efficacy differences for all diffused models; over the originating and validation locations

		Statistical performance			**K_g differences**		
Models		MAD (%)	RMS (%)	MBD (%)	Max.	Min.	Mean
Mg-1	[Eq. 2.24]	1.9	**2.2**	**0.2**	8	-12	**-0.2**
Mg-2	[Eq. 2.25]	1.8	2.6	**0.2**	8	-17	**-0.1**
Mg-3	[Eq. 2.26]	**1.6**	**2.1**	**0.1**	4	-11	**-0.2**
Constant	123	1.8	2.3	**0.2**	-	-	-
Muneer	[Eq. 2.27]	1.9	3.3	0.7	**2**	-11	-0.7
Robledo	[Eq. 2.28]	5.6	7.6	4.9	24	**0**	-5.9

Estimated efficacies values by the developed models gave means exhibiting negligible differences with the reference mean with Muneer's model showing a 0.7% difference and Robledo's a large difference of 5.9%.

2.6.6. Application of the proposed and published diffused models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data from the locations previously mentioned in **Section 4.6**.The proposed model that included cloud amount (*Md-2*) could not be tested since the measured data did not include simultaneous cloud amounts.

The statistical performances of the developed models *Md-1* and *Md-3*, and the published Muneer's and Robledo's models, in addition to the constant value 123lm/W, are as presented in **Table 2.10**, which shows that Robledo's model exhibits the best performs in Fukuoka only. The performances of all the others are generally close with differences between any two indicators generally not exceeding 1.3%. *Md-3* performs best in Edinburgh, joint top in Hong Kong (with the constant value), in Bratislava (with *Md-1*), and in Arcavacata (with Muneer's model) (see bold values in **Table 2.10**). In terms of average performance over all locations, the MAD for all of them is 11.5-11.8%, but Robledo's is 17.8%. The RMS is 14.3-14.6% and 25.1% for Robledo's.

Robledo's model shows a lack of stability with values of 20%, 33% and 40% for MAD, RMS and MBD respectively. The others have similar stabilities. In terms of MAD, the range is 11.5-13% with Muneer's the best. The range of RMS is 13.7-15% with *Md-1* and the constant value best. The MBD range is 23.8-24.2%; Md-3 and the constant value perform best.

The previous comparison shows that constant value of 123lm/W gives the best performance along with the developed models *Md-1*, and *Md-3*, in addition to Muneer's model. Given very close results, they may be ranked according to their simplicity as: constant value first, the linear formula of solar altitude *Md-1* next, and the polynomial formulas of clearness index *Md-3*, and finally Muneer's model.

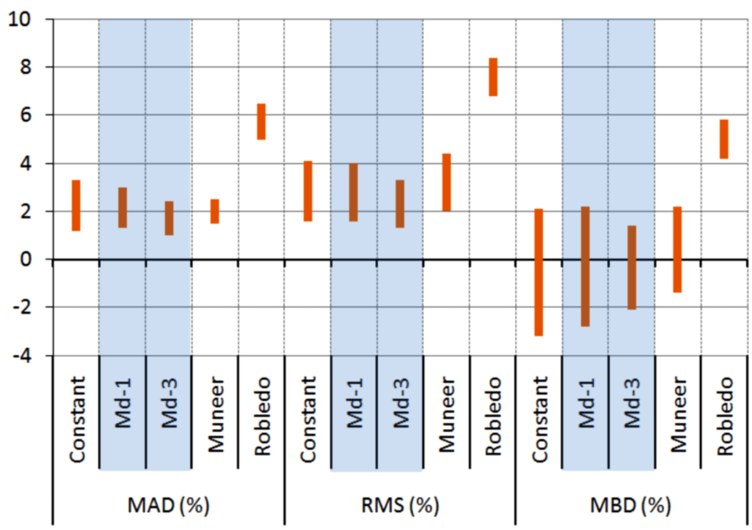

Figure 2.17: *Ranges of MAD, RMS and MBD values between the estimated and given diffused luminous efficacy.*

2.7. CONCLUSION

Design processes of daylighting systems face barriers of lack of measured daylight data. Therefore, conversion of the much more widely available irradiance data emerges as acceptable way to obtain illuminance data using the concept of luminous efficacy. A number of models and constant values are suggested in solar literature to estimate luminous efficacy; based variously on the relation between luminous efficacy and solar altitude and/or metrological parameters. Some of them require more extensive data to calculate local coefficients, which is a limiting factor in their wider applicability.

This work presents a new method of estimation of horizontal direct, global and diffused luminous efficacies based on satellite data which is available for all points on earth's surface. The result is constant values and universal models with a minimum requirement for additional variables or coefficients. It makes the availability of realistic design illuminance data independent of the availability of local measured daylight data. For these reasons the satellite based approach to generation of illuminance data is likely to become increasingly important for design purposes.

The new approach was developed using satellite data for ten locations in Europe and North Africa. The proposed methods were developed from the relation between the luminous efficacy and any of solar altitude, cloud amount or sky clearness index. The methods presented here produce more accurate estimates of luminous efficacy than existing published models. The work suggests that the methods can be applied to a wide range of geographical locations.

Direct, global and diffused horizontal illuminance values were estimated using the proposed models. A statistical assessment of estimated and actual values showed that the direct models *Mb-2* and *Mb-4* give the best performance over the fourteen locations. The same statistical assessment tools were used with the published models. Comparison between proposed and published models showed that the use of models *Mb-2* and *Mb-4* gave efficacy values with low statistical errors over a wide range of locations, regardless their characteristic sky conditions and more than three times more accurate than the published models. Among the proposed global and diffused models, the models based on solar altitude, *Mg-1* and *Md-1*, emerged as the simplest and best statistically performing models over the fourteen locations. Compared with the published models, the statistical performance of *Mg-1* is up to three times more accurate than the best performing published global models, Ruiz's model. The global constant value showed better statistical

Table 2.10: Average statistical performance of proposed and published diffused models

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Hong Kong		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
Md-1	5.4	6.2	**0.7**	**10.1**	**13.0**	**3.3**	**14.4**	**20.0**	-1.9	17.5	19.4	-17.5	11.4	14.0	6.6
Md-2	**4.6**	**5.3**	**0.8**	**10.1**	**13.2**	**3.2**	**14.4**	**20.2**	-1.2	17.5	19.2	-17.4	**11.0**	**13.6**	**6.4**
123	5.4	6.2	**0.6**	**10.0**	**13.0**	**3.1**	**14.4**	**19.9**	-2.1	17.7	19.6	-17.7	**11.2**	**13.8**	**6.2**
Muneer	5.1	5.7	1.9	11.1	14.0	5.7	**14.6**	20.5	**0.2**	16.6	18.5	-16.5	11.7	14.3	7.7
Robledo	11.0	14.3	1.7	31.2	47.8	28.1	16.8	24.7	8.7	**14.4**	**16.1**	**-12.4**	15.5	22.4	11.6

performance than the published models, but *Mg-1* still twice as good as illustrated in **Table 2.7**. *Md-1* performance is up to 1.5 times more accurate than the best performing published diffused models, that of Muneer. The diffused constant value achieved similar performance to *Md-1*.

In the final part of each illuminance component in this study, the constant values, the published and proposed models were used to estimate direct, global and diffused illuminance data for five locations for which actual irradiance and solar altitude data was available. The statistical indicators showed that both *Mb-1* and *Mb-2* produced comparable illuminance values with that produced by the published models by Robledo and Molineaux, but the proposed models got the simplicity advantage (see **Table 2.6**). The statistical indicators showed that *Mg-1* and the global constant value slightly produce more accurate estimates of global luminous efficacy than the published models, but without the use of extensive local data (see **Table 2.8**). All of the diffused constant value, *Md-1* and Muneer's model produce very close estimates of the diffused luminous efficacy (see **Table 2.10**). Therefore, simplicity points out the constant value as the most favourable method.

This work has its origins in study of daylight guidance systems but could equally be applied to other lighting technologies. The results suggest that the different methods of estimating luminous efficacy show substantial differences. Those between some of the models and the reference data are of the order of 10 to 15 lm/W. This is a significant difference when converted to illuminance. This has implications for sizing of devices such as roof-lights or guidance systems, which in turn may influence their performance in use and economic viability. Importantly the techniques described here permit accurate estimation of direct, global and diffused luminous efficacy, and hence daylight amounts, for all locations for which satellite irradiance data is available. This makes daylight data available to designers at locations remote from current measurement sites.

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CHAPTER

3

HLS Review

3.1. INTRODUCTION

Electric lighting is dominant in the majority of modern buildings. It offers the designer the opportunity to create an attractive and economic lit interior within any building configuration. Since electric lighting is a major energy consumer there is a case for the provision of daylight as a substitute. Also research has confirmed user preference for daylight in working interiors which has implications for user satisfaction and well-being. Taken together this makes the provision of daylight, or at least the perception of daylight, a powerful design aspiration for modern commercial buildings.

In vernacular architecture elements evolved to reflect, re-direct or control daylight. Conventional glazed windows can provide daylight some five metres into a building. But since daylight levels decrease asymptotically with distance from the window, a disproportionate amount of daylight and associated heat gain must be introduced into the front of a room to provide small amounts of daylight at the rear. Attempts to direct daylight to areas remote from the building envelope using techniques such as atriums and skylights are limited in effectiveness by contemporary technology.

Over the last fifty years or so, a number of highly efficient reflective and refractive materials have been developed making possible what has become known as 'light guidance'. Light from both daylight and electric sources may be guided. Both have a common characteristic that the light path from source to receiver may undergo a large number of optical processes over a distance, typically, of some metres. It is this feature that sets the systems described in this chapter apart from conventional lighting techniques in which distance from source to point of use is kept to a minimum.

3.2. SYSTEMS CLASSIFICATION

There are two main approaches to increase the penetration distance of daylight into buildings, either by redirecting or guiding it. The former may called '*Beam daylighting*', in which redirection of sunlight by adding reflective or refracting elements to conventional windows; essentially enhancing traditional devices such as louvers or light shelves using the new optical materials. *Guided daylight* introduces it deep into electrically lit buildings through light pipes or fibre optics, although current practice is to use the electric and daylight systems separately with minimal interaction. The most widely used guiding system is known as Tubular Daylight Guidance Systems (TDGS).

Attempts to improve guided daylight seek to better combine the delivery of daylight and electric light to the same space using two main approaches - ‘integrated lighting’ and ‘hybrid lighting’. *Integrated lighting* uses separate daylight and electric lighting systems (the daylight being either conventional or guided) but with adjacent output devices and a linked control system. *Hybrid Lighting Systems* (HLS) attempt to simultaneously deliver daylight and electric lighting to an interior space. In these systems, daylight is channelled into the core of a building where it is combined with electric light within luminaires that are equipped with controls that maximise use of available daylight. Optical control is thus similar to a luminaire rather than the simple diffusers used in the more basic daylight guidance systems.

Table 3.1 summarise the main characteristics of the three classified guided daylight systems; named daylight guidance, integrated daylight systems, and hybrid lighting systems. The following sections describe them in details and give examples for some developed systems, either released or not, in each category.

3.3. DAYLIGHT GUIDANCE

Although TDGS is the only form of guidance having wide commercial application, a number of other types, notable because their technology has been adapted for use in integrated and hybrid systems, are also reviewed in this section.

3.3.1. TDGS

TDGS are simple passive devices, cheap to manufacture, and effective under both clear and overcast skies. Their main application is in single storey buildings. Light transport is usually via a rigid tubular guide lined with a highly reflective material. A clear polycarbonate domed collector at the upper end may be horizontal or inclined at some angle to the guide axis. A

Table 3.1: Lighting system characteristics

Aspect	Tubular daylight guidance	Integrated lighting system	Hybrid lighting system
Daylight sources	Skylight and sunlight	Skylight and sunlight	Sunlight
Daylight delivery	Tubular daylight guidance	Conventional glazing, beam daylighting or tubular daylight guidance	Tubular daylight guidance
Electric lighting	Conventional luminaires at point of use	Electric light may be guided as supplement to daylight	Electric light may be guided
Method of use	Separate daylight and electric light	Uses daylight as main source automatically supplemented by electric light as required	
Control system	Usually no daylight linking	Fully daylight linked	
Output device	Separate daylight output devices and electric luminaires	Separate output devices for daylight and electric light, electric lighting may be ‘intelligent’	One output device is used for both lighting sources
Quality of delivered light	Optical control of daylight by diffuser and electric light by luminaire, source colour differences apparent	Optical control of daylight depends on particular system. Electric light control by luminaire, source colour differences apparent	Optical control of all light by luminaire, source colour may vary

diffuser at the lower end distributes light within the building (see **Fig. 3.1**). TDGS have been the subject of considerable research. CIE Report 173 discusses system characteristics and selection and sets out standard photometry and design/analysis methods [1]. Using these it is possible to estimate likely flux outputs, system efficiencies and daylight distributions of TDGS under a variety of sky conditions. The CIE Report puts forward the Daylight Penetration Factor (DPF) to quantify daylight penetration via light guidance devices. This is analogous to the Daylight Factor (DF) used for conventional glazing. Whilst DF is the illuminance received at a point indoors expressed as a percentage of the **exterior skylight illuminance**, the DPF is the illuminance received at a point indoors via a light guide expressed as a percentage of the **global exterior illuminance**. Area weighted average values of each may be calculated (ADPF or ADF respectively). Combination of the two quantities (ADPF+ADF) enables a quantitative assessment of the total daylight contribution from the various daylight providers.

Post-occupancy evaluation studies of TDGS in offices suggest that although TDGS devices are recognised as daylight providers, current design practice produces ADPF+ADF of the order of 1% on the working plane. This was not considered by users to produce a well day-lit interior, a result that led to the suggestion that a design criterion nearer 2% may be required [2]. A long term cost study showed that TDGS provided poor economic return when viewed solely in cost terms but that this needs to be balanced by consideration of the value of the daylight delivered into a working area [3].

3.3.2. Façade mounted systems

These consist of a façade mounted light gathering device oriented toward the equator, a horizontal guide system within a suspended ceiling, and output devices located deep in a building. They are used in conjunction with conventional lower windows and electric lighting systems. The light collector is a curved mirror or other device which deflects daylight into a mirrored guide. This technology is intended for office buildings but only a few systems appear to have advanced beyond the prototype stage.

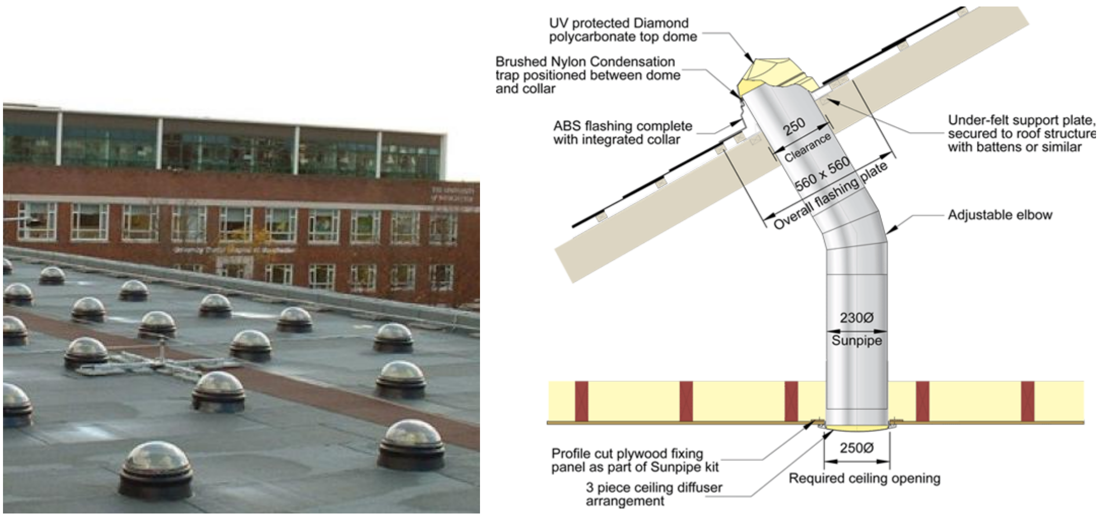


Figure 3.1: *TDGS collectors* (left); *TDGS schematic* (right).

Courret et al. report the design, simulation and full scale testing of an ‘anidolic ceiling’ - a rectangular cross section horizontal duct using anidolic optics at each end to collect and distribute light (see **Fig. 3.2**) [4]. The device is intended to use a predominantly overcast sky as a source. The design of the collector is based on the principle of matching the admission sector on the visible part of the sky. To avoid projections higher up the façade obstructing light rays the admittance angle varies along the entrance aperture. The collector is covered with insulating double glazing and the whole duct, which is almost 0.5m high, is lined with polished aluminium. The emitting element is located between 3.5m and 4.5m into the room and consists of a further anidolic mirror reflecting light onto a diffusing panel. Validation of the device by both simulation and measurement under overcast skies established that DF on the working plane was enhanced at the rear of a room, some 4% at depths of between 3m and 6m into the room, or approximately 1.7 times the un-enhanced value. A value of 32% efficiency for the whole system is quoted.

Façade mounted systems have been used in tropical latitudes. A proposal for an office in Kuala Lumpur was evaluated using computer simulation and scale models [5]. In this example the collector was a fixed laser cut panel (LCP) light that deflects predominantly high angle sunlight axially into a polished aluminium duct. Extractor LCP located inside the duct to redirect light 90 degrees into the room (**Fig. 3.3**). Studies using scale models indicated that daylight levels of between 200 and 300 lux would be achieved on the

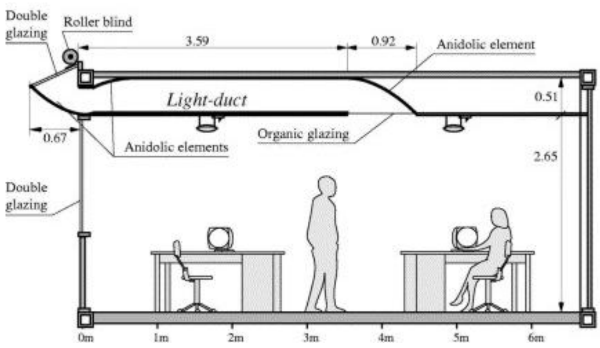


Figure 3.2: *The anidolic ceiling principle* (above); A *facade incorporating an anidolic ceiling collector* (right).

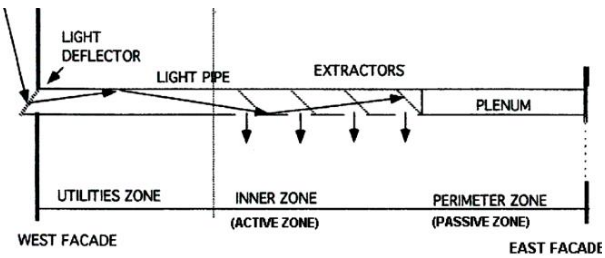


Figure 3.3: *Light pipe section* (left); *Model of the interior LCP light diffuser* (right).

working plane some 6m from the façade during the hours from noon to 1600. A computer simulation of use of similar technology in dwellings in Hong Kong suggested a working plane DF 1.5% and a distance 4m into a room [6].

3.3.3. Active guidance systems

Active guidance systems employ a collector to track and mostly concentrate sunrays to maximize the daylight utilization. Many systems have been developed and some of them are commercially available such as Himawari and Sundolier systems.

3.3.3.1. Himawari system

Himawari system, developed in Japan, collects and concentrates sunlight using tracking fresnel lenses (**Fig. 3.4**). Light may be transported up to 200m by optical fibres, and distributed using a range of custom made luminaire-like devices. Each six 95mm diameter lens cluster focuses sunlight with a concentration of 10000 onto one cable, itself made up of a bundle of six 1mm-diameter quartz glass fibres. The size of the application determines the number of lenses and cables. For example a 15m long cable each of six fibres would deliver 1630 lumens from 98000 lux of direct sunlight on the collector [7, 8]. The author estimate that this would result in a workplane ADPF+ADF of approximately 1.2% if the output devices were at 1:1 spacing to height ratio. A major advantage of fibre optic transport is illustrated by the fact that some Himawari systems have been retrofitted to existing buildings. Notwithstanding the fact that the systems are self powered, they represent an extremely large capital cost which is unlikely to be justified for other than specialist applications.

3.3.3.2. Solux system

Solux system, developed by the German company Bomin solar research, is based in a 1m diameter Fresnel lens to track and collect sunlight. The system filters and concentrates the sunlight 10000 times before it enters a liquid light guide, which is a flexible pipe filled with an optical clear liquid (**Fig. 3.5**). The light from the liquid light guides is released into diffusing tube that spread the light in the room. Electric light source possibly added to

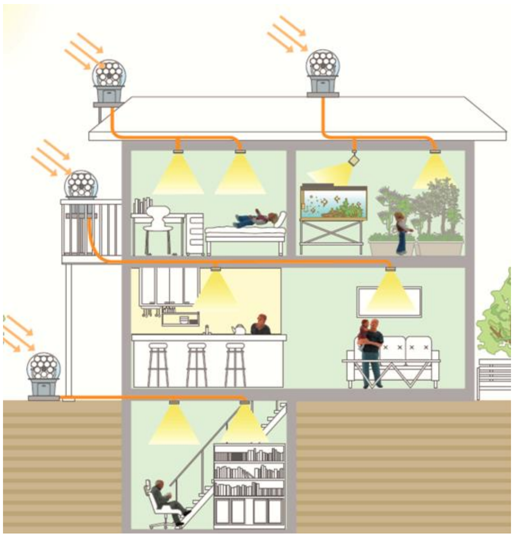


Figure 3.4: *Himawari collectors* (left); *Himawari system schematic* (right).

provide supplementary light when the sunlight is not sufficient. Therefore, natural light from the collector enter one end, and in the other end an electric lamp laid [9, 10].

3.3.3.3. Sundolier system

Sundolier system, developed in the USA, concentrates and collimates daylight that can be re-directed, and evenly distributes it across ceilings and walls. Collecting systems consists of a large-banana-like primary mirror, which redirects sunlight to a secondary mirror that pushes the light through to apposing planar mirrors down into the space (**Fig. 3.6**). Two axes active tracking technology follows the sun path using proven systems for tracking from active solar and satellite communications industries. The system requires very low roof penetration (<0.4%) that is capable of meeting general lighting requirements for 100 to 250 m^2 of space [11, 12].

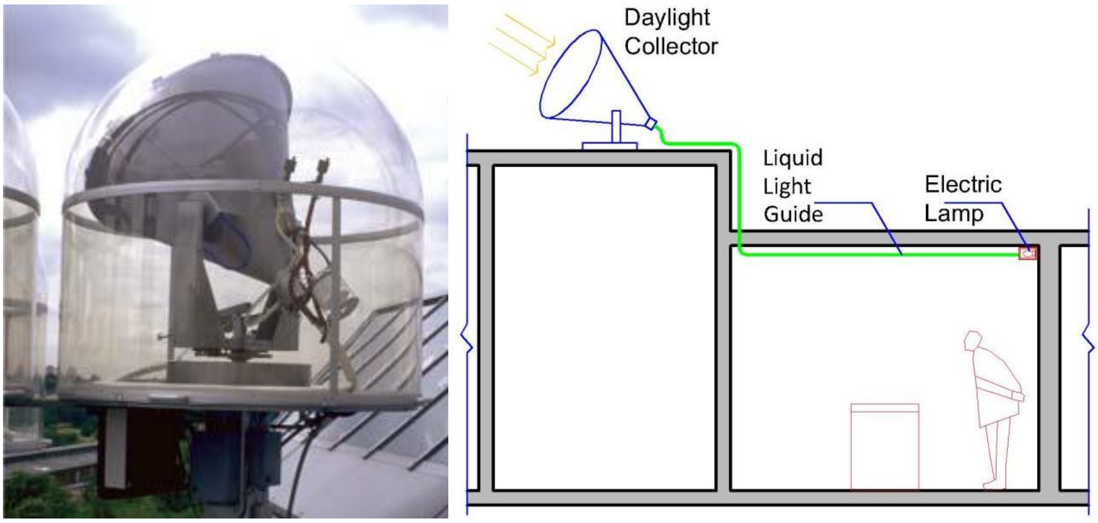


Figure 3.5: *Solux system collectors* (left); *Solux system schematic* (right).

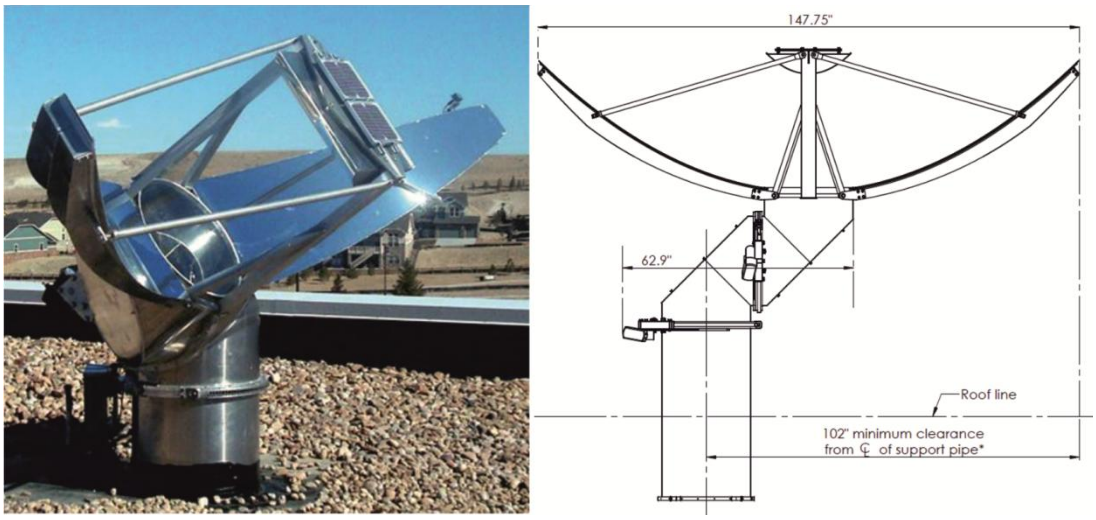


Figure 3.6: *Sundolier system collectors* (left); *Section in the collector shows the mirrors set and the light guide* (right).

3.4. INTEGRATED LIGHTING SYSTEMS

'Integrated lighting' is a generic name for systems which deliver daylight and electric light separately but which are equipped with control that maximises use of available daylight. There are two main approaches. The first uses custom made daylight devices with adjacent linked electric sources. The second is effectively an 'intelligent' electric lighting system with enhanced controls which seek the maximum benefit from any source of daylight.

3.4.1. Integrated Skylight Luminaire (ISL)

The ISL combines in one unit a skylight with a sunlight control device, an electric lighting system, and a photosensor control system to automatically dim the electric output (**Fig. 3.7**). The system uses passive daylight collection and was created for flat-roofed, high-bay buildings such as retail, warehouse, and light industrial buildings. It delivers daylight via 1.2mx1.2m double-glazed clear roof-lights that capture both sunlight and skylight. This is supplemented by twelve T8 fluorescent lamps. The two light sources are linked by photosensor and luminaire controllers which automatically reduce the electric light outputs when sufficient daylight is available. A 1.2m-high daylight diffuser box is mounted below the roof-lights and distributes the sunlight via white acrylic diffusing panels. Diffuse skylight also enters the interior through the bottom of the diffusing box which is constructed of sandblasted clear acrylic. The electric lamps are housed in four industrial luminaire assemblies arranged in a square configuration 1.2m outside the sunlight diffuser box. Four prototypes were tested showing a mean horizontal illuminance (taken on sunny afternoon between 1400 and 1500 in early September) of 240 lux over a working plane approximately 7m below the skylight [13, 14]. The author estimates that this represents an ADPF+ADF of some 0.5%.

3.4.2. Intelligent lighting systems

In essence these are an electric lighting system with enhanced controls which seek the maximum benefit from any source of daylight – guided or otherwise. A number of manufacturers market systems of this nature, some of which are based on 'open'

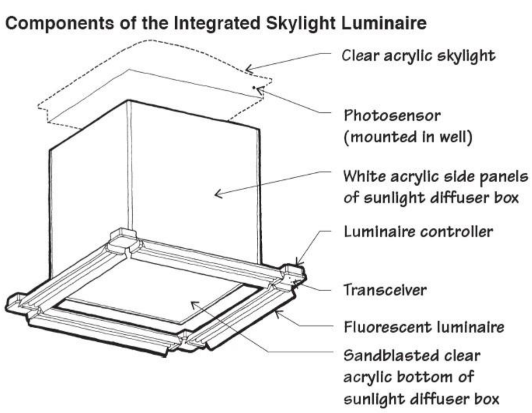


Figure 3.7: *Components of the ISL* (above); *An installation of ISL in a warehouse* (right).

communication protocols such as digital addressable lighting interface (DALI). All are integrated into an appropriate building management system. In most cases luminaires are installed over individual workstations or defined visual task areas and equipped with, variously, integrated network controls, occupancy sensors, personal dimming or daylight dimming. The luminaires usually designed to also provide ambient lighting [15, 16]. Depending on the individual circumstances of use, the combination of features listed above can yield substantial energy savings. For example a field study of a deep plan office building having luminaires with occupancy sensors, daylight linking and individual dimming control saved 69% compared to a conventional lighting system. Electric lighting substitution by daylight accounted for 20% of this total [17].

3.5. HYBRID LIGHTING SYSTEMS

The systems described so far have used a variety of methods of delivering daylight into a room which is also equipped with conventional electric systems. Although control systems may regulate the flux output of each, light from the two sources are delivered using separate output components whose optical properties may differ substantially. In 'hybrid lighting' daylight is combined with electric light prior to delivery. Optical control is more akin to that of an electric luminaire and the two sources may not appear as distinct. **Table 3.2** by the end of this review; summarises some features of HLS.

3.5.1. Enhanced tubular daylight guidance

The first developments in HLS lighting were enhancements to tubular daylight guidance systems to attempt to provide light during night hours. These use heliostats, and combine electric and natural light within the light guide rather than at point of use.

3.5.1.1. Heliobus

There are a number of examples of this type of system but one suffices to illustrate the principle. **Fig. 3.8** shows a school which is partially lit using a roof mounted static mirror heliostat with a shape optimized to gather and redirect the largest possible amount of daylight. Light is directed into a vertical prismatic light guide through three floors. Reflective diffusing extractor foil distributes daylight over the entire surface of the guide to allow each floor to receive similar quantities of light. At dusk or night, three 400W metal halide lamps located at the top of the light pipe are turned on and the light distributed via the guide [18, 19]. Measurements quoted in Reference [1] for an overcast sky providing 10000 lux horizontal indicated an internal illuminance ranging from 420 lux adjacent to the output device to 30lux at 3m from the device. The author estimated that this would give an approximate working plane ADPF+ADF of the order of 0.8%.

3.5.1.2. Arthelio

The Arthelio study developed systems combining daylight and electric light from sulphur lamps, and culminated in the construction of two large installations – one of which was in a single storey warehouse in Milan (see **Fig. 3.9**) [20]. This uses a single axis light capture head based on a Fresnel lens. The sunlight is then reflected via an anidolic mirror into a 13m-long, 90cm diameter circular guide lined with prismatic material. A diffuser unit, shaped like a truncated cone is located at the end of the guide. This delivers a working plane daylight illuminance varying between 100 and 400 lux depending on time of year [1]. Connected to the diffuser unit are two horizontal prismatic light guides powered by dimmable sulphur lamps. These provide an additional uniform illuminance of 250 lux over the working area by a control system that tops up or replaces the daylight as necessary.

3.5.1.3. Solar light pipe (SLP)

The system is suitable for use in high-rise buildings with internal core. It composed of an active Heliostat and a multiple-mirror system mounted on the building roof. While tracking the sun, the Heliostat leads the sunlight to secondary mirrors. The multiple-mirror system brings the sunlight down in the 36m-long light pipe (see **Fig. 3.10**). The pipe has a double-

Figure 3.8: *Heliobus collector* (left); *Heliobus light guide* (middle); *A schematic shows the heliostat, light guide including reflective diffusing extractors and an end diffuser* (right).

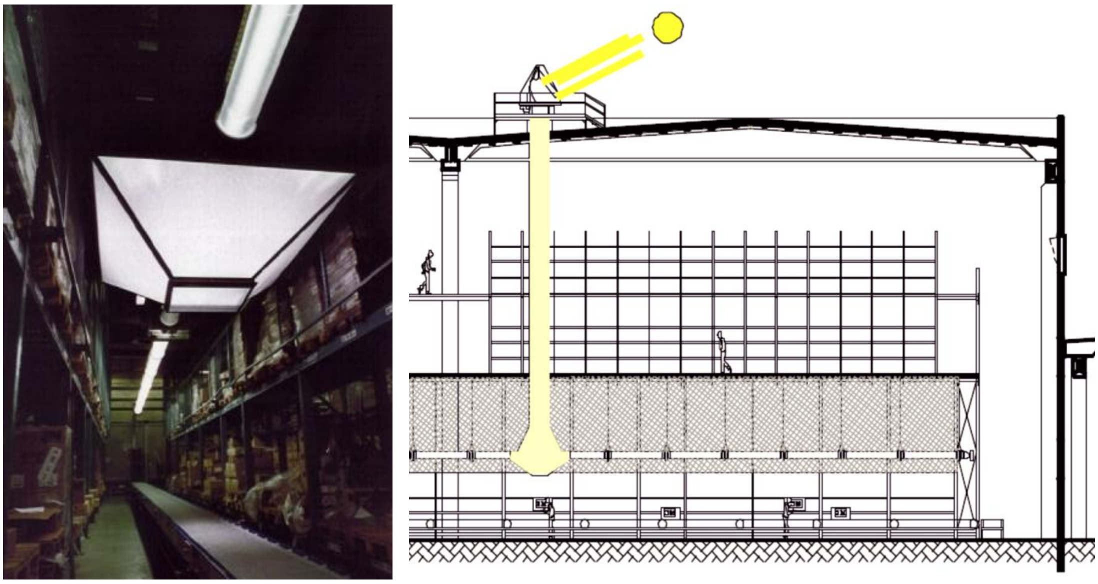


Figure 3.9: *Arthelio diffuser and light pipe* (left); *A schematic shows the heliostat and vertical and horizontal light pipes* (right).

skin construction; an outer light-diffusing tube consists of tensioned translucent Lycra fibre reflects the sunlight horizontally into each floor, and a core consists of prismatic glass panels with optical film. The glass core tapers from a diameter of 175cm at the top to 50cm at the bottom. When the sky is overcast, an artificial light from two 2000W xenon lamps in the roof is reflected in the pipe to illuminates the multiple-mirrors and allows the lighting of the inner spaces [21, 22]. To our knowledge, no published data show its efficiency.

3.5.2. Hybrid Solar Lighting (HSL)

This was developed by Oak Ridge National Laboratory for public buildings in areas of the USA where direct solar radiation is greater than 4 kWh/m^2/day and cooling is a major design concern. The sunlight collector is a primary 1.22m-diameter parabolic acrylic sun-tracking mirror with an elliptical secondary mirror (see **Fig. 3.11**). The latter separates the visible and infrared portions of sunlight and focuses the visible sunlight into a bundle of 127No 3mm-diameter optical fibres used for transport. The optical fibre system delivers the sunlight to the end of a side emitting acrylic rod located inside a conventional 1.2m x 0.6m electric luminaire also equipped with dimmable fluorescent lamps. A control system tracks the sun; light sensors monitor daylight levels; and electronic dimming ballasts regulate the electric light output to a pre-determined level [23, 24]. A second type of luminaire uses end emission from the fibres and has a light distribution similar to a parabolic reflector lamp. A

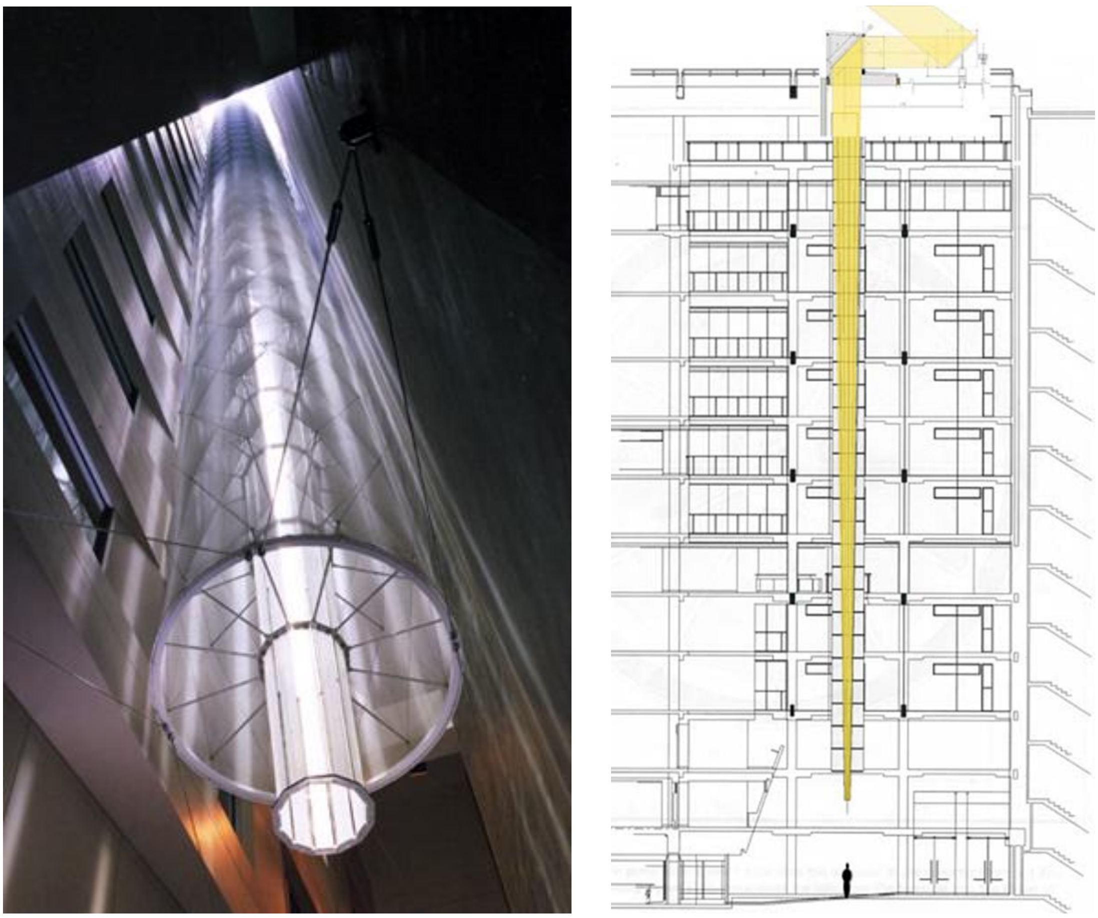


Figure 3.10: *The double-skin light pip of SLP system diffusing tube* (left); *A schematic shows the heliostat and 36m-long light pipe* (right).

prototype luminaire incorporating light-emitting diodes has also been developed. Further work suggested that system losses of the order of 50% for single-story application with an additional 15-20% for a second storey [25]. It is claimed that one collector can power 8 to 12 fluorescent, or 30 to 40 reflector luminaires, so lighting an area of about $100m^2$. This displaces about 1kW of electrical lighting load. On a sunny day one HSL system is reported to deliver 50klm per group of luminaires. The authors estimate that this would give an approximate daylight illuminance in a typical office of the order of 700–1000lux or an ADPF of about 1%.

3.5.3. Fibre Optic Solar Lighting System (Parans)

The system, developed commercially by Parans Solar Light, shares some features of the Himawari system [26]. **Fig. 3.12** shows the roof or façade mounted $1m^2$ modular solar panels containing $62N^o$ Fresnel lenses. Each lens is able to track and concentrate sunlight into a 0.75mm diameter optical fibre. Sixteen fibres are combined into a cable each of maximum length 20m. The tracking is controlled by a microprocessor which is continually fed information from a photo-sensor which scans the sky to detect sun path. The system learns and remembers the sun path at any location and thus can be moved without pre-programming. The system has five luminaire types, three of which are hybrid luminaires equipped with fluorescent or compact fluorescent lamps which dim automatically depending on sunlight conditions. Manufacturer's data for an installation with 10m optical cable and direct solar illuminance of 75klux quotes a luminaire flux output of 7500lm and 10000lm for a 4m cable. This corresponds to a system efficiency of around *60% and 80%* respectively. The system has optimum collecting hours when the solar panel is within an angle of 120° of the sun. Three generations of the system exist. The second, illustrated in **Fig. 3.12**, is investigated later in this work. Only very limited data and information on the third generation, released in 2011, is available (see **Fig. 3.13**).

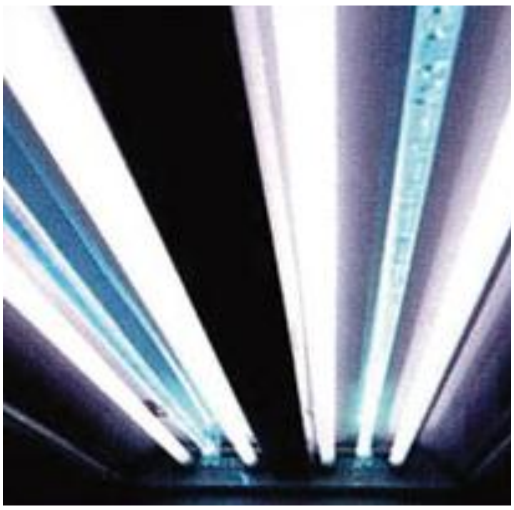


Figure 3.11: *HSL system hybrid luminaire* (above)*; HSL collector* (right).

3.5.4. Solar Canopy Illumination System (SCIS)

This facade mounted system collects sunlight using an Adaptive Battery Array (ABA) – two 35No grids of thin 16cm approximately square mirrors located inside a weather-proof enclosure with a transparent front window [27] as illustrated in **Fig. 3.14**. On the façade each unit is approximately 3m-wide x 1.3m-high x 1-0.8m-depth. This is connected to a 0.25m-high x 0.60m-wide duct which extends some 12m into a building. The orientation of the mirrors changes with sun position by means of pulleys and linear actuators and the light is concentrated and redirected by a series of mirrors into the rectangular cross section 'dual function prism light guide' (see **Fig. 3.14**). Electric light is from fluorescent T5 lamps located inside the guide. The guide inner top and side surfaces are lined with a highly reflective multilayer dielectric film having luminous reflectance of greater than 98%, whereas the bottom emitting surface of the guide covered by a prismatic film. The reflective film has high reflectance at all angles, whilst the prismatic film reflects light preferentially. Sunlight travels along the guide using total internal reflection until it hits an extractor material that diffusely reflects the light, and the portion that no longer meets the angular conditions for total internal reflection exits the guide via the bottom surface. The control system uses DALI controlled ballasts, in addition to light sensors, to maintain the desired interior illumination level. A prototype at the British Columbia Institute of Technology shows that about 25% of flux incident on the mirror array arrives on the workplane extending *10m* from the façade [28, 29]. System efficiency is significantly reduced in the early morning and late afternoon since the mirror array configuration and orientation only redirects incident sunlight three hours either side of solar noon for most of the year.

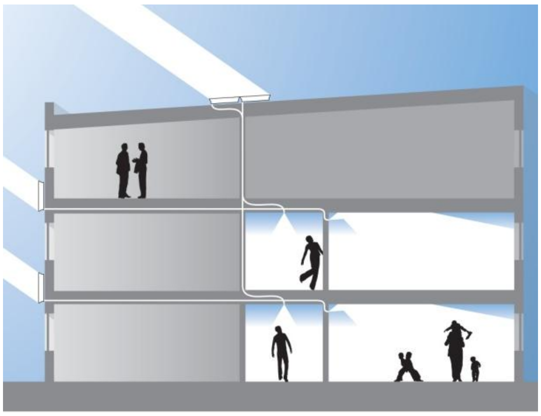



Figure 3.12: *Parans system collector* (left); *A schematic shows roof and facade mounting alternatives* (right).


Figure 3.13: *Parans system large luminaire for the three generation* (left); *Parans system collector third generation* (right).

3.5.5. Universal Fibre Optics (UFO)

This project was the result of a multinational development under the European Commission Energy Programme but does not appear to have been commercially exploited [30]. Sunlight is collected by a roof mounted heliostat with a 1m-diameter Fresnel lens and delivered to luminaires via 10m-long 20mm-diameter liquid light guides. In addition light from two 150W metal halide lamps, located adjacent to the heliostat, may be delivered to the luminaire via plastic fibre optic cables. The luminaires contain a coupling system linking both liquid and optical fibre guides to the edge of a 20mm thick sheet of 'Prismex', an acrylic material with a dotted surface developed for illuminated advertising signs (see **Fig. 3.15**). Light passes through the panel and exits such that it delivers an even brightness across its emitting surface. The luminaire also has two T5 fluorescent lamps located along the edge of the emitter. The system is photocell controlled such that when daylight fails the luminaire switches to light from the metal halide lamps. Because of the limited dimming capability of metal halide lamps, variation in output was achieved by switching but at a speed which could not compensate in real time for quick variations in the external illuminance. The output of the fluorescent lamps compensates for this [31]. A prototype, installed in Athens, had a flux output of 3060lm for a normal illuminance on the collector of 90029 lux and using 10m-long guide. The overall efficiency of the daylight system was around 3.4%, a low value presumably caused by the large number of components.

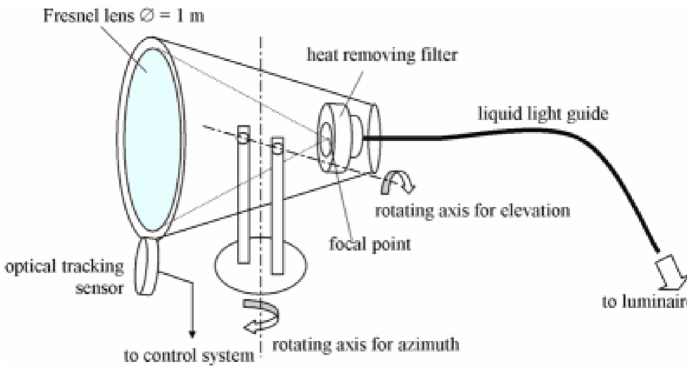
Figure 3.14: *SCIS schematic* (above), *The SCIS hybrid luminaire* (up right)*; The SCIS collector* (right).

3.6. CONCLUSION

Attempts to deliver daylight into windowless and remote spaces in buildings have lead to the development of daylight guidance, which became one of the major areas of innovation in interior lighting in the recent years. The desire to create low energy buildings with good daylight penetration means that daylight guidance has become attractive to designers. Since daylight guidance delivery of daylight is subject to external illuminance availability,

Table 3.2: Summary of hybrid lighting systems characteristics

Name	Light collection method	Light transport method	Daylight output device	Electric sources	Electric lighting location
Heliobus	Mirror Heliostat	Hollow Light guide	Side emitting prismatic guide + translucent Lycra fibre for SLP	Metal halide lamp	Top of vertical light guide
Arthelio				Sulphur lamp	End of horizontal light guide
SLP				Xenon lamps	Top of vertical light guide
HSL	Parabolic mirror heliostat	Optical Fibres	Luminaire with: a. Side emitting acrylic rod b. End emitting fibre optic	a. T5 fluorescent tubes b. Incandescent bulbs	Within luminaire
Parans	Array of mini Fresnel lenses	Optical Fibres	Diffusing luminaire with end emitting optical fibres	T5 or compact fluorescent lamps	Within luminaire
SCIS	Set of mirrors system	Hollow Light guide	Prismatic guide with diffusing extractor	T5 Fluorescent tubes	Within light guide
UFO	Fresnel lens heliostat	Liquid light guide & Optical Fibre	Luminaire with acrylic diffuser	Metal halide lamp & T5 fluorescent tubes	Metal halide lamp remote from luminaire. T5 fluorescent within luminaire



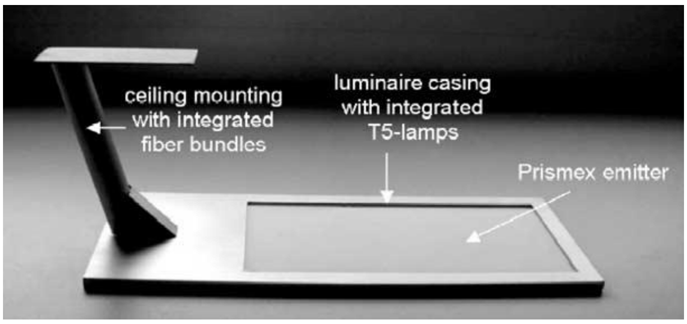


Figure 3.15: *The UFO system collector* (above); *The UFO schematic* (up right); *The UFO system luminaire* (right).

existence of electric lighting system remains indispensable. Thus, linking both daylight guidance and electric lighting systems emerges as essential to reduce building energy consumption. Integrated lighting systems, with two separate lighting systems linked with control system, satisfied the desire to create low energy buildings. HLS, the latest expression of the technology, combined both systems to ultimately maximize the benefit of daylight.

The innovative nature of HLS means that there is currently only one commercially available system. As a result there is little accumulated experience of their use. It is likely that the lessons learned from feedback from TDGS installations in respect of design criteria, integration with other lighting systems and the building fabric and economics may be relevant to HLS.

The advocates of daylight guidance advance two main arguments for its use – firstly that they deliver daylight deep into interiors and, secondly, that in doing so energy may be saved by electric light substitution. The evidence to date is that some HLS can under favourable circumstances deliver large quantities of daylight, possibly sufficient to create a 'well day-lit space' as defined by ADF criteria. The light is delivered via luminaires. The evidence from studies of TDGS suggests that under some circumstances light coming out of a guide via a luminaire-like device will not be perceived as 'daylight', particularly in the absence of the contact with the exterior. In other respects HLS can potentially deliver better quality lighting than TDGS since the luminaires used have better light control and the possibility exists of colour matching of the dual sources.

HLS represents an advance over TDGS on a number of fronts. They offer the opportunity to transport light deeper into buildings and pose less practical problems, notably in terms of fire precautions. The use of a single output device offers seamless integration of electric and daylight. However this process requires sub-optimal solutions. For example the optics necessary for electric sources may need modification to accommodate the daylight emitters and vice versa. It is arguable that an integrated lighting system with separate output devices may perform better. Most of the HLS have been developed for sunlight sources but are now being marketed in locations where other sky types predominate. The same sequence of events occurred with TDGS. The implications, in terms of requirements in other locations, are investigated in this work.

Based on this review, investigations in this work will focus only on HSL, Parans and SCIS, in addition to the TDGS for the purpose of comparison. These systems exclusively showed a considerable potential application and ability to penetrate the market. Parans system is a commercial product that is available on the market. The HSL and SCIS have been successfully tested in a prototype facility and many demonstration systems on real buildings are being constructed. The present study has not used either enhanced TDGS or UFO systems. Each of the former is custom-built for an individual application at great capital cost, and the later doesn't appear to be any more under development or commercially released.

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CHAPTER

4

HLS in Building Design

4.1. INTRODUCTION

Daylight is a major influence on building design. In some buildings, such as religious buildings, daylighting almost determines the building design strategy, but in others it is only one design issue among others. The more that daylight is the generating factor for a design, the more the daylighting strategy becomes an architectural strategy [1].

Conventional daylighting strategies often result in a building with a higher skin-to-volume ratio than a typical compact (electrically lit) building [2]. Innovative daylighting strategies seek to break the conventional strategies barriers and 'guide' daylight beyond their limits; to the remote zones and windowless spaces, and into compact buildings. Traditionally, courts and light wells were used to channel daylight into the buildings cores. The concept developed to channel daylight via smaller and more effective 'core lights' that is known as 'light guidance', which was used firstly to deliver daylight only, and then developed to combine electric light with daylight through the HLS.

Whilst daylight has formed part of architectural strategies for centuries, the HLS are not yet part of the architectural design process. Conventional daylighting techniques such as overhangs and light shelves have been turned into architectural elements, and newer techniques such as highly reflective metal louvers have become part of the modern architecture image. Incorporation of HLS into building design process is required to reach the same achievement. Besides influencing the electric lighting system design, HLS can also influence other building design considerations, such as the structural system, mechanical system, and interior design.

The vast variations in HLS characteristics and techniques make their incorporation into building design process subject to decision maker(s) (whether designer or operator) ability to select the best HLS meet building's needs and budget. In such cases with many variables (i.e., alternatives and decision criteria) decision making techniques emerge as a reasonable way to make a rational decision.

4.2. BUILDING DESIGN STRATEGIES

Interaction between building design and daylighting design is of very different degrees according to the importance of daylight in the building. Building strategy to a great extent determines illuminance performance. Building type identifies required illuminance quantity and quality; building form determines possibilities of use and illuminance distribution pattern; building systems determine HLS applicability; and building flexibility determines upgrading potentialities of lighting systems.

4.2.1. Building type

Similar needs of human beings over the time resulted in standard types of buildings for particular uses. However new building types have been developed to satisfy new functions, such as office buildings and more recently airports. Building function (i.e., type of visual activities that predominate within a space) determines the possible users and occupation schedule. Based on the function and users' age, illuminance quality and quantity that will permit the activity to be performed to the desired level of quality can be estimated, and based on the occupation schedule, utilization of daylight can be predicted. Daylight utilization may be of great importance as in religious buildings, or undesired at all in some theatres or strictly controllable illuminated rooms.

4.2.2. Building form

Light has famously been understood as a form giver throughout the history. Before the replacement of natural light by artificial light, providing an access for daylight to every space was a necessity seriously contributed in forming the building. Over the last century or so, big developments in structural and electro-mechanical systems associated with new building functions and occupant needs led to new building forms; where the conventional daylighting systems are unable to deliver required illuminance level. Innovative daylighting elements have been developed and, in turn, incorporated into the architectural fabric and influences the building form. Since electric lighting systems (ELS) are available, building form generally influences daylighting design strategies, while historically daylighting strategies determined building form. Some form-related aspects can be considered to have the most influence on daylight design. These are: external envelope area/total floor area ratio, building height, floor depth, floor-to-floor height, internal cores, and self obstruction.

4.2.3. Building systems and elements

Since lighting design history is as old as building design history itself, many building elements, architectural or structural, are dual-function elements. For example, different ceiling levels architecturally required for emotional and functional purposes, particularly in religious buildings, and at the same time used as clerestories for toplighting. Over the last century or so, daylighting design doesn't have the same importance any more in the building design process. Consequently, daylighting systems have to compete with the architectural elements and spacing, structural systems, and services networks, and make the best use of them to enhance their performance. Many architectural elements can be employed as part of the daylighting system and vice versa, such as prominent balconies for the former and light shelves for the latest. Internal space organization greatly influences the availability of daylight access and space distance from building skin. Structural systems variations in sizes, elements and positions work either as daylighting enhancement or obstructions. Façade exposed columns and slabs may work as vertical and horizontal louvers, while deep beams may block daylight or conflict with light ducts. Services networks routes, particularly HVAC ducts, may conflict with the rigid light guidance.

4.2.4. Building flexibility

Although a building lifetime may extend for hundreds of years, its function may change over the time. The accelerating technology updates is another reason for building modifications. In order to ease usage change and building upgrade and to decrease required modifications, buildings tend to be more flexible. Lighting systems, among other building systems, tend to be more flexible to cope with the different internal functions and layouts. Daylighting systems in general are less controllable than ELS, but distributing daylight via luminaire-like outputs improves their compatibility.

4.3. HLS STRATEGIES

The characteristics of each HLS determine the extent to which it will produce a satisfactory lit environment and integrate into a building design.

4.3.1. Light collector

The collector in any HLS is the main component that determines *amount* of daylight that can be delivered, *sort* of daylight that can be collected, and *period of time* over which the system can be utilized. HLS in general track sunlight and concentrate it to different ratios. Consequently, they are complicated electro-mechanical devices that define sun position, keep tracking it precisely, and project the concentrated beam right on the top end of the guidance system. Collectors are available in very different sizes and can be facade attached or roof mounted.

HSL and Parans systems are examples for high concentrating HLS, while SCIS is a low concentrating system with ratio of around 10 times. Non-concentrating systems such as TDG can as well work as HLS if provided with an electric lighting source and a proper control system. Concentrating sunlight seeks to minimize the guidance size, where the more the light is concentrated, the smaller the light guidance is needed. That in turn increases the required precision, complexity, and finally the cost of the collector. However, minimizing guidance size is achieved at the expense of system ability to deliver light under cloudy sky conditions, since concentrating light makes it possible to exclusively collect direct sunlight. HLS also seek to track the sun path as wide as possible to maximize the daylighting period. Free standing collectors, as in HSL, have more coverage limits than in-enclosure collector as in Parans and SCIS. Tracking sun is a mechanical process controlled by photo-sensors or pre-programmed microprocessors or both of them. The size of the collector usually is a function in its concentration ratio, the bigger the concentration ratio, the smaller the size required to collect the same amount. Facade attached collectors are highly recommended to be southern oriented in the Northern hemisphere, and has the advantage of working in high-rise buildings. A roof mounted collector is more flexible in terms of building orientation, and more applicable in deep-plan buildings (see **Fig. 4.1**).

4.3.2. Light guidance

The guidance determines HLS applicability to fit in the different buildings types. Its *size* and *transmittance* are the main parameters by which it can be decided whether the HLS can fit in new or existing building; may suit residential, commercial or any other building; would apply in low-rise, high-rise, or whatsoever building. Light guidance comes in two different forms: light ducts and fibre optics. Each is associated with different performance and applications (see **Fig. 4.2**).

Light ducts are normally used with non/low concentrating systems. They have relatively big circular or rectangular cross-sections, typically of range of Ø 200-500mm or around 250 X 600 mm; depending on the travel distance of the light and the required amount. They can be treated structurally as HVAC ducts but require attention to avoid bendings that cause excessive light attenuation. The transmittance of the light duct is a result of the use of highly reflective materials lining the interior surfaces of the duct, and the quality of the transmitted light is a result of the ability of these materials to reflect the entire visible spectrum. High reflective materials of as high as 99% (per light bounce) became recently cost-effectively available. Meanwhile, fibre optics are usually used with high concentrating systems. They are of few centimetres diameter and thus can be routed in building as electric cables. They are available as single solid core plastic fibre or bundle of glass fibres. The former is recently preferred for its flexibility and low price, but at the expense of its optical clarity and transmittance that ranges from 90% to 97% per metre [3].

4.3.3. Light output device

The output device in any lighting system is a critical part, since it determines to what extent benefits from collected light will be made. Proportion of delivered light is lost by the diffuser, and more importantly, it determines how the remaining proportion will be distributed over the working plan. Moreover, it contributes as to whether occupants will perceive daylight provided by the HLS as a natural light or as an artificial light, particularly if

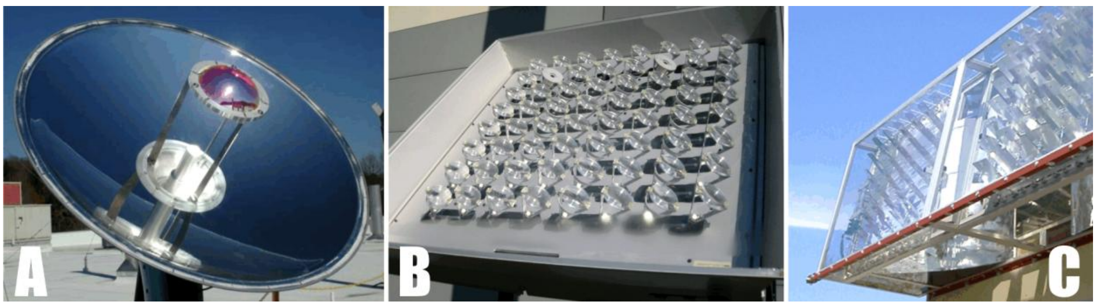

Figure 4.1: *Examples for HLS light collectors,* ***A****: HSL system,* ***B****: Parans system,* ***C****: SCIS*

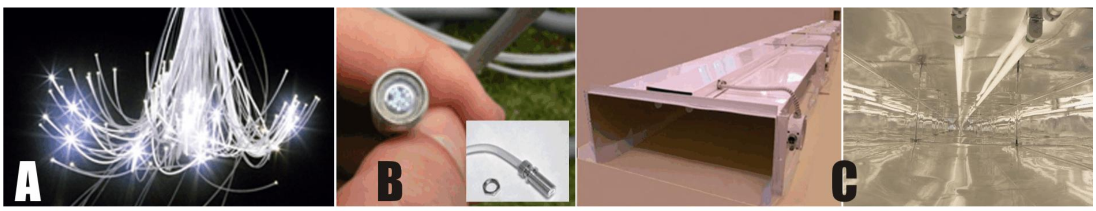

Figure 4.2: *Examples for HLS light guidance,* ***A****: fibre optics bundle of HSL system,* ***B****: fibre optics cable of Parans system,* ***C****: SCIS light duct internal and external*

taken into account that daylight provided by HLS lacking connection with outside view. Delivered light can be distributed via spot, linear or luminous surface output devices; appears as custom designed or conventional-like luminaires.

The SCIS guidance works as output device that can be considered luminous surface as it is 600mm wide and as long as 12m, located with interval of 3m over the space. Uniform sufficient illuminance was provided over the space using this configuration [3]. Highly concentrated light delivered by fibre optics is much more difficult to be 'de-concentrated'. A custom designed diffuser has to be used or additional optical object needs to be added to the end of the optical fibre to provide a uniform illumination. End emitting fibre optics provides a high-brightness very narrow light cone which may work as a spot luminaire; otherwise custom designed diffuser has to be used to uniformly distribute the light. Side emitting fibre optics may work as a linear luminaire as employed by the HSL system, which uses side emitting PMMA rods etched with scattering grooves to provide uniform illumination along the entire length of the rods [4] (see **Fig. 4.3**).

4.4. PLANNING FOR HLS

Daylighting design using HLS depends on the integration between HLS strategies and building design strategies that fulfil functional and aesthetical targets. Prior to this process, considerations have to be given to the building context to come up with some recommendations for the most likely applicable systems in terms of site conditions. Based upon daylight availability, geographical location, and building layout, sitting and surroundings; potential success of HLS can be expected.

4.4.1. Daylight availability

Availability of daylight can be determined by illuminance *value* and *composite*. Increase in illuminance value doesn't necessarily mean an increase in delivered amount of daylight. That is true only with non-concentrating systems, but with concentrating systems the changes in direct illuminance value is what significantly influences the delivered amount; since they are capable to collect direct sunlight only. Therefore, the more the sunny the conditions, the more the high concentrating systems are applicable.

4.4.2. Geographical location

Big variation in sun positions and sunshine durations increasingly occur in high-latitude locations. Sun position influences system ability to gather sunlight, and thus, HLS with tracking system of wider coverage limit is able to collect more amount of direct sunlight.

Figure 4.3: *Examples for HLS light collectors,* ***A****: HSL system,* ***B****: Parans system,* ***C****: SCIS*

The moderate differences between summer and winter sunshine duration in low-latitude locations make building working hours more probable to coincide with daylight hours.

To maintain HLS efficiency, optical elements have to be kept extremely polished. So, in locations polluted artificially (e.g. smoke) or naturally (e.g. dust, low rainfall amount) or obstructed (e.g. moist, snow), high level of maintenance has to be considered to avoid any drop in system's transmittance. HLS with difficult access (e.g. facade attached collector in high-rise building) in such locations raises the HLS running cost.

4.4.3. Building configurations

Building layout and surrounding can eliminate some solutions in the early stages of the design process. In North oriented buildings, high concentrating facade attached systems are instinctively eliminated. High-rise buildings cannot use roof mounted systems with lower floors, and as well deep-plan buildings cannot use facade attached systems with the very remote spaces from building façade. Adjacent obstructions whether vegetations or constructions have to be considered regardless collector mounting location.

4.5. HLS INTEGRATED DESIGN

Integrated design is a process that applies the skills and knowledge of different disciplines and the interactions of different building systems to synergistically produce a better, more efficient, and more responsible building - occasionally for lower first cost, but more typically for lower life-cycle cost. Integrated design considers the relationships between elements that have often been seen as unrelated [2]. The level of integration of daylighting into the design can have profound influences on the architectural design, interior design, structural system, and services networks.

4.5.1. Integration with architectural design

Integration between HLS and both building type and architectural form is essential to successfully utilize HLS in buildings. The impacts of HLS on building design can be seen externally and internally. *Externally*, light collectors may be considered 'strange elements' of a relatively big volume, attached to building facade or mounted on the roof, and have to be kept exposed to see as large area of the sky as possible. Facade attached collectors may be more influential on the architectural image and need to be employed aesthetically. Current collectors such as SCIS collector, though has the potential to work as shading device, still needs more development to be more integrable in building fabric (**Fig. 4.4.A**). Smaller collectors such as Parans', though has far less impact, still can be seen as 'added element' not part of the facade fabric (**Fig. 4.4.B**). Roof mounted collectors are more likely to be treated as satellite dishes, and thus have minimum impact. Nevertheless, some heliostat-based systems need protecting shelters, which have to be considered in building design (**Fig. 4.5**).

Internally, light ducts are new elements of considerable volumes that have to be involved in the architectural design process to avoid any modifications in building construction and/or spacing distribution. Vertical ducts can be introduced into buildings through ventilation ducts, dry risers, any hollow conduit and even suitable lift shafts if possible, otherwise they will penetrate building spaces making interference and adding more restrictions. Horizontal ducts might need extra floor height, which consequently will raise building budget and might reduce building stories number to meet local regulations regarding building total height.

4.5.2. Integration with interior design

HLS diffusers have to be integrated in the interior design as they have many impacts on ceiling layout, luminaire types, and illuminance distribution. Wide variation of HLS output devices is available, where they can be spot, linear or luminous surface, and they may be custom designed or conventional-like luminaires. Selected output has to meet function requirements and space furnishing. For example, SCIS diffuser is more suitable for commercial applications rather than residential (**Fig. 4.3.C**). Parans spot luminaire is more suitable for task or accent lighting rather than ambient lighting. Vertical light ducts might be used as a vertical luminaire emitting light along its length as in Heliobus system, which is

***Figure 4.4:** Light collector influence on building facade, **A**: SCIS collector* (left), ***B**: Parans 3rd generation collector* (above)

***Figure 4.5:** Arthlio system heliostat, Berlin*

abnormal source in typical lighting design (**Fig. 4.6**). Collaboration between HLS and interior design is essential to cope with the probable lose of usable floor area and changes in furnishing arrangements.

4.5.3. Integration with structural system

Some structural arrangement may be required for HLS collector fixation and guidance penetration, so it would be useful to be considered in the design stage though it is mostly not of high significant. Dead loads and wind resistant load of the collectors have to be structurally considered, but these are likely to be of the same order as conventional roof mounted equipments such as cooling towers or satellite dishes. Large-size slab openings required for the guidance of low-concentrating Heliostat-based systems have to be structurally accounted. Openings in building facade are required by SCIS to introduce the guidance, and thus structural elements such as beams or load-bearing walls have to be considered. Loads of light ducts present no structural impact rather than ventilation ductwork; since they are of negligible loads but must be routed so as not to conflict with structural elements. Any increase in floor-to-floor height due to the use of horizontal light ducts will considerably increase building loads.

4.5.4. Integration with services networks

HLS guidance is the main part that needs to be coordinated with building services networks. It is necessary to ensure that there is sufficient room for the light guides to pass through the ceiling cavity without interfering with the HVAC or other systems. If services networks are exposed (i.e., no suspending ceiling in use), minimum clear height has to be maintained. Fibre optic cables are small and flexible enough to be treated as electric cables, however

Figure 4.6: *Vertical luminaires influence on working space* (left) *is more critical than its influence on public space such as stair cases* (right)

avoiding unnecessarily bending improve their performance. Meanwhile, light ducts are more like ventilation ducts, and thus coordination has to be made between them and other services networks, especially HVAC, to minimise bending and avoid light lose, and keep all routes within the allowed space. Installing HLS in existing building is possible, but re-route of services networks may be required.

4.6. SELECTING HLS METHODOLOGY

Broad variation in HLS characteristics described earlier means decision must be made based on system performance, economics, relationship with the host building, and nature of HLS components. Each of collector, guidance and diffuser may vary in size, mounting method, flexibility and technology; hence vary in performance, economics, compatibility and suitability. Decision maker(s) has to take in consideration these variables in order to select a HLS for purpose and budget. In the light of the vast variation of alternatives and requirements and the complex interaction between the variables, decision making techniques might help in the selection of best matching HLS.

4.6.1. Decision making methodology

The objective of the decision maker(s) is to rank alternatives in terms of their ability to meet building (or space) needs and budget, and come up with a choice of one of them. To make a perfect decision some criteria have to be defined and the performance of each alternative has to be measured in terms of these criteria. Because of the variety of alternatives and the decision criteria, the Multi-criteria decision making (MCDM) approach appears to be a reasonable way to make these decisions. MCDM has attracted the attention of decision makers for long time, since it is suitable for addressing complex problems featuring high uncertainty, different forms of data and information, and multi interests and perspectives [5].

In this chapter, three HLS assumed alternatives for a general case and decision has to be made to decide the best selection. A set of criteria was defined, depending on HLS analysis, to measure alternative performance. The decision criteria have been assigned importance weights. A widely used MCDM method is utilized to rank the alternatives; after applying a three-step process in which weighting (of criteria), rating (of performance) and evaluating (of alternatives) have been carried out. Impact of changes in the evaluation process inputs on the decision making output has been discussed.

An online survey was conducted, targeted at decision makers in the fields of building design and operating. This was designed to measure to what extend each HLS component or requirement has been preferred. The decision criteria relative importance weights were derived from recipients responses. Forty-eight responses were received from twelve countries spread in five continents. The values obtained were used to examine the MCDM method and the impacts of changes in importance weights and performance measures.

4.6.2. Multi-Criteria Decision Making

The MCDM is one of the most well known branches of decision making. It uses numerical techniques to help decision maker(s) choose among a discrete set of alternative decisions. This is achieved on the basis of the impact of the alternatives on certain criteria thereby on the overall utility of the decision maker.

4.6.2.1. The MCDM problem

Although MCDM methods may be widely diverse, many of them have certain aspects in common. These are the notions of alternatives and criteria. Alternatives usually represent the different choices of action available to the decision maker(s). Decision criteria represent the different dimensions from which the alternative can be viewed. Each criterion needs to be assigned relative weight of importance [6].

An MCDM problem, with *m* alternatives *and* n criteria, can be easily expressed in a matrix format. A decision matrix *A* is an (*m* x *n*) matrix; in which decision maker(s) has to determine a_{ij} measures the performance of alternative A_i when it is evaluated on terms of decision criterion C_j (for $i = 1, 2, 3, ..., m$, and $j = 1, 2, 3, ..., n$). For each criterion the decision maker(s) has to determine its importance, or weight w_j. **Fig. 4.7** represents the typical MCDM problem examined in this chapter.

Three steps have to be followed, as presented in **Sections 4.7.1 – 4.7.3** respectively, to utilize MCDM:

- Define the set of alternative and the set of decision criteria.
- Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
- Process the numerical values to determine a ranking of each alternative.

	Criteria				
Alts	C_1 (w_1	C_2 w_2	C_3 w_3	... ...	C_n w_n)
A_1	a_{11}	a_{12}	a_{13}	...	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	...	a_{2n}
A_3	a_{31}	a_{32}	a_{33}	...	a_{3n}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_m	a_{m1}	a_{m2}	a_{m3}	...	a_{mn}

Figure 4.7: *A typical decision matrix*

4.6.2.2. The weighted product model

The weighted product model (WPM) can be considered a modification of the weighted sum model (WSM); the earliest and probably the most widely used method [7]. Whilst the WSM should be used only when the decision criteria can be expressed in identical units of measure, the WPM eliminate any units of measures which makes it suitable for the current application.

In the WPM each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In order to compare two alternatives A_K and A_L the following product [8] has to be calculated:

$$R(A_K/A_L) = \prod_{j=1}^{n} (a_{Kj} / a_{Lj})^{w_j} \qquad (4.1)$$

Where *n* is the number of criteria, a_{ij} is the performance measure of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.

If the term $R(A_K/A_L)$ is greater than one, then it indicates that alternative A_K is more desirable than alternative A_L. The best alternative is the one that better than or at least equal to all the others.

4.7. SELECTING HLS PROCESS

In order to apply the WPM method, four inputs have to be determined. These are the alternatives, the criteria, relative importance weights of the criteria and performance measures of the alternatives. Then pair-wise comparison will be made to rank the alternatives and determine the preferred choice.

4.7.1. Defining the alternative and criteria

Suppose decision maker(s) is planning to install HLS, the review of HLS in **Chapter 3** shows that HSL, Parans and SCIS systems are the most promising HLS. Therefore, they are defined as the most suitably available alternatives.

Table 4.1: Decision criteria relative importance weight

Decision Criteria	Relative Weight
Lighting Quality & Quantity	13.1 %
Ease of Maintenance	12.1 %
Cost	12.1 %
Fire hazard	11.9 %
Luminaire Flexibility	10.8 %
Light Guidance Size	10.3 %
Possibilities of use	10.2 %
Light Collector Location	9.9 %
Ease of Installation	9.5 %

Defining appropriate criteria able to measure different aspects of the alternatives are more complicated. The defined criteria should be systemic, reliable, measurable and comparable [5]. Defining criteria in this study based on the authors knowledge and analysis of hybrid systems' components and performance; previously discussed. Criteria defined to cover architectural, technical, economical and operational aspects (see list of the criteria in **Table 4.1**). Social criteria, such as users' productivity improvement or building prestige enhancement due to use of natural light, may be considerable if electric lighting system is considered one of the alternatives.

4.7.2. Numerical measures

Importance weights and performance measures are unavailable data and have to be determined by decision maker(s). Numerical values of the weights or the performance can be determined by subjective, objective, or combined methods. The subjective methods depend only on the preference of decision maker(s). Contrarily the objective values are obtained by mathematical methods based on the analysis of initial data. It can said that none of them is perfect, so combined methods are suggested [5].

In this study, a combined method was used. Values obtained from the survey are the recipients' subjective evaluation. These values numerically treated to obtain the importance weights and performance measures. Practically, decision maker(s) in each case has to determine the more likely related values for their situation; taking into account building use type and times, building form and orientation, location and budget.

4.7.2.1. Weighting

Recipients have weighted the criteria and the importance weights averages have been calculated. Then normalized to add up to one and ranked as listed in **Table 4.1**. In reality, change of priorities responses to decision maker(s) appraisal of the real situation, which is possibly depends on client's needs, customers' complains or even feed backs. Reprioritization leads to changes in the criteria importance weights, and as a result changes in the alternatives preferences. For instance, an existing building with low clear height; light guidance size will be of greater importance than new building or high clear height building. 'Light collector location' criterion, in another example, may be of high priority in a building with a sensitive iconic form.

4.7.2.2. Rating

Performances of alternatives corresponding to each criterion have been derived from recipients' preferences. For example, regarding 'light collector location' preferences; valid responses percentages were as follows: 65.6% prefers roof mounting, 9.4% facade attached, 6.3% facade concealed, and 18.8% any method. HSL, as a roof mounted system, obtained performance measure of 84.4% (65.6% + 18.8%). Since Parans is a roof mounted or facade attached system, it obtained 93.8%. SICS, a facade attached or concealed system, obtained 34.5%.

Since performance measure corresponds to decision criteria, corresponding to 'light collector location' criterion in iconic building will widely vary. Roof mounted method may obtain in this case 100% preference rather than 65.6% to avoid influencing elevations appearance, or obtain 0% if it is a doom roofed building and roof mounting is conceptually unacceptable. In order that, as said in the weighting, in reality change of rating could happen in response to specific situations.

4.7.3. Determining alternatives ranking

Decision matrix includes all alternatives and decision criteria was set in as illustrated in **Table 4.2**. Obtained relative weight of importance of decision criteria and performance measures of alternatives were filled in the matrix. Considering presented values in **Table 4.2**, **Eq. 4.1** was used to compare each two alternatives together. The following relations are produced:

Table 4.2: Decision making matrix

Alternatives	Decision Criteria	Cost	Ease of installation	Ease of maintenance	Collector location	Guidance size	Luminaire flexibility	Light quality & Quantity	Fire hazard	Possibilities of use
	Weight	**0.121**	**0.095**	**0.121**	**0.099**	**0.103**	**0.108**	**0.131**	**0.119**	**0.102**
HSL	*Rating*	0.30	0.79	0.60	0.84	0.93	0.87	0.29	0.50	0.17
Parans	*Rating*	0.18	0.78	0.50	0.94	0.95	0.87	0.04	1.00	1.00
SCIS	*Rating*	0.91	0.35	0.36	0.34	0.68	0.60	0.86	0.50	0.17

(0) rate means no fit at all, (1) rate means excellent fit.

$R_{(HSL/Parans)}$ = $(0.30 / 0.18)^{0.121}$ x $(0.79 / 0.78)^{0.095}$ x ... x $(0.17 / 1.00)^{0.102}$
= 1.07 > 1

Similarly, we also get:

$R_{(HSL/SCIS)}$ = 1.02 > 1
$R_{(Parans/SCIS)}$ = 0.96 < 1

Therefore, the best alternative in this case is HSL system, since it superior to all other alternatives, then SCIS, and finally Parans.

4.8. SENSITIVITY ANALYSIS

4.8.1. Background and definition

In the WPM method weights assigned to the decision criteria attempt to represent the genuine importance of the criteria. In the above case, 'light quality 'criterion obtained the best weight, therefore it intuitively attempts to be believed the most important criterion. Since the defined criteria in the current case have different units of measure, and cannot be all expressed in quantitative terms, then it is difficult to represent accurately the importance of these criteria. In a situation like this, the decision making process can be improved considerably by identifying the critical criteria. Sensitivity analysis is the approach by which the critical criteria can be identified to determine what is the *smallest* change in the current weights of the criteria, which can *alter* the existing ranking of the alternatives? The most critical criterion can be determined to see whether it will alter the rank of any two alternatives or just change the rank of the best alternative.

4.8.2. Determining the most critical criterion

Let $\Delta'_{k,i,j}$ ($1 \le i \le j \le m$ and $1 \le k \le n$) denote the minimum percent of change in the current weight w_k of criterion C_k so that the ranking of alternatives A_i and A_j will be reversed. When the WPM method is used, the quantity $\Delta'_{k,i,j}$ is given as follows [7]:

$$\Delta'_{k,i,j} > Z \qquad \text{if, } 0 \le Z \le 100$$

$$\Delta'_{k,i,j} < Z \qquad \text{if, } Z < 0 \tag{4.2}$$

Where Z is defined as:

$$Z = [(log\ (\textstyle\prod_{y=1}^{n}(a_{iy}/a_{jy})^{w_y})) \times 100\ ] / [(\ log\ (a_{ik}/a_{jk})) \times w_k\ ] \tag{4.3}$$

Also, the following constraint has to be satisfied:

$$\Delta'_{k,i,j} \le 100 \tag{4.4}$$

In order to determine the most critical criterion a total of [n x m (m – 1)] values need to be calculated. For example, the minimum quantity (expressed as %) needed to change the current weight of 'light quality', so consequently the current ranking of HSL and SCIS systems will be reversed; can be calculated using relation **(4.3)** as follows:

$$Z_{(HSL/SCIS)} = \frac{\log\left((0.30/0.91)^{0.121} \text{ x } (0.79/0.35)^{0.095} \text{ x } \dots \text{ x } (0.17/0.17)^{0.102}\right)}{\log\ (0.29/0.86)} \text{ x } \frac{100}{0.131} = -16.53$$

The quantity -16.53 satisfies **(4.4)** relation as it is less than 100. Therefore the value of $\Delta'_{k,i,j}$ have to be less than -16.53 according to **(4.2)**. Thus the modified weight w^* of the 'light quality' criterion has to be increased 16.53% at least. It can be calculated as follows (before normalization):

$$w^*_K \quad = w_k - (w_k \ x \ \Delta'_{k,i,j}) = \ 0.131 - (0.131 \text{ x } (-16.53\%)) \ = 0.153$$

The use of the modified weights values (after normalization) makes the relation $R_{(HSL/SCIS)}$ equal to one. Any further increase in the modified weight of 'light quality' criterion makes $R_{(HSL/SCIS)}$ less than one, which accordingly reverses the rank and makes the SCIS alternative superior to the HSL.

Working as above for all possible pairs of alternatives, all possible Z values can be determined as depicted in **Table 4.3**. Note that n/f stands for non-feasible value, which is value that cannot satisfy the constraint given as **(4.4)**. That means it is impossible to reverse the existing ranking of pair of alternatives by making changes on the current weight of the corresponding criterion. It can be observed that the criterion with the highest weight is the critical criterion in all cases.

Table 4.3: All possible Z values

Pairs of Alternatives	Decision Criteria								
	Cost	Ease of installation	Ease of maintenance	Collector location	Guidance size	Luminaire flexibility	Light quality & Quantity	Fire hazard	Possibilities of use
HSL/Parans	n/f	n/f	n/f	-634.28	-3006.02		**25.42**	-79.93	-36.01
Parans/SCIS	21.90	-55.63	-106.88	-42.84	-123.03	-105.73	**10.55**	-51.41	-23.42
HSL/SCIS	-17.80	30.38	38.13	26.56	72.89	58.65	**-16.53**		-1162.46

4.8.3. Degree of criticality

Importance ranking of the criteria may change after determining the critical criteria. The criticality degree, D'_k, of criterion C_k is the smallest percent amount by which the current value of w_k must change, so that the existing ranking of the alternatives will change [7]. That is, the following relation is true:

$$D'_k \quad = \min_{1 \le i < j \le m} \{ \left| \Delta'_{k,i,j} \right| \}, \text{ for all } n \ge k \ge 1$$

Therefore, from **Table 4.3**, the criticality degrees are as depicted in **Table 4.4**.

Table 4.4: The criticality degree of the criteria

Decision Criteria	*D'*
Lighting Quality & Quantity	10.55
Cost	17.80
Possibilities of use	23.42
Light Collector Location	26.56
Ease of Installation	30.38
Ease of Maintenance	38.13
Fire hazard	51.41
Luminaire Flexibility	58.65
Light Guidance Size	72.89

4.9. DISCUSSION

Although HLS have a common concept, a variety of HLS components and techniques are used to collect, deliver and distribute daylight combined with eclectic light into windowless or remote spaces in buildings. Since they are newly developed, integration between HLS strategies and building design strategies suffers from a lack of experience. Over the last decade, development of HLS focused on augmenting their performance, but more experience is required to increase their applicability in buildings.

HLS components influence building design, either functionally or aesthetically. Thus, HLS need to consider, in addition to the performance factor, integration factor with building systems. Building designers as well need to know HLS potential benefits and possible applications to incorporate them in buildings fabric. Although most HLS can be installed in existing buildings, earlier consideration of them in building design process is more likely to produce better incorporation.

The vast variety in the HLS features is what make a rational choice is a very difficult decision. Thus, this chapter aimed to study a method by which a particular HLS can be identified ideal for a particular application. The MCDM offers numerical methods to help decision maker(s). The WPM method, a dimensionless MCDM method, was utilized to make a decision in a general case, in which a HLS is desired to be selected.

In order to apply the WPM method, a set of three HLS was nominated as alternatives. A set of nine decision criteria were defined based on alternatives components and performance analysis. The relative importance weights of the criteria and the alternatives performance were derived from decision makers' responses to an online survey. Changes in these values are more likely to happen with every new situation to reflect the new circumstances.

'Light quality' and 'ease of maintenance' criteria, as whole life aspects, were selected by the surveyed decision makers as the most important criteria, in addition to the 'cost' criterion. Contrarily, 'ease of installation' criterion, as one-off aspects, emerged as the least important criterion. The criterion elected by decision maker(s) as the most important one is not necessarily to be the most influential or critical one; especially in cases where different units of measurement were used. Therefore, the criticality degree can be measured by the criterions ability to change the alternative ranking. The smaller the change in the criterion weight required to alter the ranking, the more critical the criterion is. Thus, criterion that cannot alter alternatives ranking whatever change to its weight can be eliminated.

A sensitivity analysis was carried out to determine critical degrees of the criteria. 'Light quality', the most important criterion, was the most critical one as well. Only a 16.53% rise in its relative weight is enough to nominate the SCIS the best alternative instead of the HSL. In order to bring Parans to the top, at least 25.42% reduction in the relative weight of the 'light quality' is necessary. Meanwhile, only 10.55% reduction is enough to reverse SCIS rank with Parans system.

Alternatives performance show close similarity on some criteria and wide variation on others. For example, HSL and Parans obtained 0.79 and 0.78 values respectively in terms of 'ease of installation', whilst SCIS obtained only 0.35, as SCIS collector and guidance are much bigger in size and weight, thus more supports and building modification are needed.

In terms of ‘cost’ a big variation exists which reveals the decision makers acceptance of the systems’ payback periods. The difference between 0.91 obtained by SCIS and 0.18 obtained by Parans reflects the big difference between the costs of both of them. Similarly, Parans obtained 0.90 in terms of ‘guidance size’, whilst SICS obtained only 0.30 which demonstrate the difference between the small-diameter fibre optic cables and the big-section illuminance ducts.

4.10.CONCLUSION

When selecting a HLS, the designer must be aware of all its properties and how it responses to architectural, interior, structural and building services elements. The performance parameter has the most pronounced effect on lighting design process, but integration with other systems in the buildings is also important. Throughout the early stages of the HLS development, efforts are focused on enhancing their performance. In the next stages, HLS need to develop more solutions response to building function and aesthetic demands, and building designers need to devote more efforts to incorporate them in buildings fabric.

Perfect decision in selecting HLS is not only that enhances the integration between HLS and other building systems, but also that best suit architectural design scheme, best matches users’ needs, and best meets building budget. The reviewed HLS showed vast variation in terms of HLS characteristics, performance, and cost. Rational choice appears to be more likely using the MCDM approach, which ranks the alternatives according to their performance in terms of the decision criteria.

As for many decision within the design process, there exists no definite procedure how to select a HLS. The ultimate criterion is the performance of the overall design.

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CHAPTER

5

Feasibility Study

5.1. INTRODUCTION

Although available for the past decade or so, there is still a dearth of knowledge about integration of daylight guidance system with electric lighting so as to achieve the full economic and user benefit. Daylight guidance systems in building aim to provide sufficient illuminance and save energy. The ability to deliver daylight depends on many variables such as building configuration and geographic location.

This chapter examines potential light delivery and energy savings in commercial buildings by the use of HLS and, for comparison purposes, TDGS. Results are expressed in terms of predicted energy saving and likely usage patterns (the proportions of daylight, electric and hybrid lighting used) for combinations of building configuration, geographic location and types of daylight delivery system. The considerable variation in performance as a function of system type, geographic location, and building geometry, suggests that choice of appropriate light guidance system may be strongly influenced by building location.

5.2. STUDY PARAMETERS

5.2.1. Choice of locations

The investigation is based on locations which are broadly representative of conditions throughout Europe, Africa and the Middle East. The investigation was limited to this area because the illuminance data required for the study have been derived from satellite web-site covers an area from -66° to 66° both in latitude and longitude as detailed in **Section 5.2.3**. The Northern hemisphere locations only were considered to eliminate the locations number. The 26 selected locations include both maritime and continental cities and latitudes from the Equator to 60°N at intervals of about 5°. They cover four main climatic regions according to Köppen-Geiger climate classification; tropical, arid, temperate, and cold climates (see **Fig. 5.1**) [1]. **Table 5.1** lists the selected cities, their locations and climatic regions

5.2.2. Light guidance systems

As mentioned in chapter 3, three HLS only are considered have a potential application and an ability to be used widely. These are Parans system, which is commercially available, the HSL and SCIS that have many demonstration installations on real buildings (see **Figs. 3.11 – 3.14**). The various hybrid systems are compared with passive TDGS.

Table 5.1: Location details and climatic regions

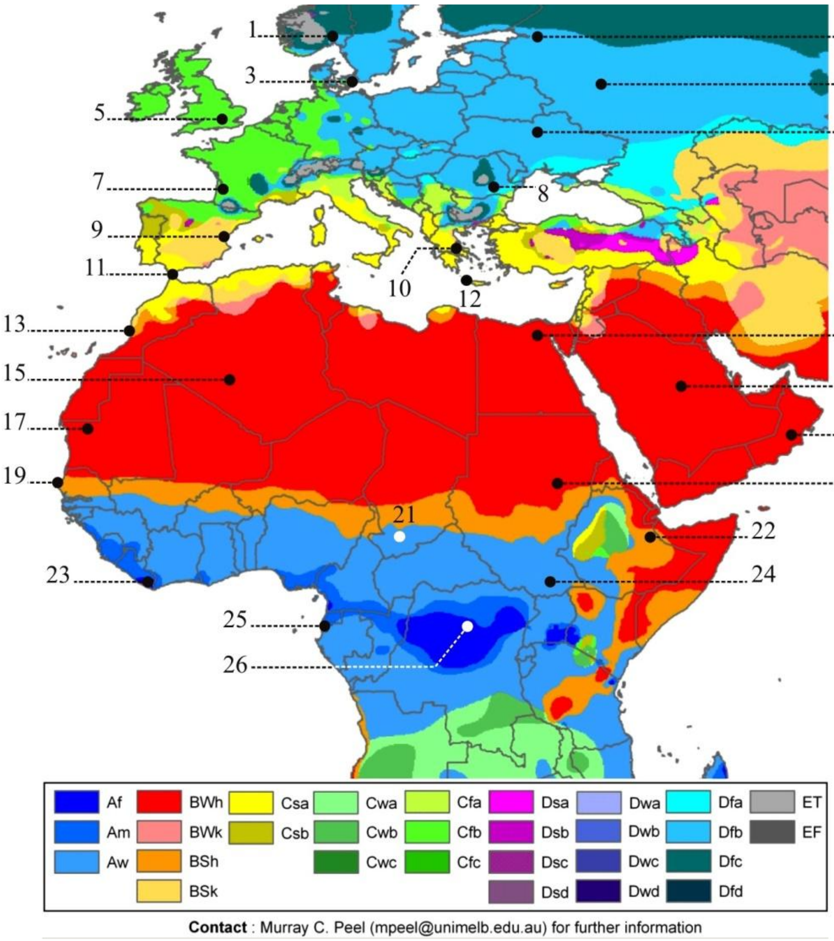
No.	Climatic region		Time zone (+UTC)	Location: City	Country	Lat. (N°)	Long. (E°)
1	Cold, *fully humid*	Df	1	**Oslo**	Norway	59.91	10.75
2			3	**St. Petersburg**	Russia	59.89	30.26
3			1	**Copenhagen**	Denmark	55.66	12.58
4			3	**Moscow**	Russia	55.75	37.61
5	Temperate, *fully humid*	Cf	0	**London**	UK	51.50	-0.11
6	Cold, *fully humid*	Df	2	**Kiev**	Ukraine	50.43	30.51
7	Temperate, *fully humid*	Cf	1	**Bordeaux**	France	44.83	-0.56
8	Cold, *fully humid*	Df	2	**Bucharest**	Romania	44.43	26.10
9	Arid *steppe*	BS	1	**Valencia**	Spain	39.46	-0.36
10	Temperate, *summer dry*	Cs	2	**Athens**	Greece	37.98	23.73
11	Temperate, *summer dry*	Cs	1	**Tarifa**	Spain	36.01	-5.60
12			2	**Khania**	Greece	35.51	24.01
13	Arid *steppe*	BS	0	**Agadir**	Morocco	30.40	-9.60
14	Arid *desert*	BW	2	**Cairo**	Egypt	30.05	31.25
15			1	**Reggane**	Algeria	26.70	0.16
16			3	**Riyadh**	KSA	24.64	46.77
17			0	**Atar**	Mauritania	20.51	-13.05
18			4	**Hayma**	Oman	19.93	56.31
19	Arid *steppe*	BS	0	**Dakar**	Senegal	14.67	-17.43
20	Arid *desert*	BW	2	**Al Khartoum**	Sudan	15.58	32.53
21	Tropical, *winter dry*	Aw	1	**Koumra**	Chad	9.25	18.20
22	Arid *steppe*	BS	3	**Harare**	Ethiopia	9.31	42.11
23	Tropical, *fully humid*	Af	0	**Fish town**	Liberia	5.19	-7.87
24	Tropical, *winter dry*	Aw	2	**Juba**	Sudan	4.85	31.61
25	Tropical, *monsoon*	Am	1	**Libreville**	Gabon	0.38	9.75
26	Tropical, fully humid	Af	1	**Kisangani**	Congo, D.R.	0.85	29.36

5.2.3. Data sources

Two sources of data were used, both web-based. The *SoDa* solar radiation data website was used as the source of irradiation data, from which external illuminance data was produced using the concept of luminous efficacy [2]. This site covers an area from -66° to 66° both in latitude and longitude. The MIDC SOLPOS application was used for calculating solar position [3]. Global, diffused and direct data on horizontal surface and on surfaces tracking the sun at normal incidence were obtained from the two data sets.

5.2.4. Building configuration and system suitability

Offices are major employment locations and constitute a large sector of the total building stock. For almost all office buildings working hours coincide with daylight hours. Daylight guidance manufacturers have targeted offices as a potential market in an attempt to satisfy user preference for daylight on visual tasks in working interiors. Also since electric lighting is a major energy consumer in offices a case exists for the provision of daylight as a substitute. Throughout this study office working hours were assumed to extend from 08:00 to 18:00.



Main climate
A: Equatorial
B: Arid
C: Warm temperate
D: Cold
E: Polar

Precipitation
W: Desert
S: Steppe
f: Fully humid
s: Summer dry
w: Winter dry
m: Monsoonal

Temperature
h: Hot arid
k: Cold arid
a: Hot summer
b: Warm summer
c: Cool summer
d: Extremely continental
F: Polar frost
T: Polar tundra

Figure 5.1: *Selected locations as numbered in Table 5.1 on Köppen-Geiger climate classification map*

Lighting needs in office work spaces are well defined [4]. Electric lighting is usually delivered via regular arrays of ceiling mounted luminaires. Daylight guidance output devices are also ceiling mounted usually in an array compatible with that of the electric luminaires. Contemporary interior design for offices is typically based on modules each containing a number of workstations. This work is based on the lighting of modular spaces of 72m^2 (6mX12m) with the short edge facing south. Interiors of common office layouts can be configured using this module thus (see **Fig. 5.2**):

- One or multiple modules side-by-side to form a single-storey narrow-plan building.
- One or multiple modules side-by-side forming a multi-storey narrow-plan building.
- Multiple modules in two directions forming a single-storey deep-plan building.
- Multiple modules in two directions forming a multi-storey deep-plan building.

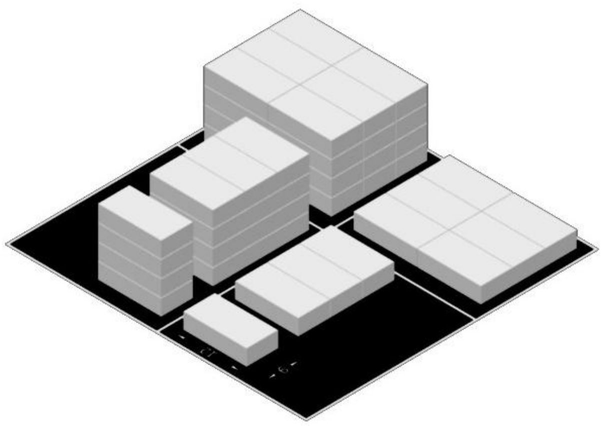


Figure 5.2: *Building form possibilities*

The first case in this study is considered the 'basic case'. This and the second case are usually lit using combinations of daylight and electric light. The latter two are usually considered to be electric light only due to horizontal and/or vertical distance of the core areas from the building envelope. However the long distances over which light may be transported using light guidance means that all of the four configurations may be 'day-lit' in some measure.

Both HSL and TDGS require roof mounted collectors. SCIS is an integral part of a building façade having a suitable orientation. The Parans system collectors may be mounted on either roofs or facades. Thus HSL or TDGS are more suitable for the first and third cases SCIS is more suitable for the second case, and Parans is suitable for all cases.

5.3. LIGHTING DELIVERY AND ELECTRICITY SAVING CALCULATION METHODOLOGY

For each site external illuminance data was obtained and numerical processes subsequently used to predict the resulting internal illuminance delivered by the guidance system. Finally an estimation of electricity savings for each combination of system, building configuration and location was made.

5.3.1. External illuminance prediction

The total annual sum of global horizontal illuminance gives a guide to the external illuminance available at a particular location. A more accurate estimation of hours of useful daylight, and hence potential burning hours of electric light, requires values of external illuminance over shorter time periods. A series of 10-minute average external illuminance, throughout an entire year, for direct normal (DN) and global horizontal (GH) illuminance was used in this study. This required more than 52000 values a year, and some 22000 over the assumed annual working hours. Using the 10-minute average values daylight guidance system performance can be simulated numerically.

The SoDa website provides 10-minute DN and GH irradiation averages for the 26 locations for the year 2005. These were converted into their photopic equivalents using the sun position values obtained from SOLPOS, and the universal luminous efficacy model developed in the illuminance data chapter. The 2005 annual irradiation values were compared with the 21-year irradiation averages (1985-2005) (see T**able 5.2**). It can be seen that in most locations the 2005 values were below the 21-year average, and the implications of this will be explored later in the discussion.

It is also evident that peak irradiance values at around 10°-15°N latitude are up to 2.5 times higher than those in the Northern latitudes. This is important since some of the systems collect and concentrate direct sunlight only, whilst others additionally collect small amounts of diffuse skylight. The high concentrating systems, HSL and Parans, effectively distribute only direct sunlight. SCIS with low concentration ratio distributes some diffused illuminance (providing internal illuminance of the order of 30lux) in addition to the direct sunlight component [5]. TDGS collect and distribute daylight with no concentration.

5.3.2. Internal illuminance calculation (basic case)

This study assumes a design illuminance of 300lux on a horizontal working surface 0.8m from the floor. Calculations were carried out to achieve this level in a windowless modular space of 6m x 12m x 3m-high using HSL, Parans, SCIS, TDG or electric lighting systems in turn. Each specification was in accordance with the recommendations of the system developer or manufacturer. In summary there was one HSL system for 90-100m^2; one Parans system for 20-30m^2; one SCIS for 3 x 12 m, and one ø300mm TDGS for each ~10m^2. The number of each system to light the 72m^2 modular space was established as follows:

- One HSL collector supplying eight luminaires via approximately 7m-long fibre optic cables.
- Four Parans solar panels supplying eight luminaires via approximately 3m-long fibre optic cables.
- Two SCIS with 0.6m-wide and 12m-long dual function light duct.
- Eight ø300mm TDGS equipped with a 1.2m guide and one elbow.

The internal planar illuminance delivered was calculated using the lumen method every 10 minutes for each location and lighting system.

Table 5.2: Annual and 2005 averages of DN. and GH. irradiance, and differences from the averages.

Location	**DN.** (W/m^2)		**Difference from Ave.** (%)			**GH.** (W/m^2)		**Difference from Ave.** (%)		
City	**21-year Ave.**	**2005 Ave.**	Actual Diff.	Min Diff.	Max Diff.	**21-year Ave.**	**2005 Ave.**	Actual Diff.	Min Diff.	Max Diff.
Oslo	109	97	*-11*	-23	32	115	109	*-6*	-13	20
Petersburg	96	107	*11*	-22	19	115	119	*3*	-9	10
C'hagen	114	116	*2*	-22	18	131	130	*-1*	-13	11
Moscow	121	101	*-17*	-22	43	129	121	*-6*	-12	21
London	84	76	*-9*	-27	48	121	112	*-7*	-14	29
Kiev	135	130	*-3*	-16	24	149	147	*-1*	-7	10
Bordeaux	138	138	*0*	-20	30	163	163	*0*	-9	13
Bucharest	175	163	*-7*	-15	10	185	174	*-6*	-6	6
Valencia	187	180	*-4*	-10	12	197	194	*-1*	-5	5
Athens	155	148	*-5*	-11	14	185	181	*-2*	-6	8
Tarifa	238	243	*2*	-6	10	226	229	*1*	-3	4
Khania	175	175	*0*	-9	11	198	199	*1*	-4	5
Agadir	216	212	*-2*	-8	16	228	226	*-1*	-4	6
Cairo	196	195	*-1*	-16	19	222	222	*0*	-6	6
Reggane	225	220	*-2*	-8	11	242	242	*0*	-3	4
Riyadh	212	207	*-2*	-24	24	237	234	*-1*	-9	8
Atar	237	231	*-3*	-22	14	258	253	*-2*	-7	5
Hayma	214	210	*-2*	-27	29	243	242	*0*	-9	9
Dakar	226	210	*-7*	-7	9	257	246	*-4*	-4	4
Khartoum	264	262	*-1*	-5	6	274	272	*-1*	-2	2
Komura	241	233	*-3*	-7	8	263	260	*-1*	-3	4
Harare	283	273	*-4*	-8	7	288	285	*-1*	-3	3
Fishtown	178	161	*-10*	-12	29	237	226	*-5*	-5	11
Juba	232	225	*-3*	-11	9	262	259	*-1*	-4	4
Libreville	177	165	*-7*	-13	24	238	228	*-4*	-4	9
Kisangani	213	215	*1*	-14	15	257	255	*-1*	-4	6

5.3.3. Calculation of energy saving

No supplementary electric lighting system is used if daylight provides more than the 300lux illuminance design level. Once the delivered daylight drops below this level, supplementary electric lighting controlled by light sensors and continuous dimming system is assumed to top up the delivered daylight. The electric lighting systems are designed to provide all of the 300lux if daylight contributes less than 50lux. The electric load is calculated every 10 minutes and the annual consumption summed. This is compared with the annual consumption for 100% electric lighting in order to estimate the saving in electric loads.

The electric lighting system is assumed to be 1200mm T5/28W fluorescent tubes (mean lumen output 2726 lm) in luminaires having an assumed Utilisation Factor of 0.59. The same tubes were assumed to be used as integral parts of the HSL and SCIS hybrid systems, and as the parallel system for TDGS. The Parans system used 600mm T5/14W fluorescent tubes (mean lumen output 1269 lm).

5.3.4. Usage pattern identification

A count of the10-minute average internal illuminance values that exceeded the design level allowed the determination of the percentage of time when daylight was the sole task lighting source. Similarly, a count of values less than 50lux represented the percentage of working hours when electric light was the sole source. The hybrid devices were assumed to be used in the intermediate range with available daylight supplemented as required by the electric system.

5.3.5. Internal illuminance calculation for multi-storey case

The multi-storey cases assume a high-rise building. Calculations were made for one module only so that the total floor area considered was similar to the basic case. The second and fourth storeys from top of the building were investigated. The configuration of the various guidance systems differ with building configuration. The SCIS, being part of the façade, will have a similar performance on all storeys in the absence of external obstruction. Parans collectors can be located on a suitably orientated façade, or be roof-mounted. In this study the shortest light transport routes are assumed and thus the second floor from top is supplied from both facade and roof collectors. The fourth floor from top is entirely supplied from façade-mounted Parans collectors. HSL and TDGS both use roof-mounted collectors. In both light transport losses will increase steeply with travel distance from roof to lower-storeys. TDGS would normally be not applicable for the fourth floor from the top because of the light loss over that distance and the practical and economic difficulties of accommodating the light guidance devices in the building (see in **Fig. 5.3**).

5.3.6. Internal illuminance calculation for deep-plan case

The deep-plan case assumed a one storey building consisting of an array of 2 x 2 modules. Since HSL, Parans and TDG are roof-mounted systems the calculation process will be the same as the basic case. The SCIS system, being façade-mounted, will have a limited use since it will not be able to efficiently redirect daylight beyond the first row of modules (>12m depth). It is assumed that the second row of modules will be electrically lit.

5.4. RESULTS

5.4.1. Relationship between external illuminance and latitude

Fig. 5.4 shows the relationship between latitude and DN and GH external illuminance respectively over the assumed working hours. Third degree polynomial curves define the relationships that show the external illuminance peak occurring between 10˚ N and 15˚N. The coefficient of determination (R^2) indicator for DN and GH illuminance is 0.84 and 0.96 respectively. The outliers in **Fig. 5.4.A** occur mainly in tropical regions (e.g. Fish Town), where there is a combination of high values of solar radiation and a high probability of clouds. Similarly London (51.50˚N) and Tarifa (36˚N) are other outliers. In these cases these locations are very cloudy, and very sunny, respectively in comparison with other cities at similar latitudes.

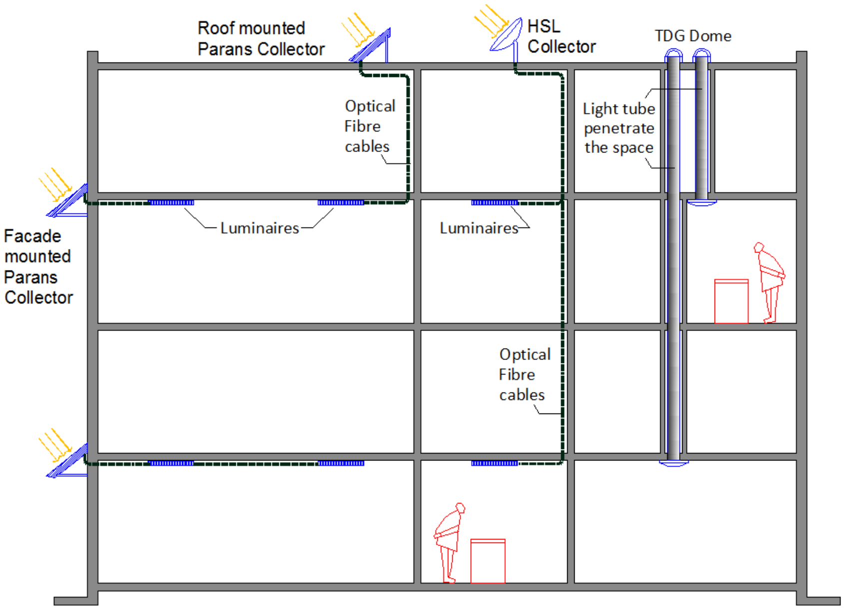


Figure 5.3*: The configurations of the HSL, Parans and TDGS in the multi-storey case.*

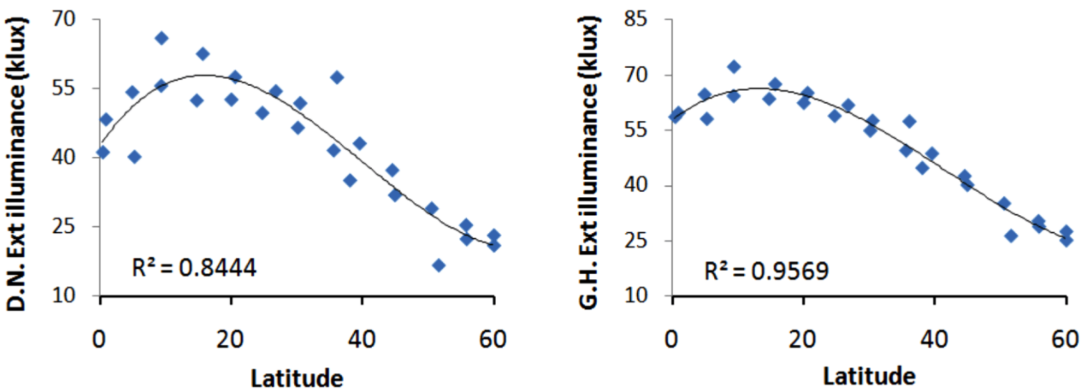


Figure 5.4.A (Left): *Relationship between direct normal (D.N.) external illuminance and latitude over the assumed working hours,* ***B*** (Right): *Relationship between global horizontal (G.H.) external illuminance and latitude over the assumed working hours*

5.4.2. Relationship between external illuminance and climatic region

Fig. 5.5 illustrates both DN and GH external illuminance, over the assumed working hours, for the different climatic regions. In terms of GH illuminance, tropical and arid regions, not surprisingly, have the highest values with an average of 61klux, followed by the temperate region with average of 44klux and the cold region at 32klux. However in terms of DN illuminance, the arid region comes first with average of 54klux, with tropical, temperate and the cold regions having averages of 48, 37 and 26 klux respectively. A big variation in both illuminance components can be seen in the temperate region where, for example, the GH and DN values in London are 46% and 29% of the comparable values in Tarifa.

The DN illuminance, expressed as a proportion of the global normal (GN) illuminance over the assumed working hours, is shown in **Fig. 5.6**. The highest values are in the arid region with average of 72%. The tropical, temperate and cold regions have averages of 68%, 65% and 64% respectively. The tropical and temperate regions show big variations among the different locations. The explanation for this is that both arid and cold regions have relatively dominant and stable sky conditions over the whole geographic area in contrast to those in the tropical and temperate regions. Systems based on sun-tracking collectors would be expected to perform better in locations where this proportion is highest.

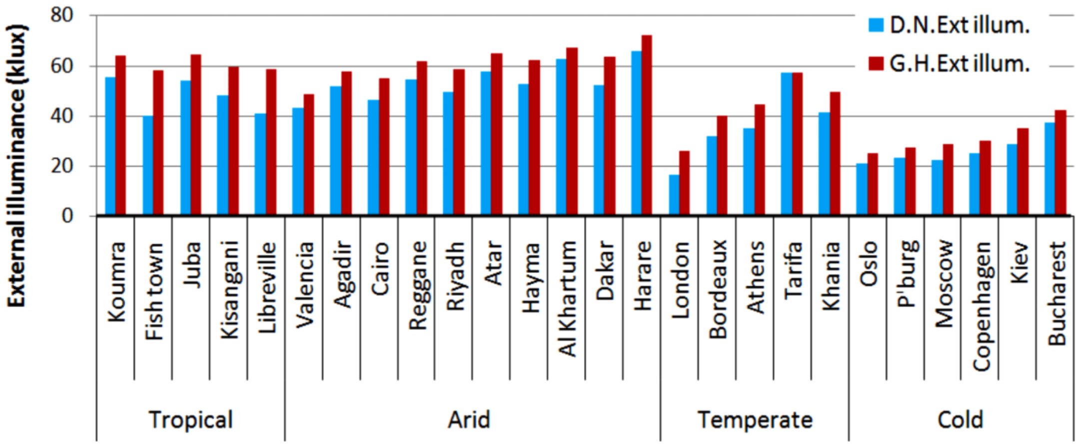


Figure 5.5: *DN and GH external illuminance over working hours for the different climatic regions*

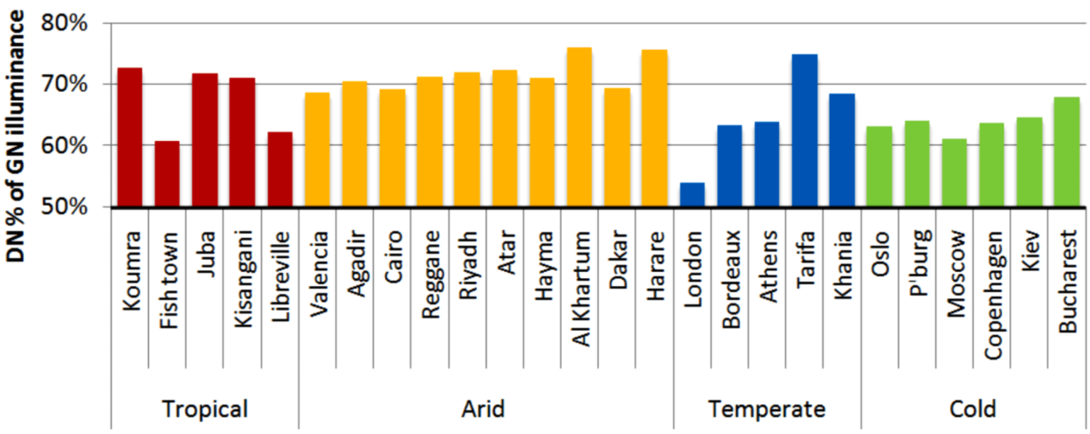


Figure 5.6: *DN illuminance expressed as a proportion of GN illuminance over working hours*

5.4.3. Electric saving in the basic case

The relative importance of DN and GN depends on nature of a particular guidance system. The HSL system has a capability to track the sun and thus collects DN illuminance for the whole sun-path. The most common configuration for passive TDGS collects GH illuminance from both sky and sun on a horizontal roof. In a minority of installations the collectors may be tilted, usually toward the Equator, so as to maximize the benefits of low elevation sunlight. Both Parans and SICS collectors are sun-tracking but are unable to cover the whole diurnal sun-path since their arrays of sun tracking elements are located in fixed enclosures.

5.4.3.1. The relationship between electric saving and external illuminance

The relationship between electric saving due to the utilization of a HSL system and the DN external illuminance is the positive linear relationship as illustrated in **Fig. 5.7.A**. A similar relationship exists for TDGS savings and the GH illuminance (see **Fig. 5.7.B**). In both cases the more illuminance available the more the savings. The relationship between Parans and SCIS electric saving and DN illuminance cannot be as simply explained (see **Figs 5.7.C &5.7.D**). For both, the illuminance gathered, and hence energy saving, is influenced by the tracking limits, which are themselves latitude dependant. **Fig. 5.8** shows the near linear relationship between the tracking limit, the percentage of total diurnal sun-path actually tracked, and latitude. **Figs 5.9.A & 5.9.B** suggest that for both Parans and SCIS the energy savings are functions of the product of the DN illuminance value and the tracking limit percentage, *T* factor. This relationship in both cases is near linear.

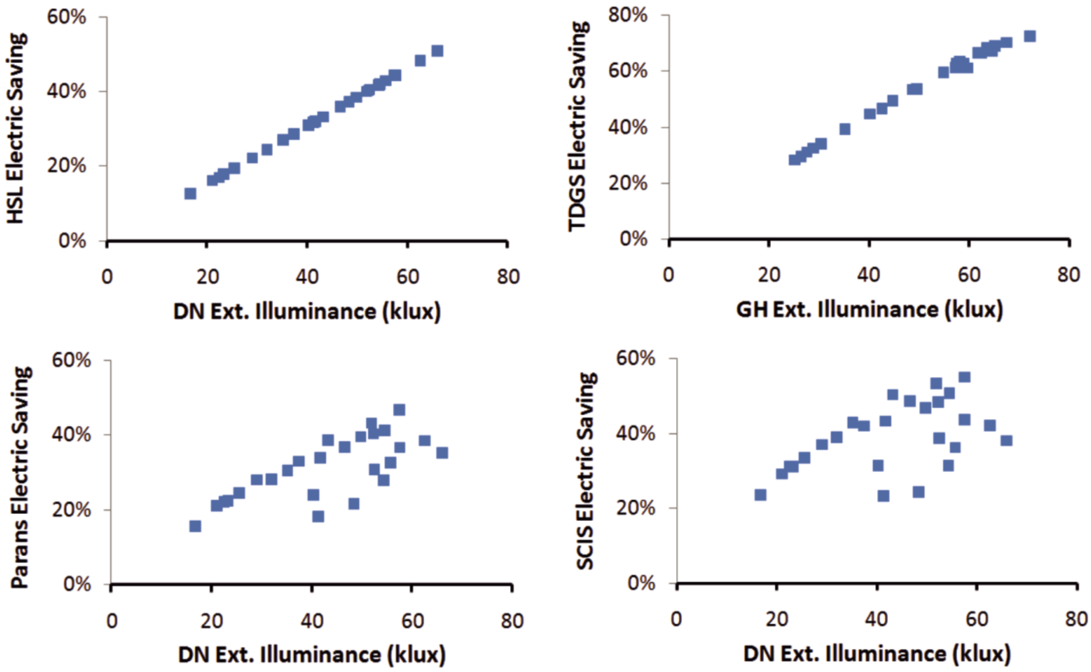


Figure 5.7.A (top left): *HSL saving,* ***B*** (top right): *TDGS saving,* ***C*** (bottom left): *Parans saving,* ***D*** (bottom right): *SCIS saving*

5.4.3.2. Electric saving amounts

Fig. 5.10 plots the percentage electric saving for the basic case system configuration. It is clear that TDGS achieved the biggest savings over almost all locations (average 55%), followed by SCIS (39%), HSL (33%) and Parans (31%). SCIS and TDGS have similar savings in the Northern locations. However TDGS was far superior in low latitudes because of the limited coverage of the SCIS tracking systems of between one- and two-thirds the working hours in latitudes lower than 30˚N. The two high-concentrating systems, HSL and Parans had similar saving magnitudes but with Parans being slightly superior in the Northern locations and vice versa.

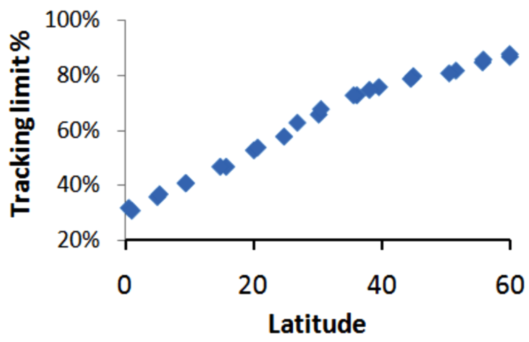


***Figure 5.8:** The relationship between the tracking limits and the latitude*

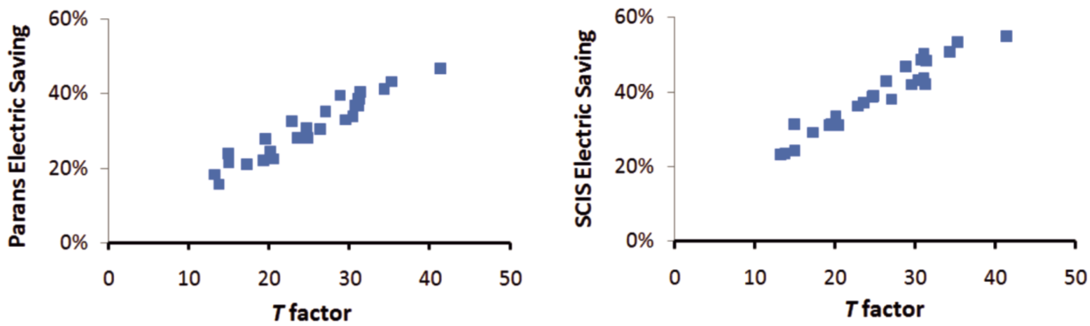


***Figure 5.9:** The relationship between electricity loads saving and the DN illuminance X the tracking limit (T factor), **A** (left): Parans saving, **B** (right): SCIS saving*

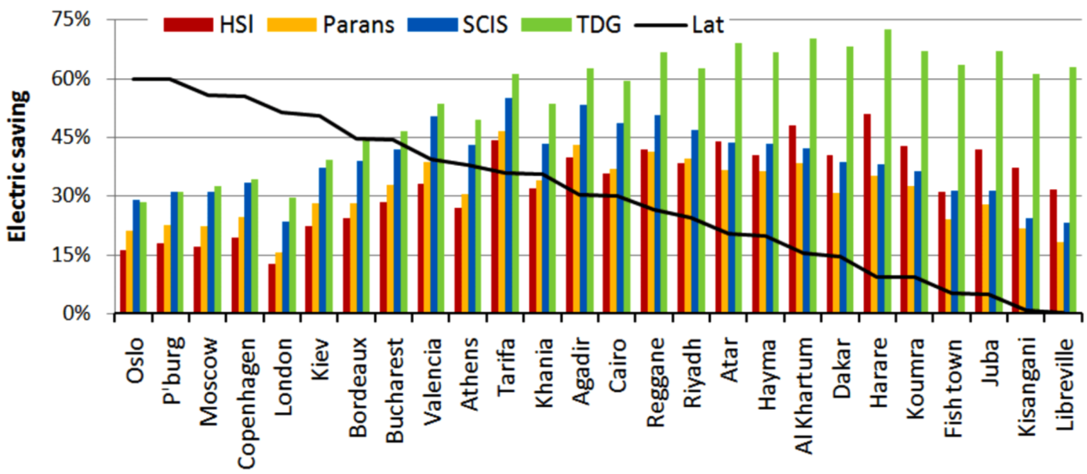


Figure 5.10: *The percentage energy saving for the basic case system configurations*

5.4.3.3. Electric saving trends

The third degree polynomial relationship between the DN illuminance and the latitude (**Fig. 5.4.A**), and the linear relationship between the DN illuminance and the HSL electric saving (**Fig. 5.7.A**) suggests that a third degree polynomial relationship exists between HSL electric saving and latitude. The same logic applies to the relationship between the TDGS and the latitude and these are plotted in **Fig. 5.11.A**. It is apparent that some locations, notably London, Tarifa and Fishtown are outliers for reasons stated earlier. The maximum savings for both systems achieved between 10˚N and 15˚N, and minimum in the extreme Northern locations.

Fig. 5.9 revealed that the electric savings for both Parans and SCIS were influenced by the tracking factor. **Fig. 5.11.B** plots the electric savings for the two systems against tracking factor and latitude. It is apparent that the largest savings occur between 15˚ N and 40˚N. In this region the DN illuminance is more than 40klux and the tracking limit covers between 47-77% of the working hours. Low savings are achieved in the very high and very low latitudes. At high latitudes the tracking limits are as high as 88%, but DN illuminance is as low as 22klux. At lower latitudes DN illuminance may be as high as 50klux but the tracking limits are below 40% of working hours.

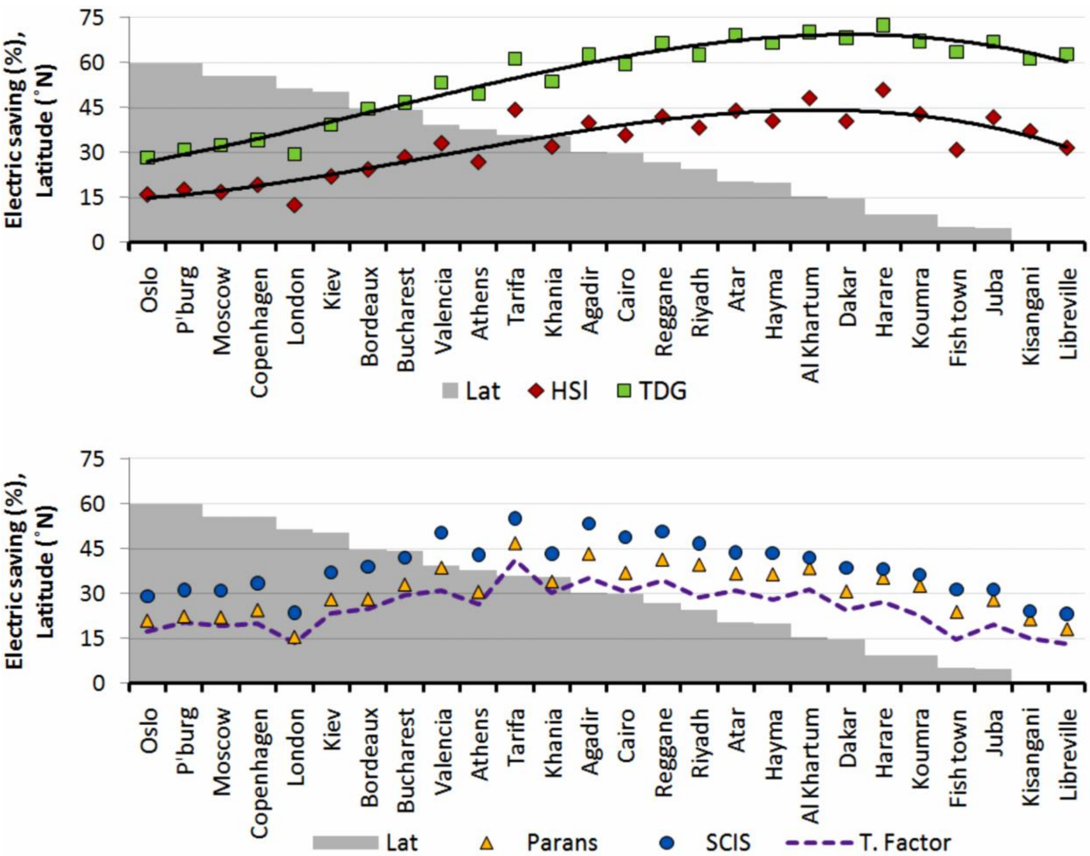


Figure 5.11: *Relationship between electric saving and latitude,* ***A*** (Top): *for HSL and TDGS,* ***B*** (Bottom): *for Parans and SCIS*

5.4.4. Usage pattern in the basic case

Large variations in usage patterns are apparent between the different systems, and at the various locations using the same system. These are related to the variations in external illuminance amounts and type. **Fig. 5.12** shows that HSL failed to deliver a fully day-lit interior for any location, but achieved the highest hybrid lighting usage mean of 61%. The SCIS with a mean of 33% achieved the best wholly daylight delivery, although this did not lead to the largest electric saving. This was achieved by the TDGS which had the lowest full electric lighting usage at 22%.

Fig. 5.13 shows usage patterns and electric savings for the four systems. **Fig. 5.13.A** suggests that HSL electric savings track the proportion of full electric lighting. **Fig. 5.13.B** shows that although Parans electric saving also are strongly influenced by electric lighting usage, there are big variations in both full daylight and hybrid lighting usage. This is caused by the characteristics of the tracking system described earlier. For example, although Koumra and Dakar have similar savings, they have 19% and 2% full daylight usage respectively. The most notable feature of the SCIS usage patterns shown in **Fig. 5.13.C** is the small proportion of hybrid usage. This is as low as 4% in some locations. In **Fig. 5.13.D** the influence of all of the usage pattern components on TDGS electric savings is evident. The high overall levels of electric saving are strongly influenced by the remarkably low full electric lighting usage, with values as low as 10% in many locations.

5.4.5. Multi-storey influence

The configuration of the assumed multi-storey building was described in **Section 5.3.5**. The SCIS being a facade mounted system has the same performance as the basic case in multi-storey application. The performance of the other systems is influenced, to a greater or lesser extent, by the building configuration. The HSL system suffered losses in the additional lengths of guide necessary to transport daylight; resulting in a significant increase in energy usage. The mean electric savings over all geographic locations for the second and fourth stories were 20% and 13% respectively, compared with 33% for the basic case. However the saving trends were almost identical to that of the basic case illustrated in **Fig. 5.11.A**. The actual saving amounts over most locations are around 60% and 40% of the basic case for the second and fourth stories respectively. Using TDGS, the mean electric

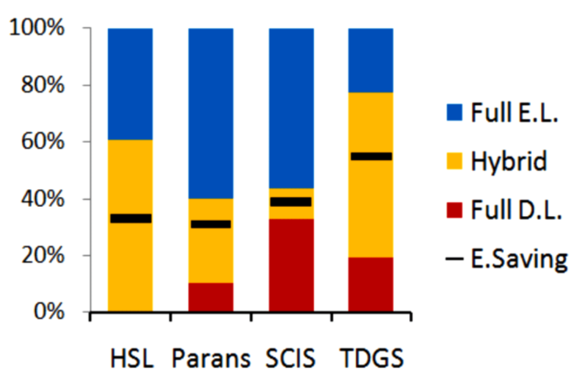


Figure 5.12: *Mean usage pattern and electric savings for all systems*

saving in the second storey dropped to 42% compared with 55% in the basic case. The savings trend is similar to that of the basic case, and the saving amounts range between 72% and 81% of the basic case.

Parans system for the multi-storey configuration is a special case because of the changed locations of some of its collectors. The second storey was supplied with daylight from both facade and roof. Two facade mounted solar collectors were linked to the four luminaires

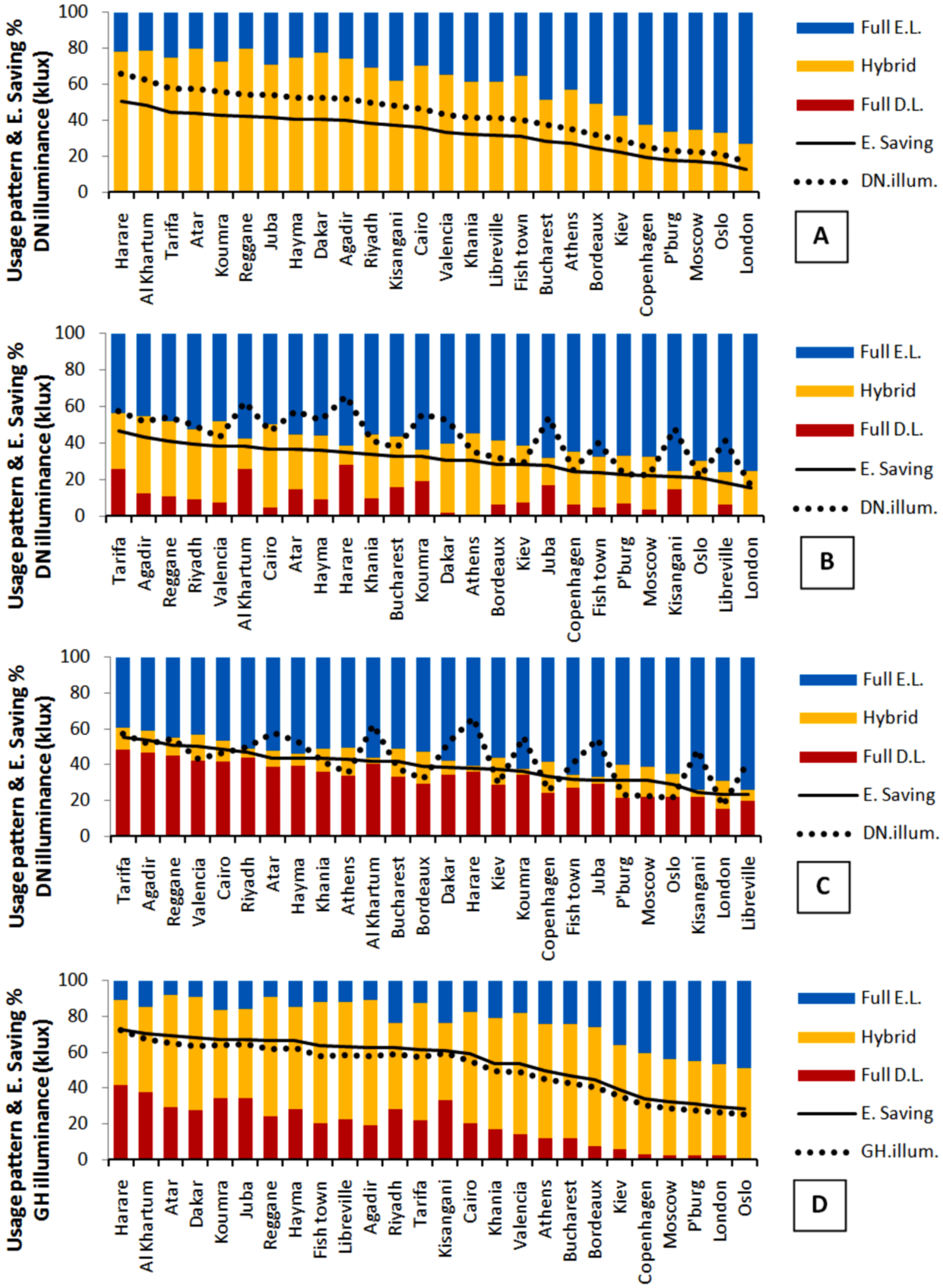


Figure 5.13: *Usage pattern and electric saving of...* ***A****: HSL,* ***B****: Parans system,* ***C****: the SCIS,* ***D****: TDGS*

next to the external wall, and another two roof mounted collectors linked to the other four luminaires. For the fourth storey, only facade attached collectors are used, with four different cable lengths for the four rows of luminaires. These arrangements minimised transport distances and thus reduced light losses. This resulted in mean electric savings of 28% and 27% in the second and fourth stories respectively instead of 31% in the basic case. Saving trends are very similar to that of the basic case and the saving amounts are around 90% and 86% for the second and fourth stories respectively (see **Fig. 5.14**).

5.4.6. Deep-plan influence

Since HSL, Parans and TDGS are roof mounted systems no changes would occur in their electric savings or usage patterns when used in deep plan. The SCIS saving is half that of the basic case since the building depth is doubled and the current arrangement of the SCIS allows for only 12m of efficient daylight transport. However for this system an increase in the height of the light guide would allow longer daylight travel distance and/or decreased light losses.

5.5. DISCUSSION

5.5.1. Deviation from the electric savings trend

There are a number of locations were the electric saving amount is at variance with the general trend. There are three possible explanations for this:

The first is the occurrence of particular local daylight conditions. London, for example, has more clouds than the other temperate location studied, and indeed has the lowest proportion of DN illuminance among all locations studied with only 54% of the GN illuminance over the working hours. The next lowest location had 61% and the average is 68%. **Table 5.3** compares the electric saving for all systems for London and Kiev, the latter having a similar latitude but with 65% GN illuminance. The Table shows that the resulting predicted daylight internal illuminance distributions, and the enhanced values for Kiev have a clear influence on load saving. A further influence on light collection amounts is the local occurrence of atmospheric dust. This has not been included in this study but this could under some circumstances be a major influence, particularly in arid latitudes.

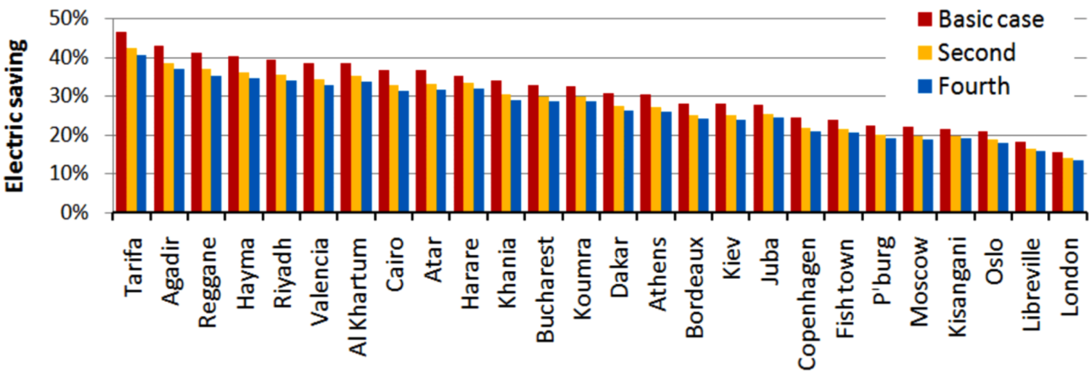


Figure 5.14: *Comparison between Parans electric saving in the basic case and the multi-storey cases*

Table 5.3. Electric saving and illuminance distribution for London and Kiev

Internal illuminance (X) ranges	Ranges percentages of working hours (%)															
	HSL				Parans				SCIS				TDGS			
	London		Kiev		London		Kiev		London		Kiev		London		Kiev	
X ≤ 50		73		58		75		61		69		56		46		36
50 < X ≤100	9		10		6		6		5		5		18		16	
100 < X ≤150	8		10		4		5		3		3		11		12	
150 < X ≤200	9	27	15	42	4	24	5	31	2	15	3	15	10	51	10	59
200 < X ≤250	1		8		4		6		2		2		8		11	
250 < X ≤300	0		0		6		10		2		2		5		9	
300 < X		0		0		1		7		15		29		2		6
Electric saving	12.7%		22.2%		15.7%		28.1%		23.6%		37.1%		29.6%		39.3%	

A second consideration is the effect of differences between the 2005 irradiance values and the 21-year average. In Fishtown, for example, the minimum difference over 21 years between the DN irradiance values and the average is -12%, and that for GH irradiance is -5%. The actual differences for 2005 are -10% and -5% (see **Table 5.2**). If the 10-minute irradiance values for 2005 were normalized to the average, the savings increased by 3.3%, 1.8%, 0.5% and 2.1% for HSL, Parans, SCIS and TDGS respectively. Although not a perfect match with the trend curve for Fishtown the points were much closer to that curve. Other influences were sky conditions. Fishtown's GH irradiance in 2005 is 87% of that for Juba which has equivalent latitude. A similar exercise for DN irradiance shows that that for Fishtown is only 72% that of Juba. This explains the large difference between the HSL saving and the trend curve, and the small difference in the TDGS case (see **Fig. 5.11**).

The third possible explanation for these deviations relates to inconsistencies between the local time zone of the location's country and the supposed time zone for the location's latitude. For example, although all of St. Petersburg, Kiev, Cairo, Al Khartum, Juba and Kisangani are approximately at longitude 30˚E, the local time zone for St. Petersburg is UTC+3, for Kisangani is UTC+1, and for the rest are UTC+2. Assuming a local time zone of UTC+2 for St. Petersburg and Kisangani, electric savings did vary. In St. Petersburg the original estimated savings for HSL, Parans, SCIS and TDGS were an insignificant 0.4, 0.1, 0.2 and 0.6% respectively more than the revised values. By the same process the original values in Kisangani were 3.2, 1.6, 2.1 and 5.3% less than the revised figures, which explain some of the variation. On the other hand many locations may have the same local time despite a big difference in the longitudes (e.g. Tarifa (6˚W) and Kisangani (29˚E)) and this would also result in unrealistic comparisons if not accounted for.

5.5.2. Variation in usage patterns

Variation in usage patterns is apparent in installations which have similar electric savings, or geographical locations. This is most apparent in the proportions of full daylight and hybrid lighting with Parans system, but is also the case for the others to a lesser extent. Using Parans system, Koumra and Dakar achieved similar savings although the full daylighting proportions are 19% and 2% respectively. **Table 5.4** shows predicted internal illuminance distributions for both locations. The main difference is that Koumra has some 20% of values greater than 300lux whereas Dakar has 12% more values in the 250-300 lux range, where minimal electric lighting contribution is required. London and Kiev have similar latitudes but using HSL hybrid lighting was 27% and 42% respectively. Similarly for Juba and Fishtown, 35% and 20% full daylighting was delivered when the TDGS was used. It is thus clear that the internal lit environment created may be very different for systems designed if the sole criteria are minimising energy.

Table 4. Parans electric saving and illuminance distribution for Koumra and Dakar

Internal illuminance (X) ranges	Ranges (%) of working hours			
	Koumra		Dakar	
X ≤ 50		63		60
50 < X ≤100	1	17	3	38
100 < X ≤150	1		3	
150 < X ≤200	2		5	
200 < X ≤250	4		7	
250 < X ≤300	8		20	
300 < X		19		2
Electric saving		32.6%		30.8%

5.5.3. The influence of tracking limits

The light collection process using both Parans and SCIS is governed by the limitations of their tracking coverage, and this result in the loss of some potential daylight. **Fig. 5.15.A** compares electric savings using Parans acknowledging both the limitations of its existing tracking system and those of possible savings assuming a sun tracking system for the whole duration of working hours. The mean saving in the first case is 31% rising to 48% in the

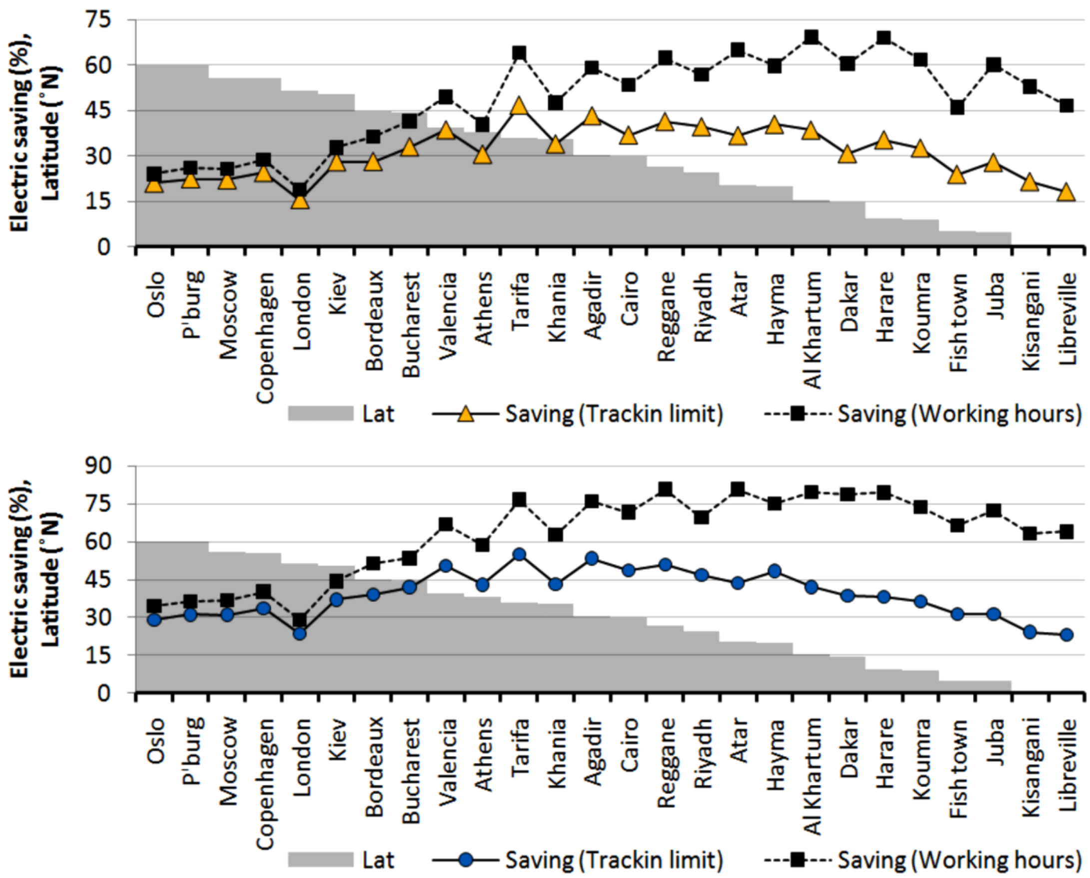


***Figure 5.15:** Comparison between saving over the tracking limit, and over the entire working hours, **A** (Top): Parans system, **B** (Bottom): the SCIS*

second. The modified tracking has a small influence in northern latitudes. Further south there is a much bigger effect, for example in Libreville the existing tracking arrangements produce savings of 39% of the revised system. Although full daylight proportions using the two methods were identical in 10 locations, in the rest the modified system was superior in this respect. Overall the mean full daylight proportion rose from 10% in the first case to 14% in the second.

A similar pattern using for SCIS is evident **Fig. 5.15.B.** The mean full daylight proportion rose from 33% in the first case to 52% in the second, giving mean electric saving of 39% and 62% respectively.

5.5.4. The influence of building geometry

In multi-storey buildings roof mounted hybrid systems are able to deliver significant amount of daylight for the top few stories. The limitation is the distance over which light can be transported from collector to output device. This is up to 20m for most of the currently available systems. Facade mounted hybrid systems may be used for lower floors of multi-storey buildings as long as the collector can be suitably oriented. The large diameter of the guide components for roof mounted TDGS necessary to keep light losses to a minimum limit its application in multi-storey building. Current practice is for two storeys to be the limit.

For low-rise deep-plan buildings, the performance of roof mounted hybrid systems is similar to that of the basic case, since collectors may be installed as close as possible to the luminaires to minimize daylight travel distance. Facade mounted systems are presently only able to deliver significant amounts of daylight to areas adjacent to the facade, 12m currently for SCIS, and thereafter electric lighting system will be dominant. Bigger light guides would enable more daylight to be delivered but at the expense of increased floor height and/or the necessity to re-route other services networks.

5.5.5. Limitations of the work

Any work of this nature has a number of limitations. A restricted number of internal configurations of buildings have been used, all of which are assumed to be offices. The light guidance equipment used is the best that is currently available and the collection, transport and internal light distribution efficiencies are those that apply now. TDGS is a mature technology and little further major development is likely. Some technical progress might increase performance of hybrid systems but the laws of physics will inevitably limit this to incremental advances. Development to increase limits of the amount of sky tracked by the non-heliostat based systems such as Parans and SCIS may be the most promising area. In this regard work is required not simply to increase the range of movement of the tracking mirrors but also to address the problems of the mirrors mutually blocking sunlight and, in the case of those with overall glass protective covers, the reflection of sunlight at glancing angles.

There are other aspects of the wide geographic spread of the assumed locations in this study that have not been included in this work. The most important of these are the thermal properties of the guidance devices. Good optical design, and the use of dichotic materials, ensures that the majority of infra-red radiation is rejected by sun-tracking systems before entering the building. However work published by CIE suggests that TDGS could act as conduits of both heat loss and solar gain [6].

The results of this work are in terms of electric savings relative to the electric lighting only case. The savings in absolute terms would be higher with increases in cost of electricity and the more attractive the systems would become economically. The wider question of the long term economics of the various systems will be addressed in the cost and benefits chapter.

5.6. CONCLUSION

It is clear that building geometry has a major influence on the choice of light guidance system. Some systems, notably SCIS, have limitations on the distance from a facade over which daylight can be transported. A similar limitation applies for vertical distances with TDGS. It also clear that the reverse is true – that some systems make demands on form and layout of the building as a prerequisite to their successful use. SCIS imposes at least a minimum floor to ceiling and at worst almost dictates that the building be built around the system. The use of TDGS in multi-storey application requires duct space which occupies potentially useful floor area. The optical fibre transport based systems make far less demands on internal building space but do, of course, require a suitable roof to mount the collection system. They also lend themselves better to changes necessary to cope with change of building use and thus could be seen to contribute to flexibility of building use.

The relationship of external illuminance and latitude was examined and the results offer information to enable an informed choice of guidance system for location. The magnitude of GH illuminance is of importance for devices like TDGS that collect from the whole sky. On the other hand the DN illuminance modified for tracking factor is of major importance to sun-tracking systems. This value peaks between 15° N and 40°N and for this reason these types of system are less effective in producing electric savings in both equatorial areas and Northern latitudes.

Generally, TDGS gives better electric savings throughout but much better nearer the equator. All of the systems except HSL are shown to have some periods when all of the necessary planar illuminance is provided by daylight. Since the specification for HLS used in this work is that recommended by the manufacturer if may be that be that this advice requires revising. The usage patterns are a major factor in the magnitude of electric savings but also have another significance. The marketing for guidance systems all emphasise the beneficial effects of the delivered daylight. However for these benefits to be real the 'daylight' element must be recognised by building's users. Work on TDGS suggests that perception of 'daylight' depends on both the amount and the nature of the output devices inside the building [7], but no similar work has yet been done on hybrid systems. It would be useful for designers to know at which point in the usage pattern a particular system is perceived to deliver 'daylight'.

It is apparent that there is a considerable variation in performance as a function of system type, geographic location, and building geometry. This means that choice of appropriate light guidance system may have differing impacts on light delivery and consequent electric saving and usage pattern in diverse locations.

In this study an overall rank order of systems by achieved electric savings over all locations would have TDGS at the top followed by SCIS, HSL and Parans. The latter two were markedly inferior in terms of electric saving but HSL performed relatively better than Parans in the Southern locations and vice versa. This is an important conclusion because it suggests that the mature and relatively unsophisticated technology of the TDGS performs generally better than the hybrid systems. The latter are complicated pieces of optical engineering and for many applications have the capital and running costs greater than TDGS[1]. Although the assumed system configurations were in accordance with manufacturers' recommendations and current practice, this ranking could be changed by variations in, for example, the number or nature of collectors used or changes to light guidance resulting varying amounts of daylight delivered.

[1] This will be discussed in detail in the costs and benefits chapter.

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CHAPTER

6

Costs and Benefits Analysis

6.1. INTRODUCTION

The general preference for daylight as a light source in buildings is due to a number of factors related to its fulfilment of human needs. Also the potential of daylight to conserve energy and hence protect the environment, and the potential to improve indoor environment and hence users' productivity - have stimulated interest in its use as an electric lighting substitute. Although daylight guidance systems (DGS) seek to maximize the utilization of daylight, and yield the consequent benefits, they are not yet as employed as anticipated. This can be assigned for many barriers, but cost effectiveness may stand as one of the most important ones.

The feasibility study indicates that choice of DGS has different impacts on light delivery and consequent energy usage for diverse geographic locations. The energy savings quoted in a lot of cases appear large and constitute a major argument for guidance systems. However other factors such as the wider relationship of the various systems to their host building, capital and running costs, and benefits to user of the building mean that savings must be viewed as part of a wider cost/benefit analysis rather than in isolation.

This chapter analyses costs and benefits of using DGS to light offices as an alternative to ELS. The study uses firstly, conventional quantifiable measures of cost and benefit and secondly, additional benefits including cooling loads savings, carbon emission savings, and user productivity improvements.

6.2. LIGHTING ECONOMICS

The most widely used method of assessing financial viability of lighting schemes, simple payback , is defined as the time taken for running cost savings to pay back initial capital cost. Its main drawbacks are that it does not consider the 'time value' of money (the fact that the present capital is more valuable than a similar amount of money received in the future) and that savings that occur beyond the payback period are not taken into account. Also simple payback takes no account of the worth of the improved lighting – e.g. increased user productivity or rental value, or environmental benefits [1]. The methodology used in this study to evaluate system costs and benefits is Whole Life Cycle Costing (WLCC) which permits diverse factors influencing a lighting scheme to be considered.

6.2.1. Costs and benefits

The main costs and benefits associated with lighting systems are summarised in **Table 6.1**. For each there are differences in both in the ease of which they may be quantified, and the

Table 6.1: Costs and benefits associated with lighting systems

	Costs	Benefits
Level 1 '*Tangible items*'	Initial capital cost Running cost	Electricity saving Electric lighting system capital and maintenance saving Residual value
Level 2 '*Intangible items*'	Opportunity cost of floor/roof space	Building heating/cooling savings Carbon tax savings Effect of daylight on human well-being Enhanced corporate prestige

magnitude of their effect on the outcome of any analysis. Cost and benefit analysis is conventionally undertaken for the more readily quantifiable Level 1 items identified in **Table 6.1**. These so-called '*tangible*' aspects include initial capital and running costs, and direct savings due to the use of the systems.

The Level 2 benefits are known as '*intangible*' as they are by their nature more difficult to identify and/or quantify. Also their relative importance varies widely between different applications. Heating/cooling and carbon tax benefits for example will vary with geographic location. The benefits of using one particular luminaire rather than another, in terms of increased company prestige, is difficult to quantify but might be reflected in building rental values. The benefits of improvements in building occupant well-being due to the beneficial effects of enhanced daylight are also difficult to quantify. However since staff costs are the largest proportion of the total running cost of many types of building, notably offices, any benefits such as enhanced productivity are potentially large.

6.2.2. Whole life cycle costing (WLCC)

The WLCC method takes into account the costs of running and operating buildings or components over the entire lifespan or some specified period of time. The 'time value' of money is acknowledged by use of the present value method (PV) which compounds and discounts cash flows to reflect the increased value of money when invested [2]. PV is computed as follows:

$$\mathrm{PV} = FV\,(1 + r)^{-t} \quad (6.1)$$

$$\mathrm{FV} = K\,(1 + i)^{t} \quad (6.2)$$

Where: PV = present value, FV = future value of capital, K= annual cost, r = discount rate, i = inflation rate, t = period of analysis.

The Net Present Value (NPV) is an approach used in WLCC budgeting where the present value of cash flow is subtracted from that of cash outflows [2]. NPV is thus a metric for measuring the net value of an investment in building assets in today's money. Accordingly, when the difference between alternative lighting systems reaches zero, this is a turn point where a system pays back the investment and gains benefits. NPV is calculated using the following formula:

$$\mathrm{NPV} = \Sigma\,(PV_b - PV_c) \quad (6.3)$$

Where: PV_b = discounted present value of benefits, PV_c = discounted present value of costs.

In this work, NPV considers costs and benefits relative to reference case. Assuming that investments in lighting energy saving measures in building occur at present and also in the future due to replacements, and that these investments result in constant annual energy and maintenance cost savings during the lifetime or until larger refurbishment is necessary. From **Eq. (6.3)** the NPV can be calculated as follows:

$$\begin{aligned} NPV &= I_{0\_EL} + \Sigma PV_{E\_EL} + \Sigma PV_{M\_EL} - [(I_{0\_EL} + \Sigma PV_{E\_EL} + \Sigma PV_{M\_EL}) + (I_{0\_DL} + \Sigma PV_{M\_DL}) + \Sigma PV_J - \Sigma \Delta PV_S - R_0] \\ &= -[(I_{0\_DL} + \Sigma PV_{M\_DL}) + \Sigma PV_J - \Sigma \Delta PV_S - R_0] \\ &= \Sigma \Delta PV_S + R_0 - [I_{0\_DL} + \Sigma PV_{M\_DL} + \Sigma PV_J] \qquad (6.4) \end{aligned}$$

Where:
I_{0_EL} — *ELS initial investment [£]*
I_{0_DL} — *daylighting system initial investment [£]*
PV_{E_EL} — *PV of ELS annual energy cost [£]*
PV_{M_EL} — *PV of ELS annual maintenance cost [£]*
PV_{M_DL} — *PV of daylighting system annual maintenance cost [£]*
PV_J — *PV of future investment for replacement [£]*
ΔPV_S — *PV of total annual cost saving over use of ELS only [£]*
R_0 — *residual value of the lighting system [£]*

This analysis considers NPV of costs and benefits of using daylight guidance to light offices as an alternative to conventional ELS. Assuming that the daylight guidance capital investment occurs at present and future costs are due to periodic maintenance, then these investments will result in annual energy and maintenance cost savings through the system lifetime. Using **Eqs. (6.1) & (6.2)** NPV can be expressed as follows:

$$NPV = \sum_{t=1}^{n} \frac{\Delta K_S\,(1+i)^t}{(1+r)^t} + R_0 - \left[I_{0\_DL} + \sum_{t=1}^{n} \frac{K_{M\_DL}\,(1+i_M)^t}{(1+r)^t} + \sum_{j=x,y,z} \frac{I_j\,(1+i)^j}{(1+r)^j}\right] \qquad (6.5)$$

Where:
ΔK_S — *total annual cost saving over use of ELS only [£]*
K_{M_DL} — *daylighting system annual maintenance cost [£]*
I_{0_DL} — *daylighting system initial investment [£]*
R_0 — *residual value of the lighting system [£]*
I_j — *the investment for replacement j at time x, y or z [£]*
t — *considered time period for evaluation [year]*
r — *discount rate*
i — *inflation rate*
i_M — *maintenance inflation rate*

Comparing **Eqs. (6.3) & (6.5)** shows that the total annual cost savings and the residual values representing benefits. Costs for a DGS are made up of initial and replacement costs and annual maintenance cost. Thus a NPV of zero indicates that the sum of the savings and residual value equal the DGS initial, replacement and maintenance costs.

In this work all systems are considered to have both a daylight and electric component and thus for hybrid systems the cost of a separate electric system is zero. TDGS costs comprise guidance system capital costs and maintenance, and a separate ELS is assumed. Some of the benefits set out in Level 2 of **Table 6.1** are discussed later and are included in the total annual cost savings (ΔK_S).

6.2.3. Inflation and discount ratios

Typical inflation in countries with stable economies is under 5%. In the UK over the last decade, the consumer price index of annual inflation ranged between 0.8% and 3.8%, with mean of 2.3% [3]. Over the same period of time electricity inflation has been between -2.1% and 23.4%, with mean of 6.5%[2] [4]. Labour costs inflation was between -6.7% and 13.8%, with mean of 2.8%[3] [5]. The average annual UK official bank interest rate is between 0.5% and 6%, with mean of 4.3% [6]. In this work the mean values are used and thus 2.3%, 6.5%, 3.5% and 4.3% represent general inflation, electricity inflation, labour cost inflation and discount rates respectively.

6.3. EVALUATION PROCESS

The feasibility study investigated the light delivery potential of light guidance at various geographical locations. This chapter studies the cost of their use in representative locations.

6.3.1. Variables in the study

Two European locations were selected: London (51˚N, 0°) and Valencia (39˚N, 0°) as representative of Northern European and Mediterranean locations. The DGS used are the only currently available hybrid systems: Hybrid Solar Lighting (HSL), Parans, and Solar Canopy Illuminance (SCIS) systems, and the widely used passive TDGS.

The systems were assumed to light office spaces. This analysis is based on the lighting of a space similar to that used in the feasibility study, which is a windowless modular space of 6m x 12m x 3m high, with the short edge facing south, using each system in turn. Reflectance of ceiling, walls and floors are 70%, 50% and 20% respectively. Average illuminance level on work plane, 0.8m from the floor, is assumed as 300lux over annual working hours of 3650 hours.

6.3.2. Calculation and results

Results of this study are expressed in terms of payback period (PB). The present work assumes the building life of 20 years used for UK health estate analysis [7]. For each system in every location PB curves are plotted using an electricity price range between 10p/KWh (£0.10/kWh) and 50p/KWh (£0.50/kWh). The electricity price median over EU-27 countries in 2009 is 14.01p/kWh, which has risen some 46% in 5 years [4]. The 50p/kWh figure represents the expected long term price. The PB curves show the variation in the PB by year against different system costs and electricity prices alternatives.

[2] Electricity inflation percentages have been calculated using the electricity prices over the last decade.
[3] Labour costs inflation percentages have been derived from the UK hourly labour costs.

6.4. TANGIBLE COSTS AND BENEFITS

6.4.1. Costs

6.4.1.1. Costs data

Initial capital cost is the one-off cost of equipment at the beginning of a project. For purposes of this work the standard elements used in the calculations include equipment price and installation fees (excluding delivery charges, taxes, design fees, building adaptation cost, and overheads). The data are either obtained from manufacturers' price lists, if available, or are calculated from engineering price databases [8, 9]. Running costs are incurred throughout the life of the project include maintenance, repair and replacement costs (hereafter, altogether called maintenance) and electric power cost. Lamps are assumed to be replaced at the end of their nominal life. Passive and active daylight elements are assumed to require regular cleaning, and active systems assumed to require also regular visits for repair and inspection by skilled labour. Labour rates and estimated cleaning time was obtained from maintenance price books [10]. Electricity rates have been obtained from the European Commission statistics [4].

6.4.1.2. Lighting systems costs

Calculations indicated that two HSL systems, two SCIS, or eight Parans systems were required to light each module to the design illuminance level assuming an external normal beam illuminance of 30klux, equal to the European average. In actual conditions there would be considerable variation in external conditions and any consequent shortfall in daylight contribution would be made up by the linked electric systems. As the HLS market is still growing two capital costs are used; the first the current cost for low volume production, and the second that predicted for high volume. In the absence of one or the other the 'experience curve' approach was used in which costs fall by a constant and predictable percentage each time cumulative volume doubles. Studies suggest reduction of 10% to 30% [11, 12], which was used to estimate Parans high volume and SCIS low volume. The low volume cost for HSL was its 2007 launch cost, and a predicted high volume cost was provided by the developer [13]. Since the Parans system is available on the market, the current list price was used. Installation costs were obtained using manufacturers' instructions and standard labour costs [9]. The SCIS is still in the demonstration stage and actual costs are not available. The developers suggest a cost of £625[4] for the whole system based on 10000 units produced per year [14]. An estimate of low volume production cost; using the 'experience curve' suggests a unit cost of £3735. An estimate by the authors based on system components prices, and standard labour costs gives £3800. TDGS numbers, estimated using the CIE calculation method, suggested that 10 N^o 450mm diameter were necessary to give 300 lux assuming an external illuminance of 35klux (hourly mean of global horizontal illuminance over Europe) [15, 16].TDGS manufacturers' high volume prices were used [17, 18].

For each office module nine luminaires are required to achieve the specification, each

[4] Currency exchange rate of £1 = US $1.6 is used throughout the paper.

Table 6.2: Systems costs summary

System	N°	Low volume production capital cost (£) Initial	Install.	Total	Cost/m²	High volume production capital cost (£) Initial	Install.	Total	Cost/m²	Annual running cost (£)
Elec.*	-	-	-	-	-	-	-	3672	51.0	126
TDGS	10	-	-	-	-	4118	2359	6477	90.0	89
HSL	2	20000	3750	23750	330	3750	1250	5000	69.4	424
Parans	8	84964	1061	86025	1195	19984	1061	21045	292.3	289
SCIS	2	7470	2184	9654	134	1250	2184	3434	47.7	314

* Fit out cost only is included to be comparable with the other systems.

containing two 40W/TT5 lamps (rated at 3150 lumens) with electronic dimming ballasts. The maximum annual electricity consumption is 2628kWh. Capital costs, obtained from SPON include shell and core costs ranging from 15£/m^2 to 20£/m^2; fit out costs from 40£/m^2 to 60£/m^2, and includes dimming controls and tax [9].

Table 6.2 summarizes the initial and annual running costs for both high and low volume capital costs.

6.4.2. Benefits

6.4.2.1. Saving in capital cost of the ELS

Since HLS, unlike TDGS, include their own lamps they can replace conventional ELS, giving a saving in the capital cost. Assuming that the light output from the HLS can provide the required illuminance level during night operating hours, the fit out costs that estimated in **Section 6.4.1.2** will be completely saved. However shell and core costs will still be required to cover the cost of items not included in the HLSs packages such as wiring and switches.

6.4.2.2. Saving in running cost of the ELS

Most TDGS may be linked to an ELS such that available daylight is used to supplement or replace ELS output, offsetting energy consumption and reducing maintenance costs. Also lamp replacement intervals will increase because of reduced burning hours. Energy load savings were obtained from the feasibility study. For the purpose of this work, the percentage maintenance cost saving is assumed to be equal to the percentage of full daylight utilization during the assumed annual working hours. The benefits apply to all maintenance costs, notably, lamp replacement and cleaning, and longer lamp replacement intervals. During periods of hybrid lighting usage lamps will be dimmed with a positive effect on lamp life. For this calculation it is assumed that cleaning costs are also a function of daylight utilization hours obtained from the mentioned software.

6.4.2.3. Residual value

No residual value guarantee scheme is offered by the developers of HLS to purchase the assets on a future date at a pre agreed value. The residual values of HLSs are likely to be solely the recycling value which is negligible in comparison with capital cost.

6.5. INTANGIBLE COSTS AND BENEFITS

Level 2 items listed in **Table 6.1** are only some examples of the probable intangible costs

Table 6.3: Power transformation forms for different lamp types

Lamp type	Radiation power %			Heat %	Total heating power %
	Visible Light	Infra Red	Ultraviolet	Conducted/ Convict	
Filament lamp GLS	9	84	<0.1	7	14.5
Tungsten Halogen	13	79	0.1	8	16.0
Fluorescent tube	25	35	0.4	40	43.5
Compact F L	24	45	1	30	34.5
Daylight (6500K)	53	42	5	0	4.0

and benefits. Heating/cooling, carbon tax, and enhanced productivity benefits are the only ones considered in this work, where they have been noticed to be the most favourable items used in the publicity of daylighting systems. In addition, they in some way can be quantified.

6.5.1. Influences on cooling/heating loads

ELS generate heat which although welcome in the heating season is undesirable in the cooling season. Luminaire design is a major influence. Recessed luminaires transfer some 50% of the heat into the ceiling cavity, whereas virtually all that from suspended luminaires enters the room [19]. All lamp types dissipate a large portion of input energy as radiant heat (Infra Red) and, to a lesser extent, by convection to the surrounding air (see **Table 6.3**). Only about 10% of the radiant heat is absorbed by the air, most being absorbed by high thermal capacity walls and room contents without any significant increase in temperature. In contrast, heat lost through convection direct affects the temperature of the surrounding air [20].

6.5.1.1. Comfort zone

The desire to provide comfort temperatures in buildings determines the duration of heating and cooling seasons. Current design thinking is that occupants accept, and perhaps even like, variation of temperature over time, provided that it remains within overall limits [21]. This work uses weather data [22] and climate software [23] to determine thermal comfort zone using either heating or air conditioning. **Fig. 6.1** shows an example of a psychometric

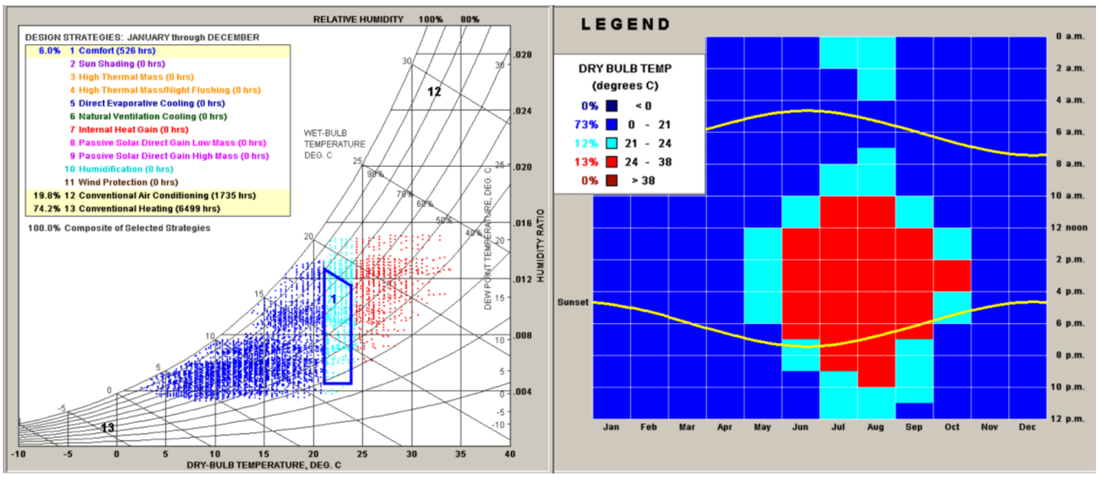

Figure 6.1: Psychometric chart for Valencia, showing comfort, air conditioning, and heating zones of 6%, 19.8% and 74.2% respectively (left); Two-hourly means of monthly average temperature zones (right).

chart for Valencia, showing comfort, air conditioning, and heating zones. The percentage of different temperature zones during assumed working hours is estimated using the two-hourly means of monthly temperatures zones charts shown in **Fig. 6.1**.

6.5.1.2. Heat replacement effect

Heat replacement effect (HRE) is the process where energy savings achieved by reducing electric lighting consumption is offset by adjustment in the energy required from the heating/cooling system. The adjustment to heating or cooling loads in their respective seasons can be estimated as set out below. This assumes UK practice of heating/cooling system is controlled by a thermostat, the heating system is a gas-fired wet central heating, and the cooling system is a chilled water fan coil units [24]. Efficiency values for other heating and cooling systems can be obtained from reference [24]. Solar heat transmission via DGS is assumed to be negligible [13, 15, 25, 26].

The following parameters are used:

h_a	*annual operating hours [hour]*
S_H	*percentage of heating season [% of h_a]*
S_C	*percentage of cooling season [% of h_a]*
W_O	*power of original lighting system [kW]*
W_N	*power of new lighting system [kW]*
HER_O	*heating efficiency ratio of old lighting system, (from **table 6.3**, column 6) [%]*
HER_N	*heating efficiency ratio of new lighting system, (from **table 6.3**, column 6) [%]*
HGE	*heat generator efficiency for heating system (84% according to **Ref. [24]**)*
EER	*energy efficiency ratio of cooling system (340% according to **Ref. [24]**)*
T_e	*electricity tariff [£/kWh]*
T_g	*gas tariff, (T_g can be assumed = 0.21 T_e) [£/kWh]*

Emitted heat of original lighting system (kWh) $= (h_a \cdot W_O)\, HER_O$ (6.6)

Emitted heat of new lighting system (kWh) $= (h_a \cdot W_N)\, HER_N$ (6.7)

From **Eqs. (6.6) & (6.7)**:

Reduction in heat emission (kWh) $= [(h_a \cdot W_O)\, HER_O] - [(h_a \cdot W_N)\, HER_N]$

$= h_a\, [(W_O \cdot HER_O) - (W_N \cdot HER_N)]$ (6.8)

HRE during heating season, HRE_H, (extra loads on the heating system)

$$= S_H \cdot h_a\, [(W_O \cdot HER_O) - (W_N \cdot HER_N)]/HGE \quad (6.9)$$

HRE during cooling season, HRE_C, (extra saving in the cooling loads)

$$= S_C \cdot h_a\, [(W_O \cdot EER_O) - (W_N \cdot EER_N)]/EER \quad (6.10)$$

Net HRE = $HRE_H - HRE_C$ (6.11)

From **Eq. (6.11)**, if there is no cooling system in operation, using more efficient lighting system results in extra loads on the heating system. Meanwhile, if there is no operating heating system, using more efficient lighting system means extra saving in cooling loads.

The HRE during moderate seasons, between 21° and 24° as indicated in **Fig. 6.3**, is neglected despite the fact that it will slightly offset the air temperature towards heating/cooling zone. The room air temperature is assumed to be remained changing within the thermal comfort zone.

The HRE annual cost and saving calculated using the following formulas:

$$\text{Annual cost of } HRE_H = S_H \,.\, h_a\,[(W_O \,.\, HER_O) - (W_N \,.\, HER_N)]\,T_g/HGE = HRE_H \,.\, T_g \quad (6.12)$$

$$\text{Annual saving in } HRE_C = S_C \,.\, h_a\,[(W_O \,.\, HER_O) - (W_N \,.\, HER_N)]\,T_e/EER = HRE_H \,.\, T_e \quad (6.13)$$

6.5.2. Carbon tax savings

ELS account for up to 30% of electricity consumption across the office sector, and substitution by daylight offers a potential for reducing this. Electricity generation is one of the largest sources of carbon dioxide (CO_2) emissions, which comprises a significant amount of greenhouse gas emissions. The amount of CO_2 released into the atmosphere depends on the fuel mix used in generation in different countries. **Table 6.4**, derived from published data, shows the influence of the fossil/non-fossil fuel mix on ‘carbon intensity’ - the CO_2 emission per unit of generated electricity [27, 28]. It is clear that wide variations exist.

A number of systems have been promulgated to ascribe a monetary value to carbon emission pollution. Global carbon trading aims, as set out in Article 17 of the Kyoto Protocol, allows countries and organisations that have emission units to spare - emissions which are permitted but not "used" - to sell this excess capacity via a carbon trading market [29]. The Kyoto Protocol established a legally binding commitment on national governments to reduce greenhouse gas emissions. A number of countries have applied the principle of carbon trading – ‘the polluter pays’ – by use of a carbon tax. These first enacted in 1990 by Finland, are effectively a tax on the use of fossil fuels, and vary in method of application between countries. The U.K. version, known as Climate Change Levy, was introduced in 2001 and is currently £0.0043/kWh added to electricity bills [30].

Table 6.4: CO_2 emissions per kWh from electricity generation for year 2007

	Energy mix (%)				Carbon intensity
Country	Fossil	Hydro	Nuclear	Other renewable	g CO_2/kWh
United Kingdom	71.4	1.3	20.3	5.3	500
Sweden	2.0	46.9	44.7	4.4	40
Spain	58.1	6.9	19.3	9.4	390
Europe	47.0	13.3	25.0	10.2	310
United State	68.8	6.6	18.4	4.4	549
World	60.6	23.1	9.1	4.3	507

6.5.3. Effect of daylight on human well-being

6.5.3.1. Preference for daylight

The popularity of daylight as a light source in buildings is due to a number of factors related to its enhancement of human well being. Daylight can deliver light of high illuminance together with a spectral composition that ensures favorable perception of color. It can also provide meaningful spatial and temporal variation in illuminance providing interior conditions that are bright, visually interesting and dynamic. Daylight providers such as windows also provide contact with the exterior and can, by influencing physiological responses such as the regulation of diurnal cycle of body activity, improve health conditions in working environments.

Office lighting installations equipped with ELS and conventional glazing systems provide interior conditions that satisfy part or all of the above. A recent study of quantity and quality of daylight delivered by TDGS in large open plan offices in the UK suggests that the light delivered by the guides was recognized by users as daylight [31]. The daylight contribution was of the order of 25% of total workstation illuminance but the guides provided minimal contact with the exterior. Although user views suggested that TDGS were inferior to windows in delivery of both quantity and quality of daylight, there was evidence that user satisfaction improved with increased daylight penetration. Thus it appears that DGS can, if correctly configured, deliver some elements of 'daylight' to areas of office buildings remote from, or devoid of, windows [15]. Under these circumstances the benefits of the delivered daylight could constitute an argument in favor of DGS in any cost/benefit analysis.

It is clear that DGS can introduce some elements of daylight into areas remote from windows. Under these circumstances the benefits of daylight might be less than that delivered via windows but the evidence is that this could still influence user well-being and, possibly, productivity. Since most DGS are sold on the premise of delivering daylight to interiors, and its consequent benefits, it is worth speculating what the magnitude of these benefits might be as part of the cost/benefit process.

6.5.3.2. Daylight and productivity

Since the majority of office costs are staff salaries (up to 85%) and in comparison energy costs are tiny, small increases in staff productivity are equivalent to large savings in energy. Recent work has demonstrated for the first time the link between lighting conditions and feelings of health and well-being [32]. It showed that people who perceived their office lighting as being of higher quality rated the space as more attractive, reported more pleasant mood, and showed greater well-being at the end of a working day. Also lighting conditions that improved visibility also improved task performance. This is a large step in the process of demonstrating that better quality lighting can enhance productivity.

In industrial or retail settings, productivity may be measurement of output per worker or sales per worker. In knowledge-based work typical of offices productivity encompasses a much wider range of variables some of which are measurable; such as speed and accurately of task completion in rule-based jobs such as call centres. Generally any assessment is confounded by factors contributing to employee productivity - motivation, health, and corporate culture for example – making it difficult to determine how much to assign to the lighting system improvement. Despite the difficulties of quantification it is clear that any small improvement in worker performance would reap huge benefits. Data from the Centre for Building Performance and Diagnostics at Carnegie Mellon University (CMU) estimates building costs/m^2 for offices. Physically housing employees and their activities is typically around £437.5/m^2 (for lease/mortgage, utilities and facilities management costs) while their salaries cost up to £2000/m^2. Costs of employees is some 160 times that of energy. The CMU work went on to demonstrate that daylight in the offices studied yielded an annual energy cost savings of £76 per employee (£7/m^2) and annual productivity gains of £1547 per employee (£142/m^2). It also identified in five case studies individual productivity benefits from daylighting ranging from 0.45% to 15%, with an average improvement of 5.5% annually [33]. The CMU case studies were conventional offices equipped with windows. Since DGS do not deliver all elements of 'daylight' it would be anticipated that any improvements in offices partially or wholly lit in this manner would be lower. For purposes of this study a 1% productivity gain is assumed amounting to £28/m^2 based on the CMU figures.

6.6. USING WLCC METHOD TO ESTIMATE PAYBACK PERIODS

The calculation was performed, firstly, for the costs and benefits set out in Level 1 of **Table 6.1** (the 'base case'), and subsequently including the effects of the heat replacement, carbon tax and productivity Level 2 benefits. Finally the effect of all of the identified costs and benefits were examined. NPV has been calculated for each of 20 years in order to determine the payback point. The calculation was repeated for all DGS at each location using the following:

- Capital and annual running costs summarized in **Table 6.2**.
- PB calculations initially assumed a capital cost for low volume production (indicated as 100%). The calculations were repeated assuming capital cost reductions in the initial cost.
- Likely savings as discussed in **Section 6.4.2**.
- Inflation and discount constant rates as set out in **Section 6.2.3.**
- Range of electricity prices as detailed in **Section 6.3.2**.

Payback periods for all systems at each location were calculated using **Eq. 6.5**. The results are expressed in two ways. Firstly, the histograms in **Figs 6.4 - 6.7** show the payback period for the base case (Level 1 cost/benefits), and the base case including the effect of each individual investigated Level 2 cost/benefit. Note that in some cases the payback period is in excess of 20 years. Secondly, the graphs in **Figs 6.6 – 6.9** illustrate the effect on payback period for both locations of the Level 1 costs and benefits, and Levels 1 and 2 combined. The dotted lines on the graphs identify the local electricity price for 2009 for each location.

6.6.1. Base case

It is clear from **Figs 6.2 – 6.5** that the two main factors influencing PB are electricity price and system cost. Investment in TDGS at current market prices results in a PB of 5-6 years assuming electricity prices of 50p. Whilst this price might be reached in the long term, electricity prices nearer to the EU median give PB of between 12 and 16 years. In general it can be observed that the HLS systems have longer PB than TDGS even using favourable assumptions.

The HSL system has a PB period above 20 years except when assuming a low capital cost

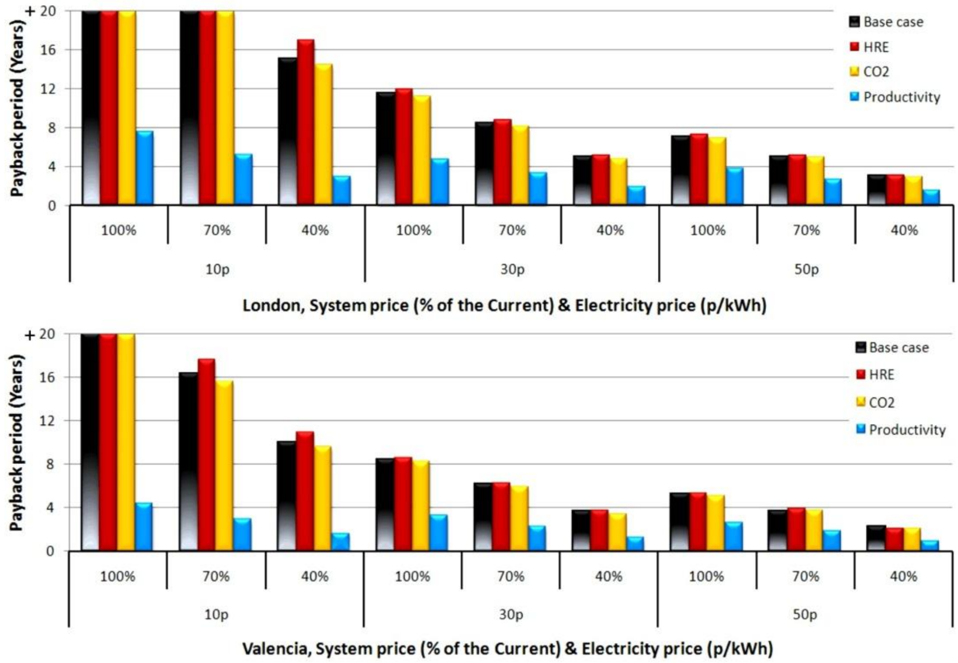

Figure 6.2: *TDGS – payback period for base case, and base case including the effect of individual intangible cost/benefits.*

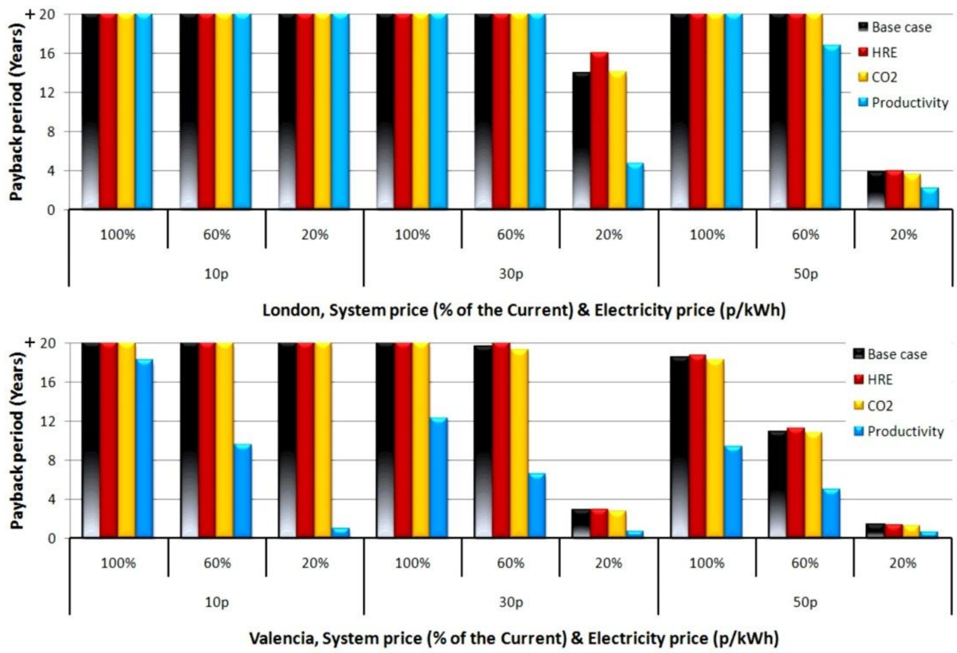

Figure 6.3: *HSL – payback period for base case, and base case including the effect of individual intangible cost/benefits.*

(20% of current) and electricity prices in access of 40p for Valencia. Parans system has PB of over 20 years for all locations even under the most favourable circumstances of a Southern location, electricity at 50p and a mean external illuminance greater than 60klux. The lower estimated capital cost of SCIS gives PB of 5 years in Southern locations using 50p electricity. Ten year PB are achieved even using current capital costs assuming 30p electricity prices in the South and 40p in the North. In general it can be observed that the more complicated HLS systems (HSL and Parans) have a long PB; the simplest system, TDGS, has a short PB; while SCIS may have a short PB in sunny locations.

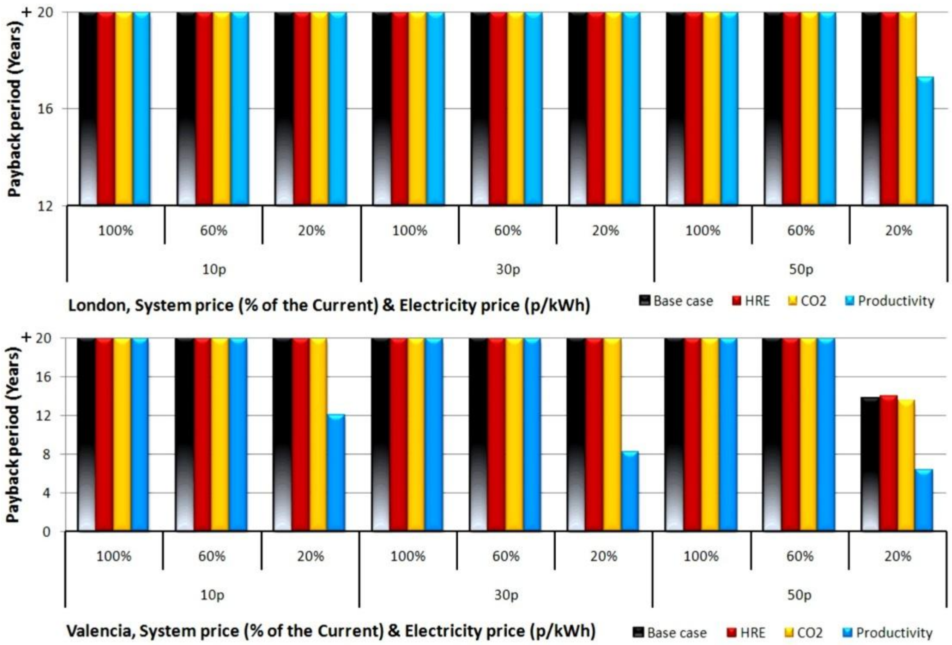

Figure 6.4: *Parans – payback period for base case, and base case including the effect of individual intangible cost/benefits.*

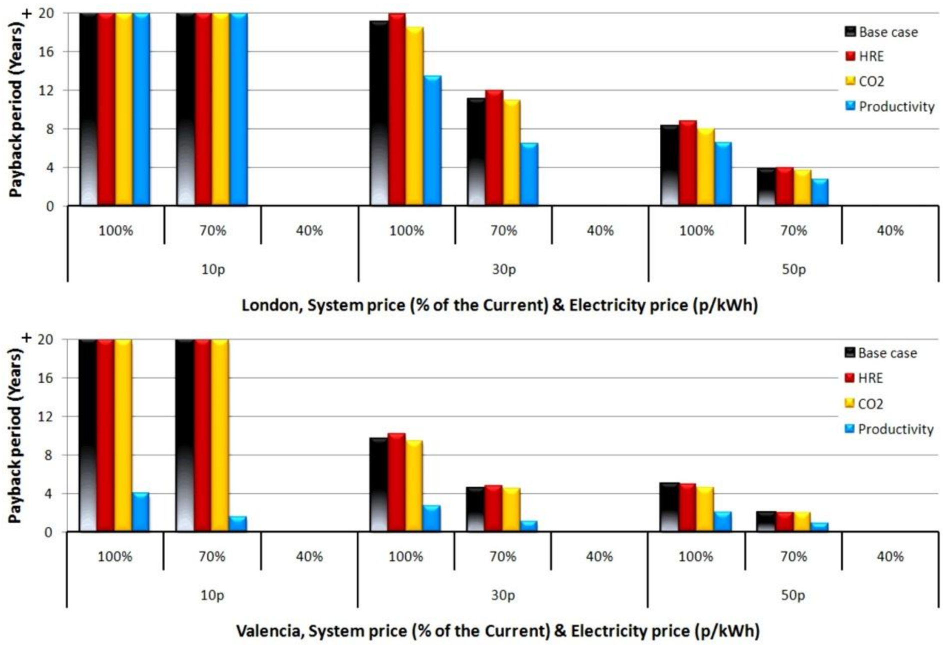

Figure 6.5: *SCIS – payback period for base case, and base case including the effect of individual intangible cost/benefits.*

6.6.2. Heating/cooling savings

The heating periods in London and Valencia are 96.7% and 60% respectively of annual working hours from 0800 to 1800 (see **Table 6.5**). From inspection of **Figs 6.2 – 6.5** it is apparent that the heating replacement effect raises the PB due to the extra loads on the heating system. Although 25% of the working hours in Valencia fall in the cooling zone, this is not enough to balance the effect of the heating hours since more energy is required to increase air temperature one degree than to decrease it.

Figs 6.2 – 6.5 show that the HRE slightly raised the PB for all systems in both locations, though that in Valencia is generally about half that of London. In Valencia the PB of TDGS rose by 0.2-0.5 years, that of HSL system by 0.1-0.9 years, Parans system by 0.3 year and that of SCIS 0.0-1.2 year, all assuming either current market price or estimated high volume production price.

6.6.3. Carbon tax savings

The effect of Carbon tax savings on the PB is very small using the current UK Climate Change Levy tariff. This is slightly below the average of such taxes enacted in different countries but it is clear that the effect on PB is negligible in comparison with other variables. **Figs 6.2 – 6.5** suggest that the PB reduction, in both locations and with any system, ranges from zero to a maximum of 0.5 year.

6.6.4. Productivity improvement effect

The productivity improvement of 1%, which assumes the maximum possible delivery of daylight by the DGS over the working hours, is reduced by the percentage of daylight actually delivered due to diurnal and seasonal variation.

It is apparent that the productivity effect gives the most favourable payback of any of the Level 2 benefits. For TDGS and SICS the PB is generally below 5 years for all combinations of other variables. For HSL and Parans the high capital costs mean that PB are of the order of 20 years even taking into account any productivity effects. The productivity gains do vary with location due to the greater delivered quantities of delivered daylight in Southern locations. Although this result needs to be treated with caution because of the assumptions made, it does suggest that the argument that small increases in staff productivity are equivalent to large savings in energy has some substance.

Table 6.5: Temperature zones

		Comfort zone		Cooling zone		Heating zone	
		Hours	%	Hours	%	Hours	%
London	24 Hours	250	2.9	135	1.5	8375	95.6
	Working hours	122	3.3	0	0.0	3528	96.7
Valencia	24 Hours	526	6.0	1735	19.8	6599	74.2
	Working hours	548	15.0	912	25.0	2190	60.0

6.7. DISCUSSION

Daylight guidance technology has only been commercially exploited over the past fifteen years or so and consequently the accumulated technical and economic experience of its use is limited. Of the two main guidance types tubular daylight guidance systems, although commercially successful, have been used to light only a limited number of working buildings, mainly offices, worldwide. The newer HLS, although on the market, have to date been used for only a handful of actual installations.

This work concerns whole life cycle economic analysis of DLS. Current practice for application of this method to lighting systems is to include only capital cost items, and running costs such as electricity and maintenance. The associated ‘Level 1’ benefits are mainly savings in electricity by daylight substitution, and maintenance. This work uses whole life cycle methods for interiors lit using daylight guidance and electric systems but extends the analysis to include a range of ‘Level 2’ costs and benefits. The latter may include the cost of accommodating guidance systems in a building, and the range of possible benefits include reductions in heating/cooling loads, reduction in carbon taxes and improvement in well-being and productivity of occupants due to daylight.

6.7.1. Analysis assumptions

This work is based on a number of assumptions about the systems and their mode of use and, to aid the interpretation of the results, it is perhaps worth restating these. Assumptions are necessary because DGS is a new technology for which full information is not available. The Level 1 capital costs are those appropriate to high volume production. For some systems market price is used. For some hybrid systems which are not at that stage, high volume costs have been estimated using the ‘experience curve’ based on published costs of prototypes in the expectation that costs will reduce as the technology matures. History suggests that this has been the case for TDGS. Also there is little published information on DGS running costs and therefore realistic assumptions have been made on the range of present and future electricity prices and system maintenance. Throughout the work costs of building modification necessary to accommodate guidance systems, particularly in multi-storey buildings, have been excluded since these are specific to a particular building. These may be substantial for some system types, particularly in relation to light transport components, and might include capital costs of ducts and associated opportunity cost of lost floor area. For systems that use optical fibre light transport they will be minimal. TDGS guides require substantial duct accommodation whilst the SCIS requires at least extra storey height and, potentially, almost dictates that the whole building be designed around it. There are a number of assumptions relating to the Level 2 costs/benefits. The heating and cooling systems used, and the carbon taxes, were those typically used in UK practice. Although other assumptions might apply in other countries and geographic locations it has been demonstrated that the effects of both on overall cost/benefit are small.

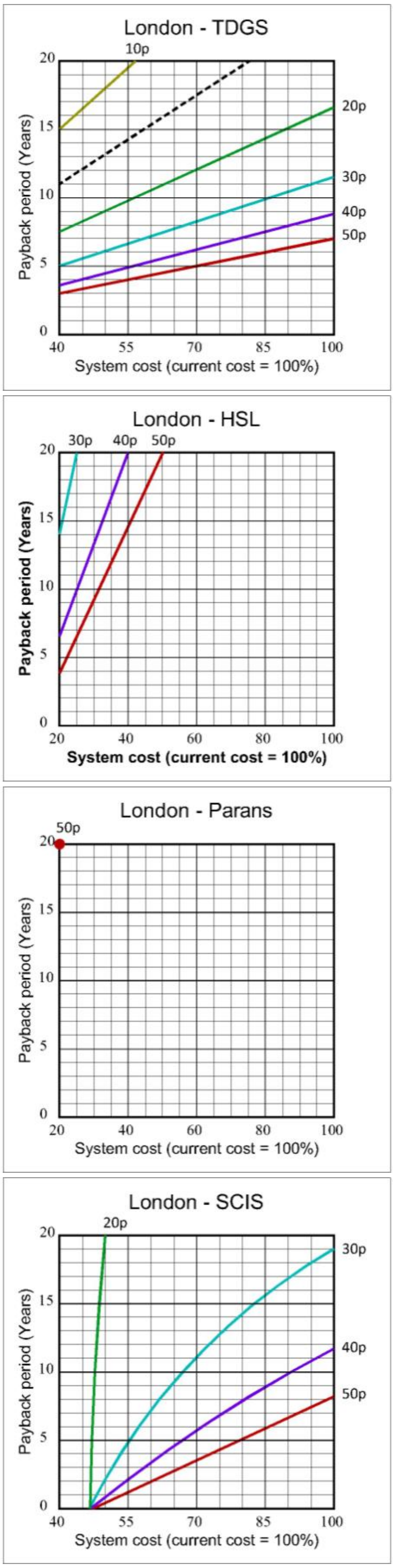

Figure 6.6: *Payback period for base case – London*

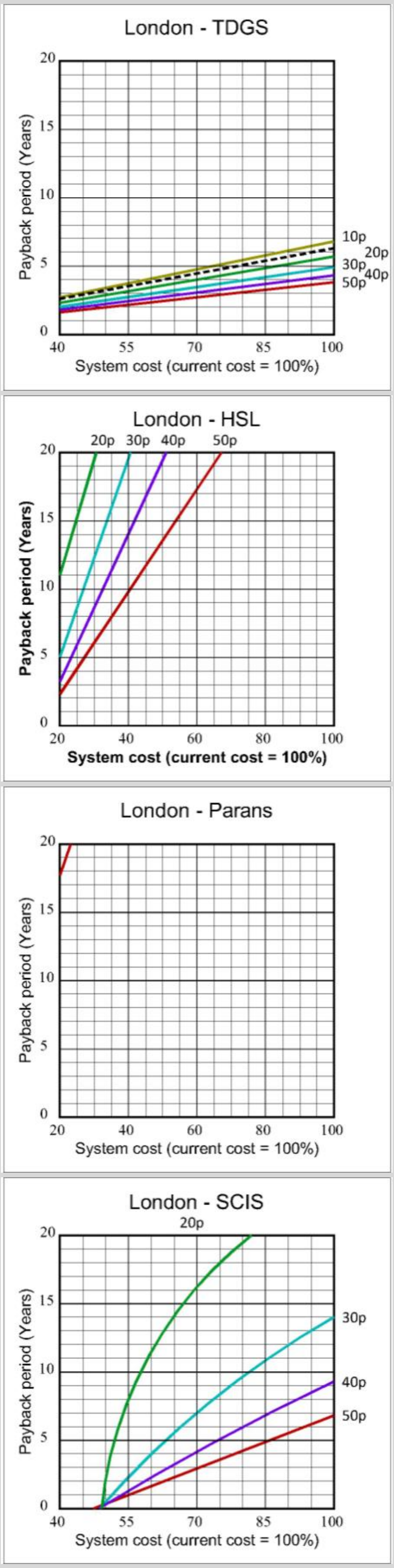

Figure 6.7: *Payback period including all intangible cost/benefits – London*

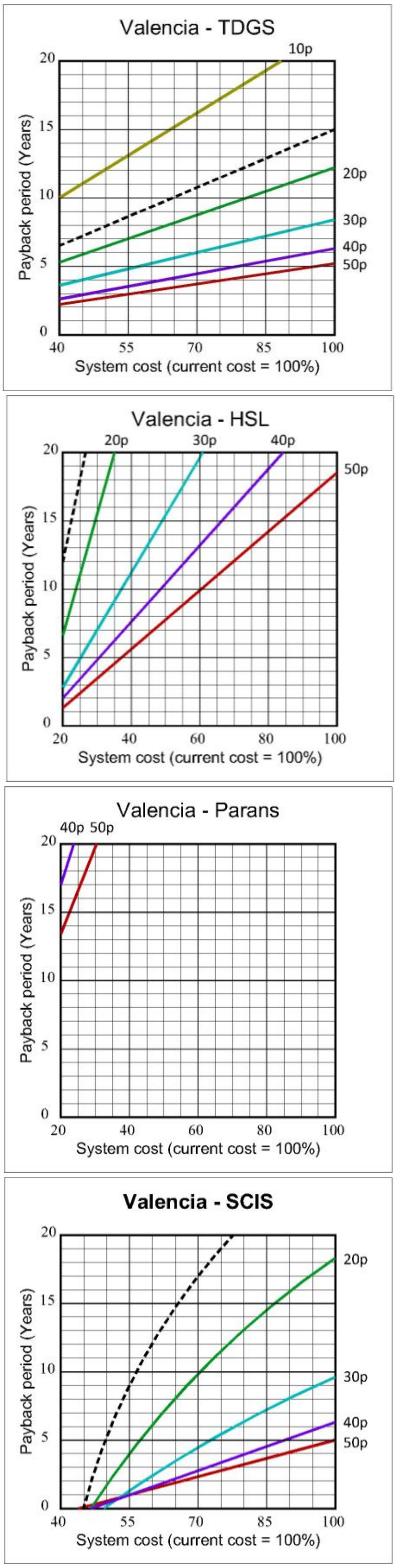

***Figure 6.8:** Payback period for base case – Valencia*

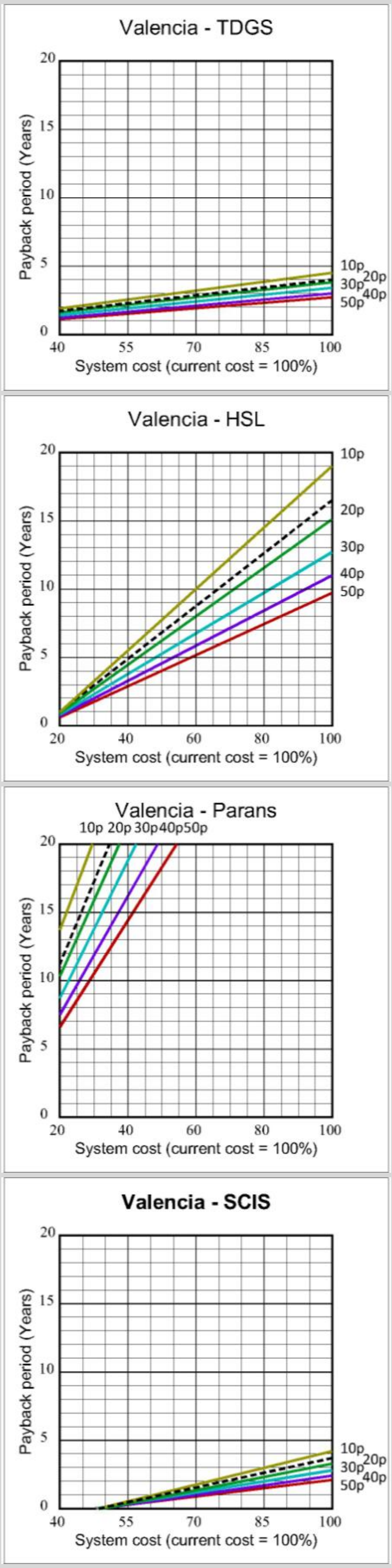

***Figure 6.9:** Payback period including all intangible cost/benefits – London*

6.7.2. Major influences on cost effectiveness

The results of the Level 1 costs/benefits analysis suggest that capital cost is the major factor in determining payback periods. The two systems with the shortest payback (see **Figs 6.6 & 6.8**), TDGS and SCIS, have low capital costs due to their reliance on simple and relatively cheap optical systems employing low concentrations of sunlight. A caveat here is that the costs of modification of the host building, particularly in the case of SCIS, may significantly increase capital cost for low concentration systems which, by their nature, use large light transport components. The best performing of the low concentration systems - TDGS - although a mature technology, is still unable to pay back investments within five years at the current European price of electricity. Indeed the use of electric lighting delivering the same task illuminance on its own would arguably represent a better investment. To approach a five year payback for TDGS, average electricity prices would need to at least double and system price be reduced to 40% of current. Whilst the former condition might, sadly, occur in Europe in the near future, further reductions in price in this technology are unlikely.

One of the major marketing arguments used for guidance systems is that it leads to improvement in human well-being in working areas due to the delivery of daylight. In order to investigate the magnitude of the possible productivity effect due to guided daylight a complex set of assumptions, each of which might be challenged, is necessary. The most important assumption relating to productivity is that it may be used as part of a lighting cost/benefit exercise. A link has recently been reported between lighting conditions and feelings of health and well-being, and that lighting conditions which improved visibility also improved task performance. This is a large, but far from conclusive, step in the process of demonstrating that better quality lighting can enhance productivity. Assuming that such a link exists the current work has used data on user productivity enhancements based on conventional offices with windows with the benefits reduced in proportion to the quantity of diurnal and seasonal daylight shown to be delivered by DGS. It should be noted that the remaining two benefits listed in **Table 6.1** have not been included in this work. Enhanced corporate prestige is impossible to quantify in this context, and the residual value of DGS are unlikely to be more than a minimal scrap value.

6.7.3. Economical performance of DGS

In general the hybrid systems have long payback periods based solely on Level 1 cost/benefit considerations rendering them an unattractive investment proposition. Three influences would have to work together to shrink payback periods: electricity price, system capital cost, and available external local illuminance. The trend for electricity price is universally upwards – over five years about 46% across the EU-27 countries [4]**.** That suggests that in ten years the electricity price in the EU-27 is likely to exceed 30p/kWh, making the technologies more economic. The current hybrid capital costs are a significant barrier to their use, but reductions in costs due, for example, to volume production are not occurring at the time of writing. The capital cost reductions required to make the systems economic are large. The best performer, HSL requires a reduction equal to one fifth the current price to approach a five year payback period in both locations assuming a 30p electricity price. On the other hand the Parans system capital cost would need to be 10% of current, combined with 50p electricity price to give the same payback. High external illuminance levels help to reduce the number of hybrid units, and hence capital cost, required to deliver a given luminous flux. A comparison of **Figs 6.6 & 6.8** shows the influence of local illuminance conditions in the marked improvement in the performance of the sunlight concentrating HSL and Parans systems between London and Valencia. The low optical concentration TDGS and SCIS units also improve their performance through increased daylight delivery in these circumstances having paybacks of less than ten years using electricity at 30p. Alas even in southern European below 40˚N latitude where hourly mean of normal beam illuminance exceeds 50klx, HSL will have a twenty year payback assuming 60% of capital cost and 30p electricity level. The payback for Parans, even in southern conditions, is considerably in excess of 20 years.

Figs 6.2 – 6.5 show that the results of the addition of Level 2 cost/benefits to the analysis. It is clear that the benefits of HRE and carbon taxes pale into insignificance in comparison with those of productivity improvements. The HRE generally increases payback by a few months but the effect of the carbon tax is largely neutral. Inspection of **Figs 6.2 – 6.5** shows that productivity gains reduce payback by up to 75%. However it is clear that daylight guidance which is fundamentally uneconomic using Level 1 cost/benefits cannot achieve satisfactory payback even taking productivity into account. Taking all intangible costs and benefits into account TDGS has a payback of between 4 and 6 years (compared with 17-25 years assuming Level 1 costs/benefits) using current electricity prices. A similar pattern of results is apparent for SCIS. Using the same electricity price HSL in the southern location have one year payback instead of 12 years, and in London the payback becomes five years instead of 14 for an electricity price of 30p. The present high capital of the Parans system ,on the other hand, means that even in southern locations the system struggles to achieve payback of approaching fifteen years assuming electricity at 50p level and capital costs at some 20% of current. Taken together the above suggests that the major influences on the costs and benefits of daylight guidance are capital cost, electricity price and the effects on productivity of daylight. The HRE and carbon taxes appear to have a minor effect.

6.8. CONCLUSIONS

It is clear that DGS require a substantially greater capital investment than ELS. Some such as TDGS have been shown to be economic over the long term if they are solely regarded as devices to enable daylight to be substituted for electric lighting – the 'tangible benefits'. The capital costs of hybrid systems are such that even favourable assumptions about economies of scale render them a very poor investment judged against Level 1 benefits. This work has attempted to quantify the 'intangible' benefits of the delivery of guided daylight to an interior. These are by their nature more difficult to quantify and a number of assumptions, each of which may be questioned, are necessary to make this possible. The results suggest that the benefits of HRE and carbon taxes pale into insignificance in comparison with those of productivity improvements. The latter suggests that investment paybacks could be reduced by up to 75% of those calculated using only Level 1 assumptions. However it is evident that DGS which are fundamentally uneconomic using Level 1 cost/benefits struggle to achieve satisfactory paybacks even taking productivity into account. However in the case of those systems that are only marginally uneconomic the inclusion of productivity does give a more favourable balance of cost and benefit.

This work has established that the economical performance of daylight guidance systems has several dimensions. System payback periods are mainly determined by levels of capital cost, energy costs, external illuminance level (which in turn is influenced by geographical location) and, potentially, considerations of the influence of productivity gains due to daylight in working areas. This study, although based on current technology and costs and a limited number geographic locations, has set out the principles of economic analysis of guidance systems. Work of this nature is essential to enable lighting practitioners to realise the exciting possibilities of daylight guidance.

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CHAPTER

7

Experimental Study

7.1. INTRODUCTION

Although a number of hybrid lighting systems have been developed the technology is so new that no post-installation or post-occupancy studies of actual installations have been published. Also little information exists on design methods or criteria or performance of the systems in use.

This chapter presents measured data for a commercially available HLS located in temperate latitude. These are compared with parallel measurements for a TDGS in a similar location. The implications in terms of light delivery from HLS for other geographic locations and for HLS design methods are set out.

7.2. STUDY PARAMETERS

The work investigated luminous flux output, luminous intensity and planar illuminance distribution for Parans HLS and TDGS. Parans luminaires tested were suspended rectangular 'small' (45 x 45 cm and supplied by one cable) and 'large' (90 x 90 cm and supplied by all four). The 'hybrid' system investigated consisted of a daylight-only device, which was the subject of the measurements, with the assumed addition of electric lamps for purposes of the subsequent energy consumption calculations.

7.2.1. HLS location

The HLS collector was installed on the roof of the University of Liverpool, School of Architecture, Liverpool, UK (53°25'N, 3°0' W). It was installed around 14m above ground facing due South and tilted at approximately 35˚ from horizontal (See **Fig. 7.1**). This enabled it to track the entire vertical path of the sun and a 120˚ cone of the horizontal path, between 120˚and 240˚ from North. The collector faced Abercromby Square which is


Figure 7.1: Parans solar panel installation in the Uni. Of Livrepool *(*left*)*; **Figure 7.2:** Parans 'L1-large' luminaire *(*right*).*

approximately one hundred metres wide and contains no tall buildings or trees and other obstructions. Buildings on the other side of the Square are of a similar height to the School.

Parans luminaires were ceiling mounted in part of the room adjoining the collector site (approximately 3m x 1.8m x 2.2m) (See **Fig. 7.2**). This space had a dark grey carpet with three walls and the ceiling painted matt black. The fourth side was made of dark heavy duty blackout material such that all external sources of light were excluded. The connection from collector panel to luminaire was four 20m-long fibre optical cables (See **Fig. 7.3**).

7.2.1. Liverpool solar resource

Liverpool has a maritime temperate climate with an annual mean daytime global horizontal illuminance hourly value of 23.8klux made up of diffuse and direct components of 14.7 and 9.1 klux respectively. Over the measurement period, the corresponding monthly mean values are 29.9, 18.7 and 12.1 klux with peak values of 34.7, 19.6 and 15 klux in July [1].

Typical sky conditions over the measurement period are 28.5% sunny, 40.7% intermediate and 30.8% overcast [1]. Daily sunshine duration ranged between 10:50 and 17:02 hours with mean of 15:00 hours. The earliest local sunrise and sunset time were 4:43 and 17:50 respectively. The latest local sunrise and sunset time are at 7:00 and 21:45 respectively [2].

7.3. MEASUREMENTS

7.3.1. HLS measurements and equipment

A goniophotometer, based on an optical length of 1m, was installed beneath the luminaire to measure luminous intensity in the vertical plane for the quadrant 0°–90°. Illuminance was measured using calibrated photocells connected to a sixteen channel data logger which also recorded simultaneous global horizontal external illuminance (See **Fig. 7.3**). From these measurements luminous intensity distribution was plotted and the luminous flux output calculated using the 'zone factor' method for symmetric luminaires described in the CIBSE TM5 [3]. Measurements were made from March 2010 to August 2010 inclusive. Readings of global horizontal external illuminance and nadir internal illuminance 1m below the centre of the luminaire were taken simultaneously every 10 minutes throughout the whole period.

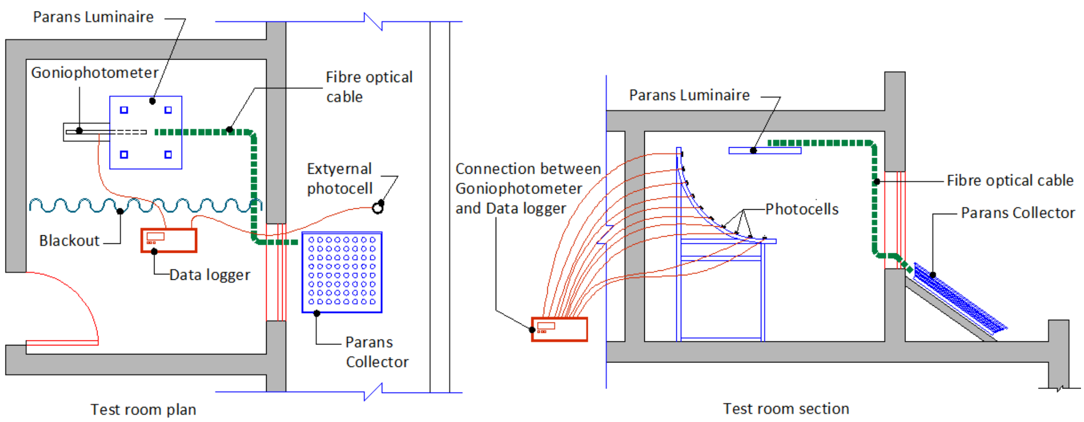

Figure 7.3: *Plan and section for the test room shows Parans system installation and measurements arrangements.*

Separately luminous flux output was measured using a cubical box that approximated the characteristics of a photometric integrator. The box consisted of a hardboard cube 0.8 m-long, with interior joints sealed and coated on the inside with matt white emulsion paint. Separate lids were constructed for the box with different sized holes in the centre to accommodate the luminaires or the optical fibre cable. A calibrated photocell, centrally mounted on a 20cm bracket facing the base of the box was used to measure illuminance whilst acting as its own baffle to light directly from the source. The box had been calibrated in the laboratory of a major lamp manufacturer using lamps of known output with one of the lids.

7.3.2. TDGS measurements

The TDGS was in the roof space of the University of Liverpool, Pilkington Building, with unobstructed collectors above the roofline. The TDGS diffuser was mounted in the roof space surrounded on all sides with heavy duty blackout material. This system was the subject of an earlier study which had determined luminous intensity distribution and the relationship of total flux output to nadir illuminance [4]. In summary the system was a 1.2m long, 330mm diameter guide with a dished opal diffuser. Limitations of the building determined the maximum length of guide that could be measured. Accordingly only nadir illuminance was measured 1m below the diffuser, and recorded using data logging equipment similar to that described above, over the measurement period.

7.4. RESULTS

7.4.1. Readings

Throughout the measurement period, maximum solar elevation angle reached 59.9˚ with solar azimuth angle between 46˚ and 312.5˚ [5]. A total of 26496 readings were recorded of which 16481 (62.2%) were during daylight hours. Of the latter only 6684 (40.6% of daylight readings) were gathered within the tracking limits of the HLS - that is within 120˚ active cone. However considerable quantities of sunlight were collected when sun paths were up to 25˚ past the tracking limits in all directions. Some 4000 more readings of this nature were collected and used in the subsequent analysis.

7.4.2. Results for HLS

7.4.2.1. Illuminance delivery

A summary of the 6684 illuminance values at 2m below the centre of the luminaire and within the tracking limits is shown in **Table 7.1**. Some 30% of the internal values are above 300lux and approximately 60% below 50lux. The relationship between average external and internal values, shown in **Fig. 7.4**, is nearly linear between 35 to 85 klux external. Below 35klux the predominantly cloudy sky generally delivers insignificant values of internal illuminance. A plot of all values in **Fig. 7.5**, however, suggests that under external conditions giving global values of below 35klux may deliver internal values of the order of 200lux. The explanation for this is that the system works efficiently under clear skies by delivering concentrated direct sunlight, but less so under overcast conditions where the low luminous intensity source cannot be effectively concentrated. Under partially cloudy conditions the illuminance delivered depends on the degree to which the sun is obscured. It is apparent that above 85klux the rise in internal illuminance tends to slow and levels out around 100klux, probably due to the external sensors going out of range.

Table 7.1: Global external horizontal illuminance and corresponding internal illuminance 2m below the centre of the luminaire

External illuminance, Y, range (klux)	External illuminance average (klux)	Internal illuminance average (lux)	Number of readings	External illuminance %	External illuminance, cumulative %
Y > 100	107.3	780	300	4.5	100
90 < Y ≤ 100	94.9	764	384	5.7	95.5
80 < Y ≤ 90	84.9	714	440	6.6	89.8
70 < Y ≤ 80	75.4	627	387	5.8	83.2
60 < Y ≤ 70	65.5	490	334	5.0	77.4
50 < Y ≤ 60	55.1	353	476	7.1	72.4
40 < Y ≤ 50	45.8	165	740	11.1	65.3
30 < Y ≤ 40	36.0	63	1061	15.9	54.2
20 < Y ≤ 30	25.6	16	1178	17.6	38.3
10< Y ≤ 20	15.3	12	1029	15.4	20.7
Y ≤ 10	7.3	14	355	5.3	5.3

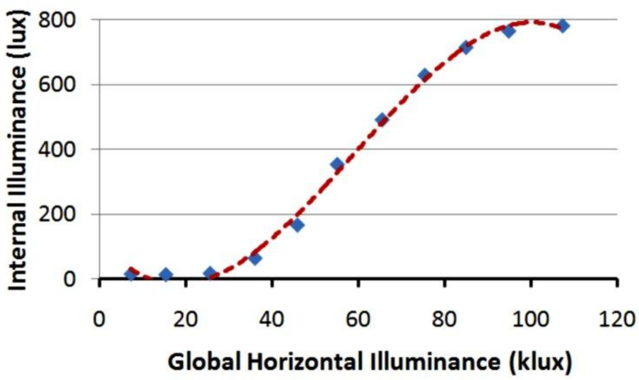

Figure 7.4: *Relationship of external global horizontal illuminance to average value of nadir illuminance delivered by Parans system*

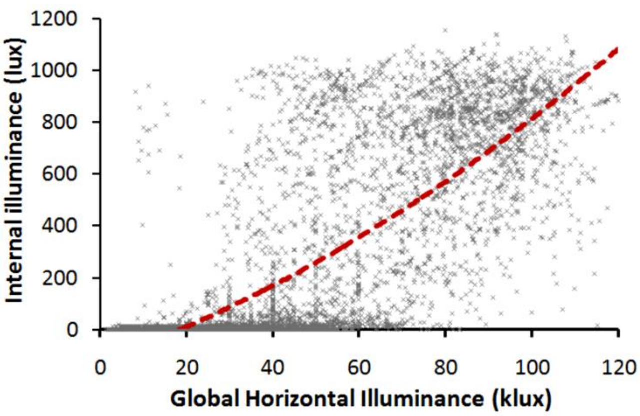

Figure 7.5: *Relationship of external global horizontal illuminance to all values of nadir illuminance delivered by Parans system*

7.4.2.2. Illuminance variation

Light delivery variation under partially cloudy conditions is illustrated in **Fig. 7.6** and shows measured internal nadir illuminance and corresponding external illuminance at 10-second intervals during a day in February 2010. This confirms that the internal illuminance becomes negligible when the external illuminance falls below 30klux. When variation over a 30 minute period is studied (**Fig. 7.7**) it can be seen that internal illuminance varies between 0 and 700 lux two or three times within one minute. These rapid changes have implications for longevity of lamps within the HLS and for its control system, and for occupier comfort. It can be observed that the internal illuminance is around 700lux in the periods 12:23 to 12:26 and 12:47 to 12:50, but that the external illuminance was 75 and 100 klux respectively. The explanation for this may be that the measured external illuminance is a global illuminance but the HLS is effectively delivering the direct component only, but further based on measuring both components separately would be needed to be verify this.

7.4.2.3. Luminous flux output

The characteristic light delivery of the system described above produces a corresponding variation in delivered luminous flux. The estimated outputs of the luminaires supplied by a 20m fibre optic cable and measured using the two methods described in **Section 7.3.1** are shown in **Table 7.2**. Note that the outputs vary almost linearly with external horizontal luminance above 30klux for the reasons described above. The differences between the

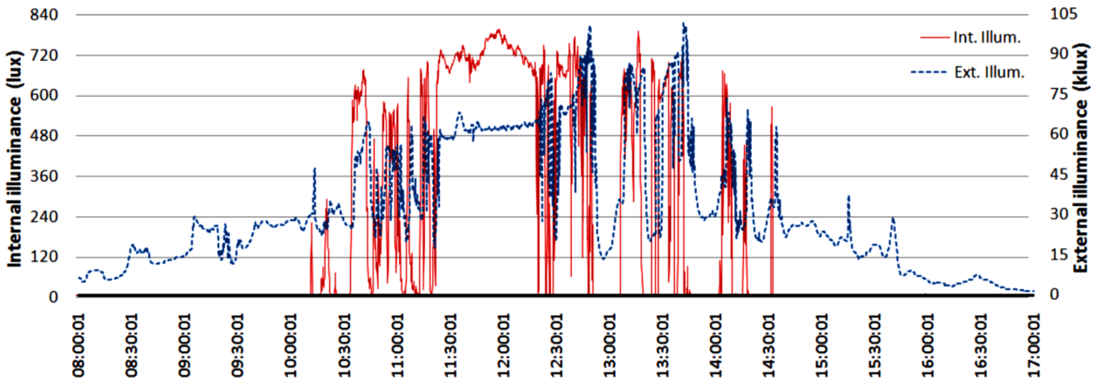

Figure 7.6: *External illuminance under partially cloudy sky and corresponding nadir internal illuminance delivered by Parans system*

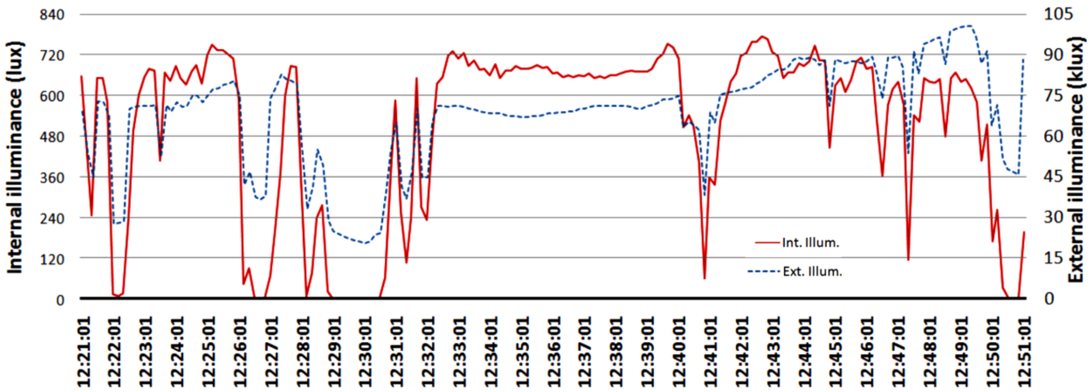

Figure 7.7: *Variation in internal illuminance delivered by Parans system over 30 minutes and corresponding external illuminance*

estimates using the two methods may be attributed to the limitations of the field measurement methods used with the integrator method producing consistently higher values. Whilst every effort was made to ensure that alignment of optical fibre tails, luminaire surfaces and measurement cells were accurate; that the cells were in calibration; and that stable sky conditions applied when measurements were undertaken, small variations in any of these influence the resulting polar curve and the subsequent TM5 calculation procedure. The integrator method would better account for such variations in spatial output from a daylight device.

7.4.2.4. Polar curve

The goniophotometer was used to measure luminous intensity for both the Parans L1-large and L1-small luminaires as supplied by the manufacturer. Readings were taken with the apparatus aligned axially (C = 0) for a range of external horizontal illuminance above 50klux and the results averaged. Polar curves for the two luminaires are shown in **Fig. 7.8**. The characteristics of the curves are related to their construction (See **Fig. 7.2**). Flux leaves the output device in three ways; some directly via the holes in the diffuser located directly below the ends of fibre optic cables, the rest scattered by the PMMA sheets or sideways via the gap between the sheets. The influence on the polar curve of the light passing directly through the holes is apparent.

Fig. 7.9 illustrates the horizontal illuminance distribution at 2 metres below a L1-large luminaire for a global horizontal external illuminance of 45klux. Peak illuminance of 390lux is directly under holes in the diffuser with that under the centre of the luminaire of 305lux. The illuminance level decreases sharply at some 50cm from the centre of the luminaire,

Table 7.2: Luminous flux from HLS output devices for given external horizontal illuminance (20m optical fibre cable)

External illuminance (klux)	20	50	100	20	50	100
Flux output measurement tool	**Goniophotometer (lm)**			**Integrator (lm)**		
Four OF luminaire	Negligible	1550	3100	Negligible	1995	3990
One OF luminaire	Negligible	380	740	Negligible	490	940

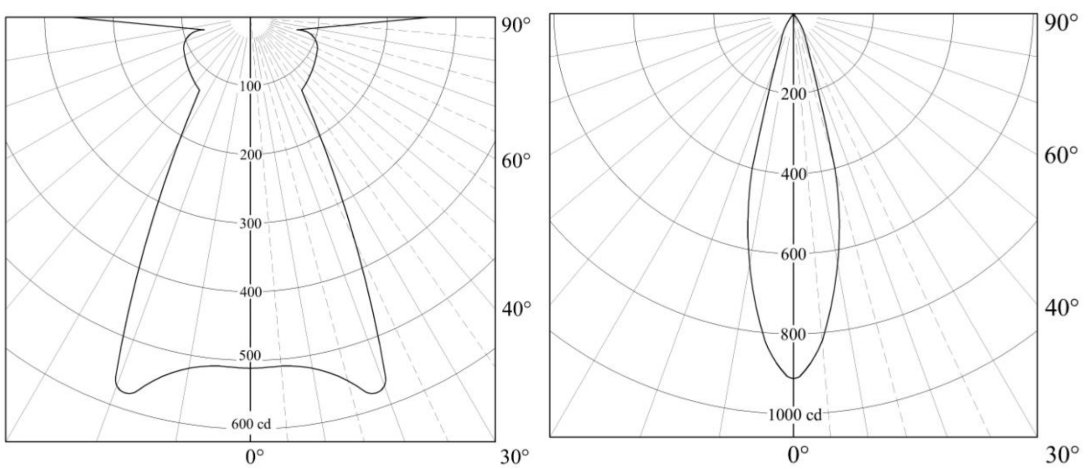

Figure 7.8: *Parans luminaire polar curves,* (Left): *L1-large (Nadir luminous intensity 273cd/1000 lumens),* (Right): *L1-small (Nadir luminous intensity 1220Cd/1000 lumens)*

Table 7.3: Calculated luminous flux from TDGS output devices for given external horizontal illuminance

External illuminance (klux)	20	50	100
Flux output measurement tool	**Goniophotometer (lm)**		
330 mm diameter output device, 1.2 m guide	1355	2554	3520
330 mm diameter output device, 5 m guide	665	1255	1720
330 mm diameter output device, 20 m guide	342	643	890

dropping to below 50lux at 1 metre and a negligible value at 2 metres. This suggests that uneconomically close luminaire spacing would be required to maintain an acceptable average horizontal illuminance and planar uniformity if the devices were to be used in daylight delivery mode only.

7.4.3. Results for TDGS

A plot of all measured nadir and external illuminance values in **Fig. 7.10** exhibits considerable scatter. This is due to the quantity of flux delivered by the short guide being heavily influenced by sun position. Using the measured nadir and external illuminance, and the luminous intensity distribution from Reference [4], estimates were made of flux output using the TM5 method for a range of external illuminance values. Row 1 in **Table 7.3** shows flux output with a 1.2m transport element and, using data from CIE 173 [6], estimates were made of outputs from similar 5m and 20m long guides. It is clear that TDGS can deliver useful quantities of flux when external illuminance is of the order of 20klux and below, and that the output of the TDGS is comparable to that of the small hybrid luminaire for external values over 50klux. **Fig. 7.11** compares flux outputs delivered over 5m travel for different

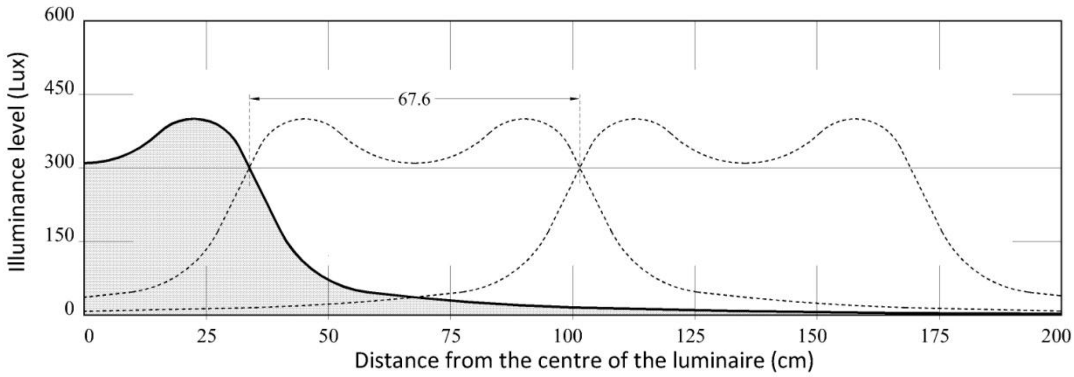

Figure 7.9: *Horizontal illuminance distribution at 2m below an array of* L1-large *luminaire*

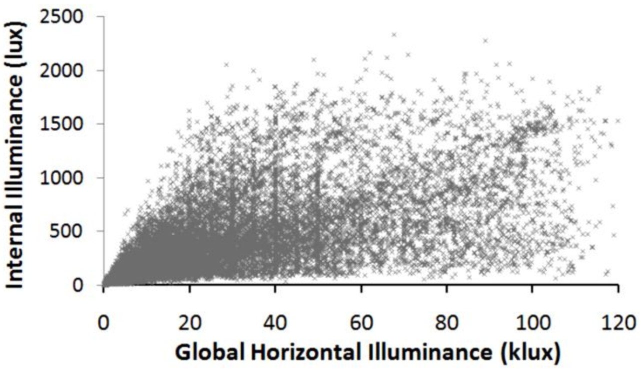

Figure 7.10: *Relationship of external global horizontal illuminance to all values of nadir illuminance delivered by TDGS*

external illuminance values using 330-diameter TDGS and one 30mm Parans optical fibre and small luminaire. The measurements, and those quoted in Reference [7], confirm that HLS deliver more flux above 30Klux external, and TDGS vice versa.

7.5. DESIGN TOOLS

Prediction methods for daylight guidance systems can usually be broken down into two parts; the first being an estimation of the amount of light delivered by the system, and the second a method of predicting the likely distribution of this light.

7.5.1. HLS light delivery

Light delivery is influenced by the optical losses that occur, variously, in collector, output device and optical fibre. Using the recorded external horizontal global illuminance and the combined area of the 62 lenses in the collector, the flux collected at a given time was estimated. The simultaneous system output was determined as described in **Sections 7.3.1**. This enabled the total efficiency to be determined. The average for the system with the 20m long optical fibre and the large luminaire was 21.7%. The contribution to light loss caused by the optical fibre can be determined using manufacturers data. **Fig. 7.12** shows both total transmittance, and that of the optical fibre only, as a function of cable length. This information was combined with the luminaire outputs for the range of external global illuminance to give **Fig. 7.13**.

7.5.2. Distribution of light within the room

The combination of luminaire flux output and polar curve can be used, either directly in point-by-point calculations, or as the basis of spacing to height ratios (SHR) and utilisation factor calculations. Selection of an appropriate calculation method for hybrid luminaires is complicated by their dual function as predominantly daylight devices under clear skies and as a conventional electric luminaires at other times.

Calculations of the type described above could be made for daylight-only devices similar to those measured in this work. However it could be argued that there would be little value in these since, firstly, the nature of the polar curve would mean that the SHR necessary to give an acceptable work-plane illuminance uniformity would be uneconomically small (spacing less than 1m for L1-large) and, secondly, in hybrid use the daylight is automatically 'topped-up 'by electric lighting. Notwithstanding this, a daylight only utilisation factor table can be calculated for the luminaires using the TM5 method [3], and an extract for a Parans large

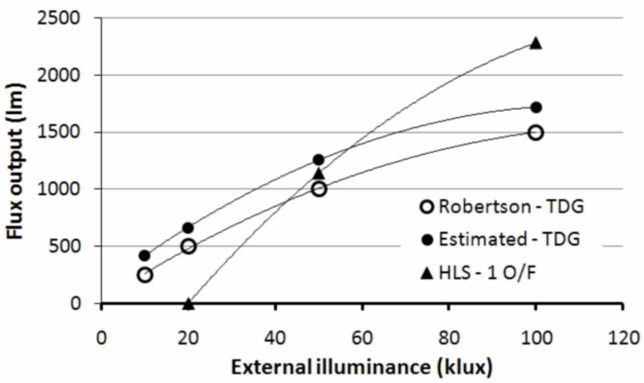

Figure 7.11: *Comparative flux outputs for different external illuminance delivered over 5m travel using 330 Ø TDGS and one 30mm Parans optical fibre and small luminaire*

Table 7.4: Extract of Utilization Factors for Parans *L1-Large* luminaire, *SHR NOM* = 1.00

Reflectance			Room Index								
C	W	F	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
0.7	0.5	0.0	0.64	0.68	0.71	0.74	0.77	0.79	0.80	0.83	0.85
		0.1	0.66	0.71	0.74	0.77	0.80	0.83	0.85	0.88	0.90
		0.2	0.67	0.73	0.77	0.80	0.84	0.87	0.90	0.93	0.96
		0.3	0.69	0.75	0.80	0.84	0.89	0.92	0.95	0.98	0.99
	0.3	0.0	0.59	0.63	0.66	0.68	0.72	0.74	0.76	0.79	0.81
		0.1	0.60	0.64	0.68	0.71	0.75	0.77	0.79	0.83	0.85
		0.2	0.61	0.66	0.70	0.73	0.78	0.81	0.83	0.87	0.91
		0.3	0.62	0.68	0.72	0.75	0.81	0.85	0.88	0.93	0.96
	0.1	0.0	0.55	0.59	0.62	0.64	0.68	0.70	0.72	0.75	0.77
		0.1	0.56	0.60	0.63	0.66	0.70	0.72	0.75	0.78	0.81
		0.2	0.56	0.61	0.64	0.67	0.72	0.75	0.78	0.82	0.86
		0.3	0.57	0.62	0.66	0.69	0.74	0.78	0.82	0.87	0.91

luminaire is shown in **Table 7.4.** Similar data exists for daylight-only TDGS output devices but, since these function separately from any electric lighting in the same room, that may be used for design purposes [8].

The flux output in **Fig. 7.13** may be used for calculation of the Daylight Penetration Factor (DPF), the metric advanced for quantification of daylight delivered by guidance systems. DPF is defined as 'the ratio of the illuminance at a point due to light received via a light guide from the sky to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky' [4]. To determine the DPF of the system, twelve measurement runs of 4-5 hours each were made, equating to some 600 readings under as far as is practical a

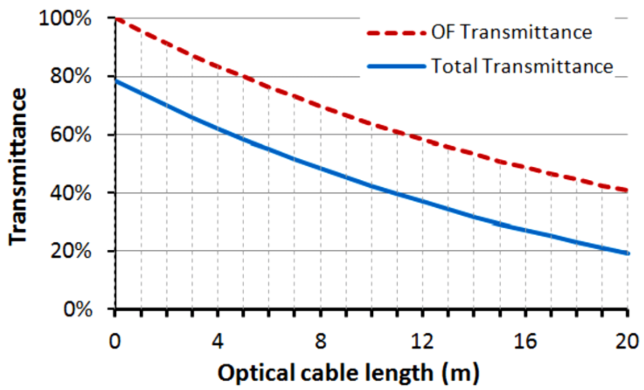

Figure 7.12: *Parans transmittance of total system and optical fibre only*

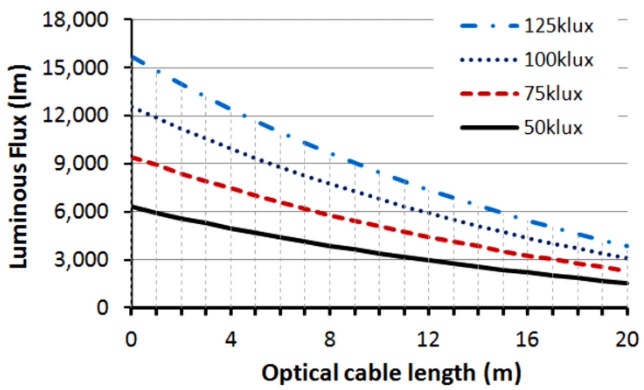

Figure 7.13: *Parans luminaire outputs for the range of external global illuminance*

clear sky. The nadir average DPF 1.5m below the luminaire varied between 0.62% and 1.53% with mean of 1.07%. Using all measurements within the system tracking limits (6684 readings) the average nadir DPF under all sky conditions was 0.71%. This compares with a DPF varying between 0.15% and 0.47% with mean of 0.29%; measured 1.5m below a 2.7m long, 250mm diameter TDGS lined with 98% specular material, topped with twin domes, and equipped with a frosted diffuser [7]. However whether the DPF concept is meaningful in the case of hybrid systems where daylight is automatically 'topped-up' by the lamps is also open to debate.

For hybrid systems to be effective at all times they must be designed for the 'worst case' which is as an electric only system. The function of the daylight element under these circumstances is to provide distinctive temporal and spatial variation of illuminance. **Fig. 7.14** shows areas of local high daylight illuminance beneath luminaires which might be considered an attractive feature. The upshot of this is that hybrids should be designed to electric lighting norms meaning that conventional electric lighting photometry is necessary. This is not currently published for the Parans devices.

7.6. POTENTIAL FOR ENERGY SAVING

7.6.1. Energy saving calculation procedure

One of the arguments advanced by the advocates of light guidance is that daylight delivered deep into interiors allows energy to be saved by electric light substitution. The proportion of each source used (the usage pattern) and any resulting energy saving varies with daylight conditions. To investigate this an arbitrary working space was lit, in turn, using an electric lighting system (ELS) with linked TDGS, and Parans output devices with the assumed addition of lamps to form a hybrid luminaire.

The specification of the room and its lighting equipment was as follows (See **Fig. 7.15**):

- Single storey windowless room 20m x 10m x 3m-high with a pitched roof necessitating light transport of 5m. Room surface reflectance of 70/30/20%.

Figure 7.14: *Daylight-only luminaire in use.*

- Lighting systems designed to deliver variously 300, 500 and 700 lux average working plane illuminance.
- An ELS of 600mm square surface mounted opal luminaires selected to resemble as closely as possible the Parans luminaires. Twenty-eight luminaires equipped with three 18w lamps were required to provide an average illuminance of 300lux, thirty-six with four 18w lamps for 500lux, and thirty-six with four 24w lamps for 700lux. These were positioned at close to recommended spacing to height ratio.
- The TDGS was designed to provide a 'well day-lit space' having a DPF of 0.5% [10]. This required twenty-eight 330mm diameter guides in a spacing grid co-ordinated with that of the ELS.
- In the absence of photometric information for the Parans devices in hybrid mode, these were assumed to have similar optical properties to those of the ELS luminaires, and with daylight delivered using one, two, three or four optical fibres connected to a Parans luminaire.

An identical procedure was followed for both ELS/TDGS and HLS. The measured external/internal illuminance data was used to generate the flux emitted by the output devices for the full range of external illuminance. Average work plane illuminance was estimated by a lumen method calculation assuming utilization factors variously from Reference [4] or ELS luminaire manufacturers' data. The study assumed working hours extending from 0800 to 1800, 7 days a week for the measurement period. Calculations were performed every ten minutes and the supplementary illuminance and wattage required by the electric lighting system to reach the design work plane illuminance for each case calculated. The energy saving relative to full electric load was computed.

7.6.2. Energy saving results

Energy savings and lighting usage patterns for the measured external conditions are shown

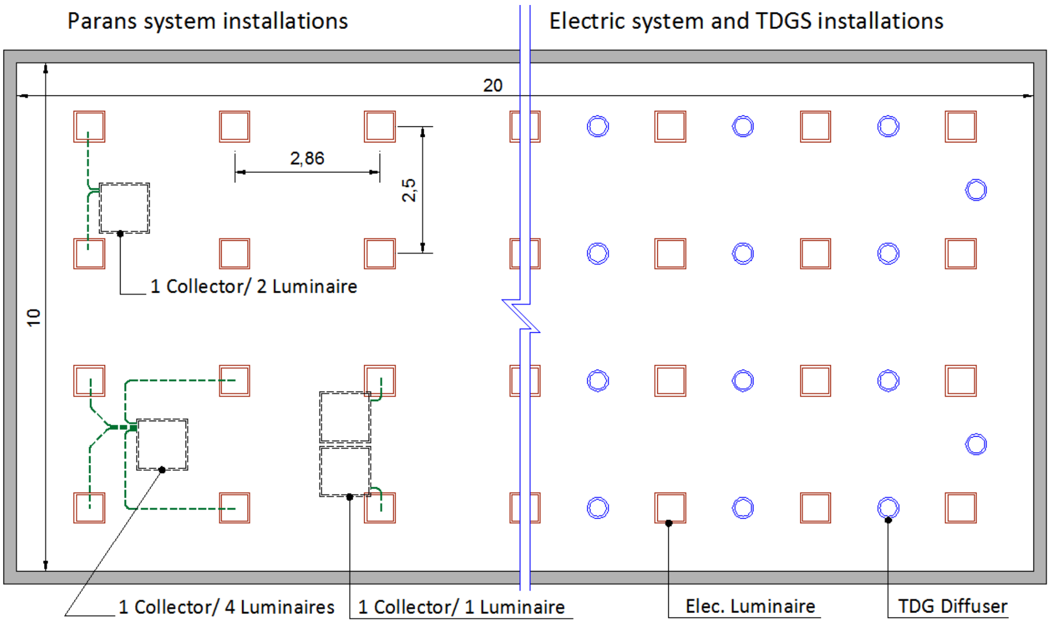

Figure 7.15: *Energy saving calculation room, the left half of the room presents Parans system configuration, and the right half presents ELS and TDGS configuration.*

Table 7.5: Lighting usage patterns and load savings in example room

Design illuminance (lux)	TDG 330 Ø			HLS 1 OF			HLS 2 OF			HLS 3 OF			HLS 4 OF		
	300	**500**	**700**	**300**	**500**	**700**	**300**	**500**	**700**	**300**	**500**	**700**	**300**	**500**	**700**
E.Saving (%)	48	30	22	24	12	9	39	25	18	49	36	26	54	43	34
Full DL (%)	11	0	0	0	0	0	12	0	0	27	8	0	42	18	6
Hybrid (%)	76	87	87	56	56	56	43	56	56	29	48	56	13	37	49
Full EL (%)	13	13	13	44	44	44	45	44	44	44	44	44	45	45	45

in **Table 7.5**. 'Full daylight' was considered to be when the system delivered an average work plane illuminance equal to or greater than 300, 500 or 700 lux, and full electric lighting when the daylight illuminance was equal to or less than 50lux. Otherwise, it is considered hybrid lighting. There is considerable variation in both usage pattern and electric saving as a function of external illuminance for both types of guidance system.

In general the electric savings are greater at lower design illuminance values where more electric light is substituted. The TDGS produce electric savings which are slightly better than the HLS with 2 OF but inferior to that with 3 OF. This is not just because of the varying capacity of the systems to deliver daylight. Inspection of **Tables 7.2 and 7.3** shows that for external illuminance above 30klux a single OF delivers a comparable output to a TDGS device for similar external conditions and transport lengths. However, **Table 7.1** suggests that some 38% of measured external values were under 30klux. At these levels the HLS cease to deliver useful quantities of daylight but TDGS continue to do so. Thus the overall energy performance of the TDGS was enhanced by its ability to work effectively in the lower range of external illuminance.

The major differences in the lighting usage pattern between the two systems are that the TDGS may operate as 'hybrid lighting' for some 80% of time, whereas the HLS varies between 30 and 50%. These figures are reflected in the amount of 'full electric lighting' for the respective systems. This further indicates the ability of TDGS to deliver light under cloudy conditions. The HLS managed to achieve 'full daylight' consistently only when equipped with 3 OF, and even under these circumstances for substantially less than half the time. The daylight flux contribution in these cases was substantially above half the total luminaire output. In summary it appears that the HLS is much better in providing a full daylight condition, but the TDGS is able to provide a more consistent delivery of daylight for a variety of external conditions.

7.7. DISCUSSION

7.7.1. Light delivery

It is clear that the quantity of daylight delivered depends on system type and mode of use, and the solar resource. Using concentrated sunlight as a source enables HLS, under favourable conditions, to deliver to luminaires flux outputs comparable to those of ELS lamps. The major drawback however is that that HLS of this type only work effectively under clear skies but much less so under overcast or partially cloudy conditions. The evidence of this study is that below external illuminance levels of about 30klux the HLS delivers negligible quantities of daylight flux. This is a major drawback for the use of these devices in temperate latitudes. The TDGS were able to transfer both sunlight and skylight over the whole range of external illuminance conditions. This is a compelling argument for their use in temperate latitudes or where cloudy skies predominate, and indeed there is evidence that TDGS has a slightly higher efficiency under cloudy than clear skies [7]. Under some sky types, notably partially cloudy, there is considerable short term variation in daylight delivery. These rapid changes have implications for longevity of lamps within the systems and for the control system.

The different light transport methods in the two types of system have implications for the distance from the building envelope that daylight flux can be delivered. Using highly concentrated sunlight and optical fibre transport, the HLS permits daylight penetration much deeper into a building than is generally possible using TDGS. Indeed the measurements in this work suggest that under favourable conditions a Parans system can deliver a flux comparable to an electric lamp some 20m into a building. In practice TDGS are rarely used with more than about 10m of guide because of their optical and physical constraints [10]. There is evidence that HLS is a more efficient way of delivery of daylight deep into a building. Based on the measurements the average work plane DPF for a typical office using the HLS was 0.71%. This is superior to that of 0.29% delivered by a 2.7m long, 250mm diameter TDGS lined with 98% specular material and topped with twin dome; lighting the same area. However the important difference in the two systems is that the TDGS output devices deliver daylight separately from that of the ELS whilst the hybrid luminaires are configured to automatically 'top-up' daylight using their own lamps. Thus the daylight component in a HLS is simply part of the luminaire output. Whether the DPF concept is meaningful in this case is open to debate.

7.7.2. Light distribution

There are a number of concerns relating to the distribution of light delivered via hybrid luminaires. This work assumed an intensity distribution of the hypothetical luminaire as that of a diffusing electric luminaire of similar size and diffuser type. It is clear that the addition of one or more end-emitting optical fibres will change this since the polar curves of the daylight (point sources) and electric lighting (linear sources) components differ markedly. For practical design purposes this information is required. Although there are published polar curves and recommended spacing to height ratios for TDGS output devices there are none for HLS luminaires. This leads to the wider question of sub-optimal optical processes within the luminaires – the optics necessary for electric sources need modification to accommodate the daylight emitters and vice versa. Whilst the use of end emitting optical fibres may be acceptable for delivering daylight to spotlights, side emission might be more appropriate for a luminaire, similar to that assumed, in which the electric light component is distributed by a diffuser. Although luminaires with the latter configuration have been developed they are not yet available commercially [11].

7.7.3. Daylight perception

A more fundamental question is whether the HLS output would be recognised as 'daylight' at all. There is evidence from previous studies that building users recognised that a TDGS could be regarded as providing 'daylight' if the amount delivered was sufficient. These studies also suggested that if the daylight output devices resembled luminaires they were perceived as delivering electric light [10]. The HLS have been shown in this work to be capable of delivering large quantities of concentrated sunlight. However given that Parans output devices have all of the characteristics of a luminaire it is questionable whether users would regard the output as daylight with all its associated benefits. Spatial and diurnal illuminance variation is one of the unique properties of daylight. There is a danger that automatic illuminance 'top-up' necessary for energy saving that is a feature of HLS will create a uniformly lit space that users will perceive as dominated by electric lighting no matter how much daylight is being delivered. Similarly any user perception of diurnal variation would require a daylight device which is capable of mimicking in some way external illuminance. It is at least arguable that control of 'top up' light on a working plane should include some diurnal and seasonal variation. To answer these questions studies of user reaction to actual installations are required.

7.7.4. Implications of daylight guidance systems

Daylight guidance systems may affect interior architecture and have implications for other building systems since they require vertical and/or horizontal paths for guides. The main unique concern is fire resistance and to the prevention of passage of smoke in both vertical and horizontal transport components which is usually addressed by provision of fire compartments. HLS and TDGS based on light guides may pass through compartment enclosures and a range of measures including fire-protected ducts, fire dampers and fire-resisting cladding may be required. HLS that deliver daylight via flexible optical fibre cables would require little more space and fire provision than electrical or communications cables. They also have few implications for interior spatial layout, and merely require coordination with other building services. On the other hand TDGS may require dedicated ducts through several storeys. These are of widths measured in centimetres and lengths in tens of metres and may occupy rentable floor area and restrict internal spatial flexibility. By way of illustration of this point the measurements indicate that a single 30mm-diameter flexible optical fibre cable can deliver similar quantities of flux to a similar length of 330mm-diameter rigid tube TDGS.

7.7.5. HLS design methods

Standardised methods of design calculation, data production and exchange are universal in the lighting industry. Electric and daylight codes set out recommendations for equipment, illuminance levels and surface properties and recent work extends this guidance to TDGS [6]. The present study makes it possible to suggest tentative design methods for HLS based on likely flux outputs and luminous intensity distributions. Estimates of flux input to a HLS based on external illuminance conditions are possible. These are more reliable in locations where clear skies predominate. For cloudy conditions the assumption must be that no useful flux can be gathered. Estimates of light loss can be made for individual elements of the HLS. In the present work the collector and luminaire appear to be account for about 20% of the total but there is little in the literature about similar losses from other types of HLS. On the other hand there is extensive published information about losses in the optic fibre transport element. In the absence of published material, the polar curves in this work were produced using short range field measurement photometry. From these it was shown that it is possible to compile an utilisation factor table for a HLS daylight component. However because the daylight is subsumed into the output of an electric luminaire it can be argued that there is little value in this approach. Before designers have confidence in HLS as an alternative to other electric and daylight systems, photometric to industry standards data for hybrid luminaires, similar to that available for TDGS, is required.

When this is available the question is 'How is it used'? In principle knowing flux output and polar curve for any source a range of calculations are possible. Hybrid systems must be able to operate at night and thus must be designed for the 'worst case' which is as an electric only system. For this photometric data in the form of an UF for the luminaire, and predicted flux outputs for likely external conditions, are necessary. The function of the daylight element under these circumstances would be to displace electric load and/or to provide a distinctive 'daylight' temporal and spatial illuminance variation. The trade-off between the two functions requires further work to balance the benefits of user satisfaction against the costs of any increased electrical load.

7.7.6. Limitations of the work

Any work of this nature has a number of limitations. The TDGS used could be considered representative of that technology but there are currently no commercially available HLS luminaires. The 'hybrid' system luminaire studied in fact consisted of a daylight only device which was the subject of the measurements, with the assumed addition of electric lamps. As noted these additions will alter the optics and photometric performance of the system. Also in practice there are likely to be efficiency losses in trading a lumen of daylight for a lumen of electric light using dimming hardware given the non-linearity in the lumen output with power reduction. Notwithstanding this the study could be considered to provide an indication of the performance of the systems. The techniques of field measurement used provide data which, although satisfactory for the estimations used in this work, would have to be replicated using test house standard photometry for design purposes. The measurements were restricted, due to building works, to a summer period when larger amounts of clear sky conditions prevailed than in a winter period of similar length. The typical winter sky condition in Northern Europe of overcast conditions suggests that HLS in these areas would operate for long periods as conventional ELS.

The results of this work are in terms of light delivery and electricity savings relative to the electric lighting only case. The savings in absolute terms would be higher with increases in cost of electricity and the more attractive the systems would become economically. No account has been taken of capital costs of providing the equipment. The wider question of the long term economics of the various systems has been addressed in the costs and benefits chapter.

7.8. CONCLUSIONS

Further research and development is necessary before sun concentrating HLS of the type used in this study can take their place alongside TDGS as a form of daylight guidance used by mainstream lighting designers. The most pressing are the development of luminaires that accommodate both types of source, suitable photometry systems for these luminaires, and of controls that permit the daylight element to be apparent. It is clear that the design process for this type of HLS is akin to that of conventional electric systems. More generally the systems work best in conditions of direct sunlight and, arguably, for temperate latitudes where cloudy skies predominate. TDGS may be a more suitable method of daylight provision.

The complete integration of daylight and electric lighting has long been an ambition of lighting designers. HLS offer one approach to make this possible but whilst hardware development is proceeding rapidly, its practical use is still very much at the exploratory stage. This work demonstrates some of the challenges of using HLS in temperate latitudes using examples of the first ‘daylight luminaires’ to come onto the market. A new generation, which promise improved light collection and transport, are now being installed in commercial applications. However these are being constructed before a full understanding of the properties of the systems and their integration into buildings are available. Only when post-occupancy data is available will the full potential of the systems be realised, a sequence of events which occurred in the early years of the development of TDGS.

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CHAPTER

8

Evaluation of HLS

8.1. INTRODUCTION

Hybrid lighting systems performance and applications have been investigated in the previous chapters. Based on this, the current chapter presents an overall evaluation of the HLS. In some cases TDGS are also considered for purposes of comparison or clarification. Two important aspects are the relationship between the HLS and building structure and fabric, and their compliance with building codes. The latter are discussed in terms of meeting illumination standards, energy efficiency requirements and fire safety. Quality aspects of daylight delivered by HLS are evaluated, and potential energy usage, and costs and benefits presented. Finally there is a discussion of recommendations for design methods.

8.2. RELATIONSHIP WITH BUILDING DESIGN

HLS installations in buildings are likely to affect architectural design, structural systems, services networks, and interior design. Each of the HLS components (collector, guidance and diffuser) influences different aspects of building design. Collectors may be seen as new elements added to the building external fabric, which need to be architecturally treated and structurally considered. Guides of different lengths and varying cross-sections penetrate buildings shell and core; whether vertically or horizontally. The effect of small cross-section guides can be considered similar to that of the electric cables, whilst big cross-section guides significantly influence interior spaces and may conflict with structural elements and services networks routes. Thus to avoid undesired relationships they are highly recommended to be incorporated in the early stages of building design process. Diffusers may be custom designed or conventional-like luminaire. They are available as spot, linear or luminous surface. Diffusers shape and layout influence interior design and light distribution in the space, and thus determine proper purpose of use. Although HLS are claimed to be applicable in new and existing building, incorporation of HLS in the building design process is more likely to produce better integration. The relationship between HLS and buildings needs more development to achieve the kind of integration maintained between conventional daylighting techniques and building design, or the kind of harmony exists between modern daylighting techniques and architectural elements.

8.3. HLS IN BUILDING CODES

Building codes are traditionally slow in adapting to changes in technology. Nevertheless, regulations regarding illumination level in buildings, energy efficiency requirements, and fire safety need to be considered in HLS design.

8.3.1. Illumination

Current illumination standards are still based primarily on illuminance levels, although current thinking is that meeting required illuminance levels may be not enough to satisfy users' needs. Achieving the current illumination standard using daylight only is impractical since the dynamic nature of daylight makes its intensity, colour and duration unpredictable [1]. The electric lighting top-up feature in HLS was developed mainly to overcome the shortage in the delivered daylight, but this might be at the expense of perceiving it as daylight. The fact that daylight is unpredictable makes it difficult to be mandatory in building regulations, though several countries have some recommendations based on achieving required illuminance level or daylight factor. Other countries mandate minimum window sizes, but this is mostly for the purposes of ventilation, safeguard occupant health or provide amenity. A third type of regulation attempts to guarantee an access for sunlight into buildings; usually by stipulating building height and their set-backs from property lines [2, 3]. Although HLS are able in principle to maintain fixed illumination level, it is still difficult to achieve daylight standard as HLS deliver daylight mixed with electric light.

8.3.2. Energy efficiency

Regulations set up in many countries aim to reduce energy use in buildings and CO_2 emissions. The UK governments released in 2006 energy efficiency requirements in the Building Regulations, and which will be significantly higher in 2013 issue. The regulations assume a fixed percentage (70% - 100%) of low energy lighting fittings. In addition, lighting becomes an increasingly significant component of CO_2 emissions, as buildings become better insulated. This means that increased use of low energy lighting may be a significant opportunity in the drive to achieve CO_2 reductions [4]. In the building sector, large commercial and industrial buildings were included in the emission trading systems, which mean they have to pay for any emission over the allowed target [5].

DGS could be a significant contributor in saving lighting energy consumption, which will help buildings to adopt to meet energy efficiency requirements, and consequently achieve CO_2 emissions target.

8.3.3. Fire safety

Fire safety regulations set up rules for fire protection and determine means for fire fighting. The former is more related to the DGS applications. In which restrictions seek to avoid fire flaming, and fire and/or smoke spread within and between buildings. Building fire zoning is a general requirement for fire protection, by which the building(s) is divided into fire compartments that can be completely isolated in fire cases. Any perforation of the compartment enclosure is a potential fire and/or smoke spread threat that has to be treated to protect the compartment integrity. Vertical and horizontal light ducts are likely to penetrate fire compartments. Codes stipulate that whenever they penetrate fire resisting wall/floor they must be fire-stopped. Light ducts can be treated as ventilation ducts, which can be routed through fire-resisting enclosure, made of fire-resisting material, or use fire dampers at the point of penetration [6, 7]. Neither HLS nor TDGS developed a fire-resisting guidance or optically suitable fire damper. Even though current codes make no specific reference to the DGS new technologies, manufacturers need to develop devices responses to the possible changes in building codes.

Highly concentrating HLS may cause thermal stress if the concentrated sunrays are incorrectly focused on, for example, secondary mirrors. This could lead to lighting system damage and fire flaming.

8.4. LIGHT DELIVERY

The various systems' ability to deliver daylight depends on illuminance availability, light collection methods, and light travel distance.

8.4.1. Illuminance availability

The suitability of any system depends on illuminance availability at its location. Illuminance availability does not only depend on the available daylight amount but also on diurnal and seasonal changes in sun position, and daylight type. The available daylight amount determines the required collector size, the sun path dictates a suitable sunlight tracking system and daylight type determines collector concentration ratio. Daylight type 'seen' by the collector is influenced by sky condition and collector orientation and position

The following explains the relationship between daylight amount and daylight type. London (51°30'N 0°7'E) and Hassleholm in Sweden (56°12'N 13°40'E) are examples of two locations having a similar average annual daily sum of global horizontal illuminance of around 306klux, but with the direct components of 116klux and 139klux respectively [8]. TDGS are generally able to deliver more light under diffused conditions so they would be expected to perform slightly better in London, with the high concentration systems such as Parans being likely to deliver more light in Hassleholm [9].

Sun position influences both passive and active daylighting systems. Tracking devices in some active systems have a limited coverage meaning that the system will not necessarily be able to deliver daylight for the whole day. Parans system tracking limit, for example, is 120°[5], and thus if used in Liverpool where the sun path extends from 46˚ to 312˚ in summer it will be able to track sun light only 45% of the time. The same system if used in Athens would be able to deliver sunlight potentially for 61% of day-lit hours. For passive systems such as TDGS which are usually equipped with a horizontal collecting dome, lower sun angles cause more light reflections in the guide, and thus the more light loss.

The schematic in **Fig. 8.1** explains how illuminance availability influences light delivery amount. High concentrating systems are able to deliver larger amounts of daylight under clear skies, which may lead to overall delivered amount through a day being more than that delivered by non-concentrating system. But taking into consideration an arbitrary illuminance design level may lead to different results. Assuming light delivered which causes the design value to be exceeded, the illustration suggests an arbitrary overall light

[5] The second generation is what meant here, as the third one is of 360˚ tracking ability.

delivery of 5200 and 3800 for typical high-concentrating and non-concentrating systems respectively. However the amount of usable light delivered by non-concentrating system is superior at 3400 against 3000.

8.4.2. Light collection methods

Light collection methods determine the component(s) of daylight that can be collected, the effective collecting hours during the day and the necessary orientation of light collector. The major variation in light collector characteristics is the concentration ratio. These vary from no concentration in the case of TDGS to as high as 1000 for systems like HSL or Parans. TDGS are able to collect both direct and diffuse daylight. HSL or Parans work efficiently under clear skies by delivering concentrated direct sunlight, but less so under overcast or cloudy skies where the low luminous intensity source cannot be effectively concentrated. Systems such as SCIS, with a concentration ratio of around 10, can concentrate sunlight and also deliver a small proportion of diffused skylight [10, 11].

Concentration ratio also influences guide size and light travel distance, and collector size determines the amount of daylight that can be collected. The greater the concentration ratio, the smaller the guide size required and the longer the distance the light can be transported. Similarly, the bigger the collector size, the more flux is collected. For instance the high concentration ratio of Parans system enables it to transfer light effectively some 20m via 3cm-diameter fibre optic cables. A TDGS, of the same collecting area, is only able to transfer a comparable light flux some 10m via 45cm-diameter tube.

8.4.3. Light travel distance

The building form dictates the distance to spaces remote from the building envelope. Daylight in narrow buildings can be supplied using facade mounted systems and low-rise

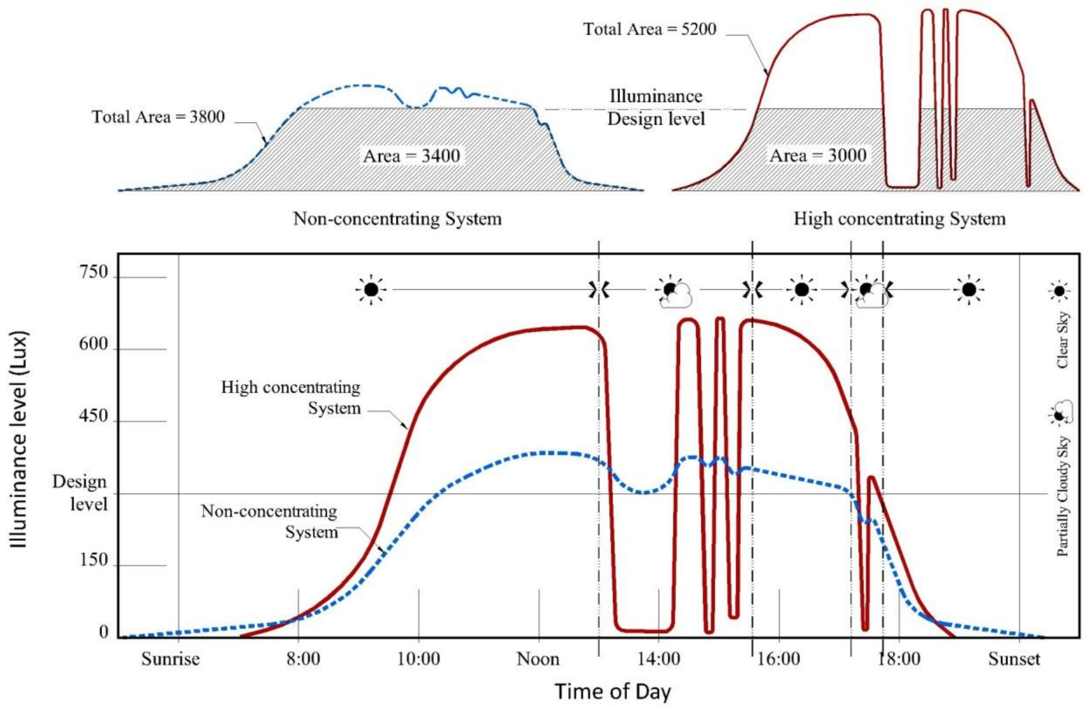

***Figure 8.1**: Illuminance availability for high-concentrating and non-concentrating systems*

buildings from roof mounted systems. Daylight to spaces in deep-plan high-rise buildings necessitates the use of systems able to transport large amounts of daylight long distances. The two major influences on possible travel distances are collector concentration ratio and overall system efficiency. While collector and diffuser efficiency are fixed, guidance transmittance is a function of distance and has a major bearing on overall efficiency. Transmittance of the optical fibres used in Parans system, for example, is 95.6% per metre [12]. Over 10m losses are about 36% and, after addition of some 21% loss in the collector and diffuser, the system overall efficiency after 10m is around 50%. A modern TDGS delivering light via guides lined with 99% reflective materials would have an overall efficiency of 40% for 10m travel assuming losses of 40% in the collector and diffuser. The practical limit of travel for TDGS is of the order of 10m, notwithstanding their use for a 36m-long sunpipe developed by Bomin solar installed in an office building in Washington DC [13].

8.5. LIGHT QUALITY

Many aspects influence perceived light quality including light colour, light distribution, variation of delivery and the relationship with other lighting systems.

8.5.1. Light colour

Daylight guidance systems are invariably used in association with electric lighting systems which creates two challenges. Firstly, colour temperature of daylight varies between 4000°K and 10000°K depending on sky condition and is very different from electric sources which fall in the range 2,700°K to 3,500°K. Spectral coatings on collectors used to eliminate UV and IR wavelengths may change the daylight spectrum. Transport of daylight via fibre optics may cause some colour shift due to the absorption of some wavelengths that make the light emitted depart somewhat from the natural distribution. Although since detection of subtle lighting colour and intensity changes is considered to be one of the greatest advantages of using daylight, occupants may still be disturbed by colour temperature shift within the overall lit environment. Matching colours of electric sources to correspond to variation in daylight is possible, but the necessary equipment is still at an experimental stage. Secondly, spatial and diurnal illuminance variation is also a unique property of daylight, and there is a danger that automatic illuminance 'top-up', a feature of some guidance systems, will create a uniformly lit space that users will perceive as dominated by electric lighting no matter how much daylight is being delivered. Similarly user perception of diurnal variation would require a daylight device capable of mimicking in some way external illuminance. It is at least arguable that control of 'top up' light on a working plane should include some diurnal and seasonal variation.

8.5.2. Light distribution within a room

The light distribution within a room depends on the type and layout of the output devices. The TDGS output devices are discrete units which are mainly used in regular arrays complimenting the electric luminaire layout [14]. As such the TDGS devices solely provide, or supplement electric system in providing, a uniform work plane illuminance with some diurnal variation. In principle the HLS luminaires can do the same but their role is complicated by their dual function as predominantly daylight devices under clear skies and as a conventional electric luminaires at other times. For hybrid systems to be effective at all times they must be designed for the 'worst case' which is as an electric only system. Daylight is delivered from sunlight concentrating luminaires either by end-emission or side-emission from the optical fibres. The former, used in Parans, produces narrow beams of light which result in a non-uniform work plane distribution. The use of side emission, as proposed in HSL, potentially would produce a more uniform planar illuminance but these luminaires are not available commercially. The SCIS guide transfers the internally reflected light along its length and distributes it via the bottom surface. This functions as a 'luminous surface' of 60cm width and up to 12m long. Measurements show a well distributed illuminance over the working plane giving a lit appearance akin to that of a luminous ceiling [10].

8.5.3. Usage pattern

Usage patterns express the percentages of full daylighting, full electric lighting, and hybrid lighting periods in an illuminated space due to operation of linked electric and daylighting systems. The major differences in the lighting usage pattern between TDGS and HLS relate to the ability of the former to collect usable quantities of daylight from cloudy skies giving a global illuminance of less than 35klux, but markedly less than the sun tracking and concentrating systems under sunny conditions. Sun tracking hybrid systems collect insignificant quantities of light under cloudy conditions. Thus in temperate latitudes TDGS makes a contribution to interior light for typically some 80% of working hours whereas that for HLS under similar circumstances varies between 30 and 59%. In geographic locations where clear skies predominate concentrating systems tend to provide the majority of useful light throughout working hours [15].

8.6. ENERGY SAVING

One of the arguments advanced by the advocates of light guidance is that daylight delivered deep into interiors allows energy to be saved by electric light substitution. The proportion of each source used (the usage pattern) and any resulting energy saving varies with daylight conditions. The concept of illuminance availability described in **Section 8.2.1** *provides the basis of a reliable guide to estimate energy savings*. To illustrate this, the systems represented in **Fig. 8.1** are presented in **Fig. 8.2**. This assumes a desired average work plane illuminance of 300lux, and a control system able to dim the electric system to 50lux and then shut off. The resulting electric lighting top up may be expressed as an arbitrary value of 2700 for the non-concentrating system, and 3100 for sunlight concentrating system. The 400 difference between the two represents the respective delivered illuminance. In the non-concentrating case, moderate daylight amount delivered, but enough to satisfy the required illuminance. In the concentrating case, high daylight amount delivered; too much than required. Consequently, delivered amount in the second case sums more than that in the first case; therefore it intuitively attempts to be believed to be more energy saver. The fact that the moderate amount delivered in the first case lasts longer than the high amount delivered in the second case may result in more efficient distribution of the delivered daylight over daytime, and thus more energy saving. Moreover, tracking limit exists in many high concentrating systems add more constrains over daylight delivery time.

Previous assumption was examined by a numerical simulation study carried out in **Chapter 5** to estimate the potential energy saving for different DGS over 26 locations broadly representing conditions throughout Europe, North Africa and the Middle East. According to the configuration assumed in the study, the non-concentrating system TDGS achieved the biggest average saving over all location; followed by the low-concentrating system SCIS, and then the high-concentrating systems HSL and Parans. The results showed that systems without tracking limits, TDGS and HSL, have the same saving trends, and also systems with tracking limits, SCIS and Parans, have similar saving trends. In the first case, the maximum estimated potential energy savings achieved between 10˚N and 15˚N are up to three times the energy savings achieved in the extreme North. In the second case, the estimated potential energy savings roughly doubled from North to around 30˚N.

Although HSL and Parans system produce savings of comparable magnitude, Parans system

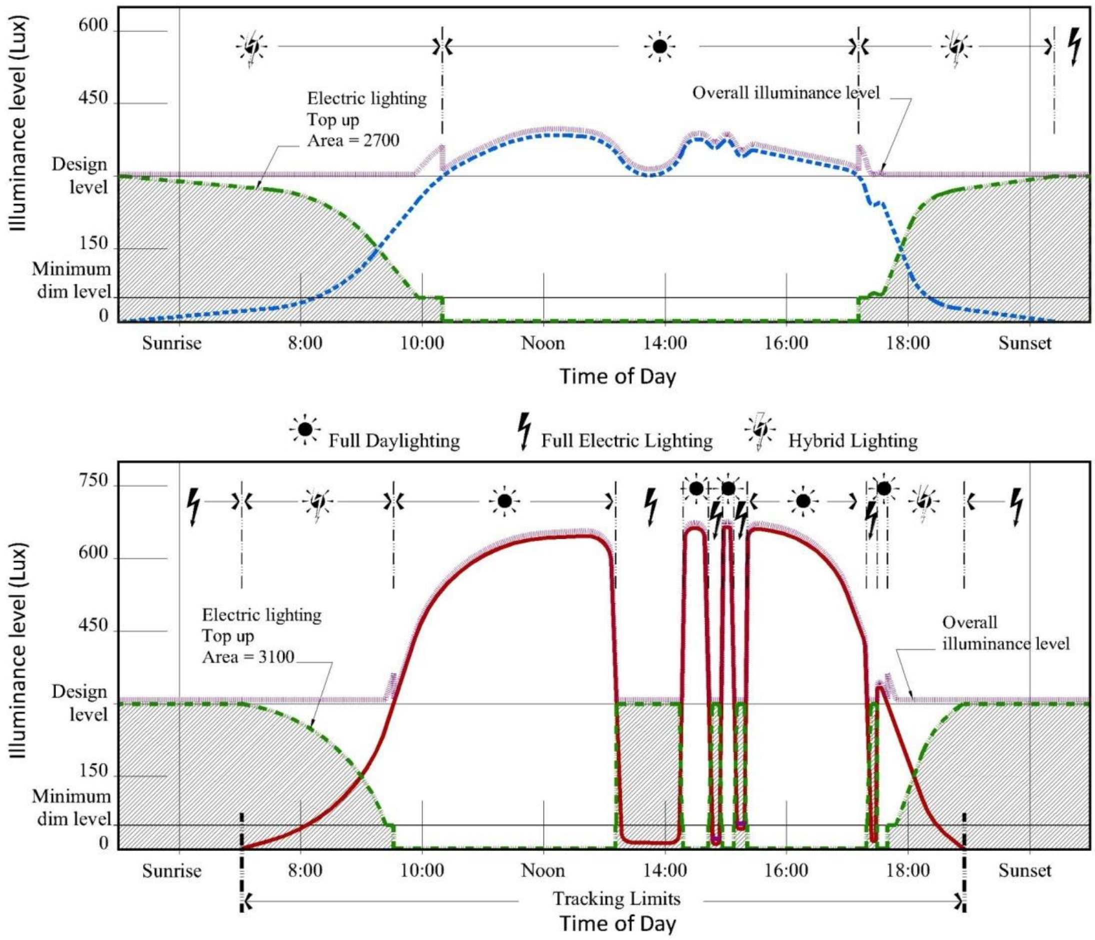

***Figure 8.2**: Daylighting levels and electric lighting top-ups for high-concentrating and non-concentrating systems*

achieved more saving in the Northern locations while the HSL headed in the South where the tracking limits significantly reduced Parans system ability to deliver daylight. Similarly, TDGS and SCIS achieved close saving the Northern locations, while in the South TDGS energy saving was up to three times that of the SCIS due to the tracking restrictions.

8.7. COSTS AND BENEFITS

The main arguments for employing DGS in buildings are, as described above, the potential for saving building running costs and the provision of daylight in working areas. Daylight is a preferred source due to a number of factors related to its enhancement of human wellbeing. To investigate the economic implications of these arguments a cost and benefit analysis was carried out, in **Chapter 6**, using whole life cycle costing with the results expressed in terms of 'payback periods' in investment.

The main costs and benefits associated with lighting systems are summarised in **Table 6.1**. For each there are differences in both in the ease of which they may be quantified, and the magnitude of their effect on the outcome of any analysis. Cost and benefit analysis is conventionally undertaken for the more readily quantifiable Level 1 items. These 'tangible' aspects include initial capital and running costs, and direct savings due to the use of the systems. The Level 2 benefits are known as 'intangible' as they are by their nature more difficult to quantify and their relative importance varies widely between different applications. These may include heating/cooling and carbon tax benefits, the benefits of using a DGS in terms of increased company prestige, is difficult to quantify but might be reflected in building rental values. The benefits of improvements in building occupant well-being due to the beneficial effects of enhanced daylight are also difficult to quantify. However since staff costs are the largest proportion of the total running cost of many types of building, notably offices, any benefits such as enhanced productivity are potentially large.

Initial capital cost of any system mainly depends on the optical materials used and the collection technology. In general the equipment for non- concentrating systems is much cheaper than sun tracking systems but, because of the larger size of their guidance components the cost of building modifications and the 'opportunity cost' of lost floor area may be substantial. The sunlight concentration systems are by their nature complex engineering and for this reason have a higher initial cost. The initial cost of Parans system for instance is some 10 times that of a comparable TDGS. Major savings include energy costs, which are dependent on electricity price, reductions in heating or cooling loads and reductions in carbon emissions taxes. There is emerging evidence that improving the lit environment can be shown to improve users' productivity [16]. Since staff costs are the largest proportion of the total running cost of many types of building, any benefits such as enhanced productivity are potentially large.

Taken together the above suggests that the major influences on the costs and benefits of daylight guidance are capital cost, electricity price and the effects on productivity of daylight. It is clear that DGS require a substantially greater capital investment than equivalent electrical systems. Some such as TDGS can be shown to be economic over the long term if they are solely regarded as devices to enable daylight to be substituted for electric lighting - the ‘tangible benefits’. The capital costs of hybrid systems are such that even favourable assumptions about economies of scale render them a very poor investment judged against Level 1 benefits. The ‘intangible’ benefits of the delivery of guided daylight to an interior are by their nature more difficult to quantify and a number of assumptions, each of which may be questioned, are necessary to make this possible. The results suggest that the benefits of saving on heating/cooling and carbon taxes pale into insignificance in comparison with those of productivity improvements. The latter suggests that investment paybacks could be reduced by up to 75% of those calculated using only Level 1 assumptions. However it is evident that DGS which are fundamentally uneconomic using Level 1 cost/benefits struggle to achieve satisfactory paybacks even taking productivity into account. However in the case of those systems that are only marginally uneconomic the inclusion of productivity does give a more favourable balance of cost and benefit.

8.8. DESIGN METHODS

Standardised methods of design calculation, data production and exchange are universal in the lighting industry. Electric and daylight codes set out recommendations for equipment, illuminance levels and surface properties and recent work extends this guidance to TDGS [14]. For Hybrid systems to be effective at all times they must be designed for the ‘worst case’ which is as an electric only system. The function of the daylight element under these circumstances is to provide distinctive temporal and spatial variation of illuminance. The upshot of this is that HLS should be designed to electric lighting norms meaning that conventional electric lighting photometry is necessary. This is not currently published for any hybrid luminaires and this represents a barrier to their use in lighting practice.

A fundamental design question is whether the HLS output would be recognised as ‘daylight’ at all. There is evidence from previous studies that building users recognised that a TDGS could be regarded as providing ‘daylight’ if the amount delivered was sufficient. These studies also suggested that if the daylight output devices resembled luminaires they were perceived as delivering electric light. Hybrid systems are capable of delivering large quantities of concentrated sunlight but given that the HSL output devices, for example, have all of the characteristics of a luminaire it is questionable whether users would regard the output as daylight with all its associated benefits. Spatial and diurnal illuminance variation is one of the unique properties of daylight and the danger that automatic illuminance ‘top-up’ will create a uniformly lit space that users will perceive as electric lighting with no perceived benefit from the delivered daylight is a real one.

8.9. CONCLUSION

This chapter has shown that incorporation of HLS in buildings, and technical and economical performance of DGS has several dimensions. Care needs to be taken at the design stage to integrate HLS with building elements. Also some development of building codes is necessary to acknowledge DGS in terms of fire safety. However it is clear that they can significantly help buildings to meet illumination and energy efficiency requirements. The output devices or luminaires are capable of delivering, under favourable circumstances, substantial quantities of light deep into buildings. This process, however may have implications for the fabric of the building itself. In economic terms the case for the use of the systems is weak and only assumes a more favourable complexion of the user benefits if the delivered daylight is taken into account. Even under these circumstances care must be taken to configure systems so as to be seen to be delivering 'daylight'. Design methods are needed that acknowledge these issues.

The complete integration of daylight and electric lighting has long been an ambition of lighting designers. DGS offer approaches to make this possible but whilst hardware development is proceeding rapidly its use in actual lighting installations is still very much at the exploratory stage. Only when post-occupancy data from these systems has been analysed will the full potential of the systems be realised.

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CHAPTER 9

Conclusions

9.1. INTRODUCTION

The new work in this thesis commenced with the generation of the required illuminance data. Six subsequent chapters identified the concept of HLS, investigated their performance and applications, and carried out an overall evaluation. The review chapter established a definition of HLS and set out their unique features, one of the research objectives. The investigations in the next four chapters examined the hypothesis validity. The evaluation chapter discussed the overall research objectives in the context of the investigation results.

Although the design of the HLS has to take into account all performance and application aspects, they have been deliberately dealt with in separate chapters and their conclusions are presented separately as well. The reason for this is that there is no ideal or standard solution that ultimately achieves all requirements, but rather an optimum solution that balances performance and application aspects against the design requirements. Also, in an investigation of this nature, every aspect needs to be evaluated in isolation from other influences and thus the potential of each system in that area can be established. Knowing this, priority can be given, in the design process, to the system with the best performance or applicability in terms of the most critical aspect in the case; whether it is the initial price, the guide size, the delivery distance or whatsoever.

By the end of the chapter the hypothesis will be examined to prove its acceptance or rejection, and the contribution of the work is assessed.

9.2. CONCLUSIONS

9.2.1. Illuminance data

Producing estimated illuminance data is essential for the daylighting design process to overcome the lack of measured data. New methods presented in this work include constant values and developed models to convert the widely available irradiance data into illuminance data; with a minimum requirement for additional variables or coefficients, and applicability under any sky conditions. The new methods and related published models have been examined and validated.

Comparison between the proposed and published models, to estimate the direct illuminance data from satellite irradiance data, showed that the proposed models are more than three times more accurate than the published models. The same comparison between models to estimate the global illuminance showed accuracy of the proposed models up to three times more than that of the published models, while it is up to 1.5 times for models to estimate the diffused illuminance. The proposed diffused constant value achieved similar performance to the diffuse model.

A validation of the new methods and published models using measured data showed a similar or slightly more accurate performance of the new methods against the published models. But in all cases the new methods had the advantage of simplicity.

9.2.2. HLS review

Light guides have become a solution to deliver daylight into windowless or remote spaces in buildings. Whether the purpose is to meet the desire to save energy or enhance occupant well being, linking the daylighting system and electric system efficiently is the key to reducing energy consumption and maintaining a good visual environment. This work classified the presence of two linked electric lighting and daylighting systems in one space as an ‘integrated lighting’ system. The ultimate integration is HLS, in which both systems are combined in one system with one output device, so as to maximize the utilization of daylight and minimize the energy consumption. A number of systems having some of these features have been developed over the last fifteen years or so. Although prototypes have been designed and installed, no fully featured commercial products have yet been produced.

9.2.3. HLS performance and applications

9.2.3.1. HLS application in building

Successful incorporation of HLS in building design requires integration between HLS and building systems and elements, which include architectural elements, interior design, structural system, and services networks. The vast variation in HLS components makes the selection of HLS a crucial decision, around which the success of HLS incorporation in building design can be established. Each of the three main components of HLS -collector, guide and diffuser- influences building systems and elements. Light collector size and mounting method is likely to affect the external appearance of the building, and might need some structural requirements. Light guide size and route may be treated as electricity cables with minimum effects on the other systems, or may be treated as ventilation ducts. Thus choice of guidance system is likely to affect the interior design and necessitate coordination with the structural and electro-mechanical systems. Light diffuser size, shape, location and layout also significantly influence the interior design, and to far extend stipulate the proper purpose of use, whether it is general, task, or other lighting, and for residential, commercial or other application.

Facade mounted systems tend to be more suitable for use in multi-storey buildings, as long as they are properly oriented. Roof mounted systems are more suitable for deep-plan buildings. However, systems with big size guide are mostly not applicable for more than the top storey. Systems with the two mounting possibilities follow the shortest possible route, but taking into account that roof mounting allows longer exposure for the sun.

The results of the applications of HLS in buildings strongly support the part of the hypothesis that suggests that the HLS '*should be more integrable in building to be more applicable*'. The early stages of the HLS development, as expected, focused on augmenting their efficiency so they were engineering oriented. Some systems very recently began to pay more attention to the integration between HLS and building to expand the application area.

9.2.3.2. Light delivery and energy saving

There is a considerable variation in HLS performance as a function of geographical location. This means that choice of appropriate HLS may have differing impacts on light delivery and consequent energy saving in diverse locations. System ability to deliver daylight is based on systems efficiency and daylight availability, which vary in components and times in the different sites. This work obtained the daylight availability and investigated HLS ability to deliver daylight and save energy over a wide geographical area in the Northern hemisphere. It is found that energy savings of the non-concentrating systems -that collect global illuminance- increases southward with peak occurring between 10˚N and 15˚N. A similar trend is apparent with the high concentrating systems –that collect direct illuminance- but less predictably since Southern tropical regions have a high probability of clouds which affects the amount of direct illuminance. Systems with limited tracking coverage have a different trend because the operational hours decrease as we head south. According to the assumed working hours in this work, the tracking hours decreased from around 90% of the assumed working hours in the North to as low as 30% in the South. The best performance occurs between 15˚N and 40˚N where the direct normal illuminance annual mean is more than 40klux and the tracking limits covers 47-77%.

Distribution patterns of the delivered daylight over the working hours affects the relationship between light delivery and energy saving. Non-concentrating systems deliver moderate amounts of daylight, compared with the concentrating systems, but this amount may be enough to satisfy the recommended illuminance. Meanwhile concentrating systems under similar conditions may deliver daylight amounts that massively exceeds that required. Under such circumstances, concentrating systems may deliver more daylight, but this doesn't necessarily imply more energy saving, since a uniform distribution of a moderate amount of daylight over a specific time may be more efficient than delivering excessive amount over a shorter time.

The investigations of the light delivery and energy saving of HLS provide an evidence for a conditional acceptance of the first part of the hypothesis that states that the '*HLS have the potential to save energy and provide sufficient light in remote spaces by maximizing the benefits of daylight and optimizing the integration with the electric lighting systems*'. The integration between daylighting and electric lighting supply is supposed to be optimal for HLS, but the capability to maximize the benefits of daylight is subject to the proper choice of HLS that suit the daylight availability in building location. HLS can provide sufficient daylight in remote spaces from building skin under favourable conditions, but not for the entire daytime. The integrated element of hybrid systems allows provision of sufficient light for all daylight states.

9.2.3.3. Economic performance

Two levels of costs and benefits analyses have been carried out to examine HLS economic performance. The first is based on the tangible costs and benefits, which include the initial cost, the running cost, the energy saving, electric lighting systems capital and maintenance saving, and the residual value. The HLS substantial capital investment in this level, if compared with that of the electric lighting systems, makes it very difficult for any HLS to present an economical attractive alternative. So as to enhance the economic performance – expressed in this work by shrinking the payback periods- of the HLS, three influences would have to work together: considerable rise in the electricity price, big reduction in the systems capital cost, and installation where more daylight availability exists - preferably more than 40klux for the global illuminance annual mean.

The second level of costs and benefits analyses is based on the intangible costs and benefits, which add more indirect benefits that might help bringing investment in HLS into an attractive zone. Intangible aspects include many aspects such as the cost of loss of rentable area, cooling loads saving, carbon tax savings, user productivity improvement, and rental price increase. These aspects, by nature, are difficult to quantify and their relative importance varies widely between different applications. This work has attempted to quantify three aspects identified from the literature. These are the cooling loads saving, or what is more accurately called the heat replacement effect (HRE), carbon tax saving, and productivity improvement. The results suggest that the benefits of the first two pale into insignificant in comparison with those of the third. The productivity improvement suggests that payback periods could be reduced by up to 75% of those calculated using only the first level assumptions. However, achieving productivity improvement is subject to the users' perception of the delivered illuminance as daylight, which is still questionable.

The economic analyses strongly confirm the hypothesis condition that says the HLS '*should be available at a price comparable to alternative systems*'. The investment in HLS is remarkably more costly than that in the electric lighting systems or other alternatives such as the widely commercially available TDGS. Cost effectiveness is proved to be essential for new products to penetrate the market or replace current substitutes.

9.2.3.4. Light quality

The unique spectrum and unpredictable changes in colour and intensity are what make daylight a favourable choice. The big challenge facing HLS is how to carry out all the optical processes and mix with electric light without losing the perception of daylight. The daylight spectrum is likely to change due to the use of the spectral coatings to eliminate UV and IR wavelengths, and the obstruction of some of them in the fibre optics. The electric light instant top up is likely to mask welcome changes in daylight intensity, and may be the changes in colour as well if not mimicked by the electric system.

Uniform distribution of the light within the space and over the working time is another quality required for most applications. De-concentrating sunlight by the output device to achieve a uniform planar distribution within a reasonable spacing to height ratio is challenging. The end emitting fibre optics produce narrow beams of light, which result in a non-uniform planar distribution, whilst the side emitting fibre optics potentially would produce a more uniform planar distribution. None or low concentrating system's output devices can produce a uniform planar distribution using the regular electric luminaire layout arrays. A uniform distribution over the time is much easier to achieve by non-concentrating systems as they collect both diffuse and direct illuminance. Highly concentrating systems suffer severe changes in delivered daylight under partially cloudy condition. Switches between light sources may happen many times a minute. Using the current technologies, occupants' note of rapidly changes in light sources is highly likely, which may cause inconvenience.

The results of the light quality investigation suggest the addition of more conditions to the hypothesis. The capability to provide a uniform distribution within the space is essential to provide a sufficient daylight. The provision of a uniform distribution over the time enhances the economic performance of the systems by raising the possibility to save energy, and improving the perception of daylight and thus the productivity gain.

9.2.4. Design methods

The ever-changing nature of daylight makes the use of daylight, as a sole source of lighting in most of the modern buildings, insufficient. Attempts to design HLS must allow the provision of sufficient illuminance under the worst case, which is the full absence of daylight, in other words, when the HLS work as electric lighting systems. Under external favourable conditions, daylight may be able to entirely substitute electric light. Decreasing the number of lamps allocated in every output devices increases the opportunities to attain more time of sufficient daylighting. The control system will regulate the use of electric light to maximize the benefit of daylight and minimize the electricity consumption. The design of the output devices has to enable both light sources to spread uniformly within the space using the same spacing to height ratio.

9.3. DISCUSSION

From the conclusions of individual chapters, it can be seen that a lot of factors interact to determine HLS performance and applicability. This knowledge may be used by system developers to find out how to improve systems performance; or by building designer to know which system is perfectly applicable in a particular case. For both, a full understanding of system potential and limitations is fundamental. Unlike the previous chapters that dealt independently with each aspect, the Discussion will firstly examine all performance and applications aspects related to each component of the HLS to reveal its potential and limitations. Where the relationships among the large number of aspects interlocked they will be fragmented for better understanding. At the end of this section, a summary will discuss the most important issues raised from a comprehensive perspective. . Many of these aspects have been discussed based on the investigations conducted in this work; however, some of these aspects have been derived from the developers' literatures.

9.3.1. Light collector

The main aspects that stipulate the light collector performance and applicability are its light concentration ratio, the area size of the effective collecting part, the mounting location, and the sun light tracking system. These are more detailed below.

9.3.1.1. Concentration ratio

Both none and high concentrating systems are more efficient between 10˚N and 15˚N in the Northern hemisphere. Other aspects related to systems with high concentrating ratio are mentioned below. For non-concentrating systems opposite characteristics apply.

High concentrating ratio leads to:

- Collecting direct illuminance only, and thus it is more applicable under sunny conditions.
- More optical processes are required to concentrate sunlight.
- Smaller size for the collector than comparable none or low concentrating collectors.
- Smaller guidance is required to channel the concentrated sunlight.
- More accuracy is required to focus the concentrated sunlight on the guide mean.
- Technically more complicated and thus more expensive.
- More possibility of fire hazard.
- High skilled labour may be required for installation and adjustment.
- Potential need for more technical maintenance due to its high-tech.

9.3.1.2. Size

Small size collectors have opposite characteristics to what are mentioned below for the big size collector.

Big size leads to:

- Potential ability to collect more light than smaller collector with similar concentrating ratio.
- More influence on building appearance.
- More difficulty in mounting, and structural support may be required.

9.3.1.3. Mounting

Roof mounting leads to:

- Potential ability to collect daylight across the entire daytime.
- Less influence on building appearance than facade mounted system.
- Occupation of the roof, especially systems that need protection constructions.
- Roof opening may be required to connect with the guide.
- More applicable in deep-plan buildings.

Facade mounting leads to:

- Preferably being south oriented, otherwise eastern or western.
- 'See' the sun or the bright sky less time during the day than the roof mounted system.

- More influence on building appearance than roof mounted system.
- Facade openings are likely required to connect with the guide.
- More applicable in high-rise buildings.
- Almost inapplicable in spaces reachable form the North facade only.

9.3.1.4. Tracking system

No tracking option leads to:

- Less collected daylight, since the system will benefit from the horizontal illuminance rather than the normal illuminance; assuming that the collector is horizontally installed, even if it is tilted it will benefit from the normal illuminance for short time.
- Less complicated systems, which is likely cheaper and need less maintenance.

Limited tracking coverage leads to:

- Less operation time, and thus less collected daylight.
- More efficient between 15˚N and 40˚N in the Northern hemisphere, where the available illuminance and the tracking limits are balanced to achieve the most benefit.

9.3.2. Light guidance

The main aspects that stipulate the light guidance performance and applicability are their size, routes in the building, and transmittance.

9.3.2.1. Size

Big cross-section guide (i.e. light duct) leads to:

- High potential for conflict with other building services networks and structural system elements.
- Likely to require extra spaces or cause loses of usable spaces.
- Less flexible routing.
- A considerable attenuation in transported light is likely to happen with every bending.
- The bigger the light duct, the more efficient, since less internal reflections happen.

Small cross-section guide (i.e. optical fibres) leads to:

- High possibility of colour shifts, and thus poor quality delivered.
- More applicable and more potentiality to reach further distance.
- Less modification in building is required for installation, and consequently more saving in the installation cost.

9.3.2.2. Route

Horizontal routing leads to:

- Floor to floor height bigger than the minimum is required for big light guidance.
- Openings in the external and internal walls are required; with sizes relative to the guide size.

Vertical routing leads to:

- Openings in the building roof and floor slabs are required; with sizes relative to the guide size.
- They can be routed through any suitable vertical ducts such as ventilation ducts, dry risers or lift shafts.
- The big ducts penetration of usable spaces is possible, which causes potential loss of rentable areas or disturbing the interior design.

9.3.2.3. Transmittance

The better the light guidance transmittance, the further the distance that light can reach. High reflective materials of transmittance exceeds 99% per light bounce became recently cost-effectively available, which are used to increase light ducts efficiency. Assuming light duct with 0.25m height, 99% transmittance, and light incidence angles range between 30˚ and 60˚, the number of bounces per meter are between ~7 and ~2.5. That means the remaining light after 5m are of the range 70 - 88%, and after 10m are 49 – 78%.

The transmittance of the plastic fibre optics used currently in the daylighting applications ranges from 90% to 97% per meter. Assuming fibre optic with transmittance of 96% used to channel light 5 and 10 meters, the remaining light are 81.5% and 66.5% respectively.

The above mentioned examples that are derived from real applications; prove that the light ducts are not less efficient than the fibre optics, but on the contrary, it may be more efficient if the duct size is increased. The ducts are only less applicable due to their sizes, although the fact that they have the potential to deliver better quality.

9.3.3. Output device

The main aspects that stipulate the output device performance and applicability are its size and shape, in addition to the number of luminaires, the mounting method and their layout.

9.3.3.1. Size

Systems that transport light via fibre optics more usually provide spot luminaires due to the nature of the narrow beams emitted from the end of the fibre optics. These can be used for many purposes such as task lights, wall washers or accent lights. Side emitting fibre optics provides linear luminaires. Light ducts use circular and rectangular luminaires, which can also be provided by the fibre optics if proper diffuser is used to de-concentrate the emitting light. Luminous surfaces can be provided by dual-function light ducts that transport light, but at the same times contains internal extractors to force proportions of light to emit along certain parts of the duct route.

9.3.3.2. Shape

Some systems distribute light via custom designed luminaires. These may be functionally required for better distribution of light, but as well may be wanted to enhance the perception of daylight. Conventional-like luminaires provided by some systems may increase the applicability, but on the expense of the perception of daylight.

9.3.4. Summary

From the above, it can be noticed that the concentrating ratio can be considered the most influential aspect in both performance and application for the following reasons:

- *It determines which daylight component can be collected*, thus what the favourable sky condition is, and thus in which geographical location the system can be more efficiently used.
- *It determines collector size*, which has a major influential on building appearance.
- *It determines guide size* to a great extent. That in turn is likely to affect the delivery distance, and more likely to affect the degree of ease to integrate with other building systems and elements. Ultimately this determines the system applicability in buildings; where from this concern only, high concentrating systems is far more applicable.
- *It influences light quality*. Low quality is more possibly to combine the high concentrating systems. The fibre optics used with them is likely to notably change the light spectrum. Collecting direct illuminance only results in non-uniform distribution over the time under partially cloudy condition. De-concentrating the transported light if not effectively carried out, badly affects the uniform planar distribution.
- *It influences system cost*. High concentrating systems are more complicated and have to be more precise, which raise the system cost in comparison with none or low concentrating systems.

In brief, high concentrating systems are generally more applicable but at the expense of the cost and light quality. In terms of light delivery and energy saving, a fair comparison between the two types is inapplicable, since it depends on how many systems are used to illuminate the required space. Any increase in system number leads to increase in the delivered illuminance. So how many systems of each alternative have to be considered for a fair comparison? The number of systems may be assumed equal to the number required to achieve the recommended illuminance level, but systems' ability to deliver daylight vary with daylight availability. So under which circumstances will the systems will be designed? This argument shows the difficulty to select the best HLS, which has to be based on the balance between system performance and applicability on one side, and design requirements on the other side.

Knowing the HLS features, a very important question arises: is the delivered light still perceived as daylight? The daylighting effect is based mainly on three aspects, the visual connection with outside world, the unique spectrum of daylight, and the seasonal and diurnal changes in daylight colour and intensity. The first impact is completely unavailable. The second one is subject to notable changes throughout the different optical processes, particularly in the high concentrating systems, additionally, mixed light in cases of hybrid operation is likely to change the original spectrum. The third one is very questionable because the continuous and instant top up fades the intensity changes and risks the awareness of colour variations.

The comparison carried out across the research with the passive daylighting system, TDGS, showed that although it is very simpler and cheaper, it is competitive in terms of light delivery, but it is less applicable and has to be linked with a separate electric lighting system to save energy.

9.4. CONTRIBUTION TO KNOWLEDGE

In **Chapter 1** six research questions were asked. Answers of these questions present a significant part of the contribution of this work. The research questions and answers were summarised below.

I. What is the HLS? What are their main features?

HLS combine daylight with electric light prior to delivery and distribute them via the same output devise to appear as one luminaire. This definition briefs HLS features, which have been explained in detail by this work.

II. What is the relationship between HLS and building systems and elements?

Each of HLS components (collector, guide and output device) influences building systems and elements to some extend according to its characteristics; mainly its size and place. Potential application of HLS in building bases on its ability to integrate with the architectural elements, interior design, structural system, and services networks. Influences of HLS components on these systems and elements have been elucidated throughout this work.

III. How much daylight can a HLS deliver?

A HLS can deliver a sufficient illuminance using both sources of light. However, excessive amount of daylight is likely to be delivered by hybrid systems with high-concentrating ratio under a clear sky only. Meanwhile, a moderate amount of daylight may be delivered by non-concentrating systems under any sky conditions. Performance of HLS, in terms of light delivery, in different geographical locations has been investigated in this work.

IV. What is the quality of the delivered daylight by HLS?

Although this research has not got the opportunity to measure most of light quality aspects for different reasons, analysis of the available data makes the perception of the delivered illuminance as daylight questionable. Colours and distribution of illuminance delivered by high-concentrating systems tend to be less quality than that delivered by none or low-concentrating systems.

V. How much energy can HLS potentiality save?

Energy saving is not as dependent on light delivery amount as it is on the distribution of the delivered illuminance over the time and space. Thus, although delivered illuminance amount by high-concentrating system may be far ahead of that delivered by non-concentrating system, their energy saving may be comparable. Amount of energy saving depends mainly on the number of hybrid systems in operation in the space, room finishing, building geometry, and geographical location.

VI. Is HLS economically viable as a lighting alternative?

Current initial costs of HLS make it challenging for them to present an economical attractive alternative. This is expected for a new technology, but they need to be less than 20% of the current prices to be cost-effective. Consideration of intangible benefits, such as productivity enhancement, might bring investment in HLS into the attractive zone.

Additionally, this work has the following contributions:

- Universal and more applicable models have been developed and constant values have been suggested in order to produce illuminance data from satellite data.
- Recommendations for HLS design have been suggested.

9.5. RECOMMENDATION FOR FUTURE WORK

The need for more work raised throughout the work in the different stages of this research to fill in more gaps and satisfy more questions, include:

- Users' survey is essential to investigate their perception of the delivered illuminance by HLS in both the hybrid case and daylighting case.
- More field measurements of light delivery in different locations are suggested to validate energy savings studies.
- Regular updates are recommended for the costs and benefits analyses with the recent tangible costs and benefits, and more rational intangible costs and benefits. That leads to the need for more research to quantify the productivity gain due to the utilization of daylighting systems, and to what extend the effect of the absence of a visual contact with the outside view is.
- Laboratory studies are required to investigate the light quality in terms of changes in daylight spectrum delivered by different HLS technologies, the effect of mixing with electric light, and how the mix can optimize to keep daylight characteristics.
- The output devices used in the high concentrating systems need to be developed to provide more uniform planar distribution.
- Tracking systems, especially in the in-enclosure collectors, need more development to increase their tracking limit.
- Development of architectural-oriented alternatives is needed, especially for none or low concentrating systems mounted on the facade, to enhance their integration capability with building systems and elements.
- More photometric measurements are required to develop HLS design methods.