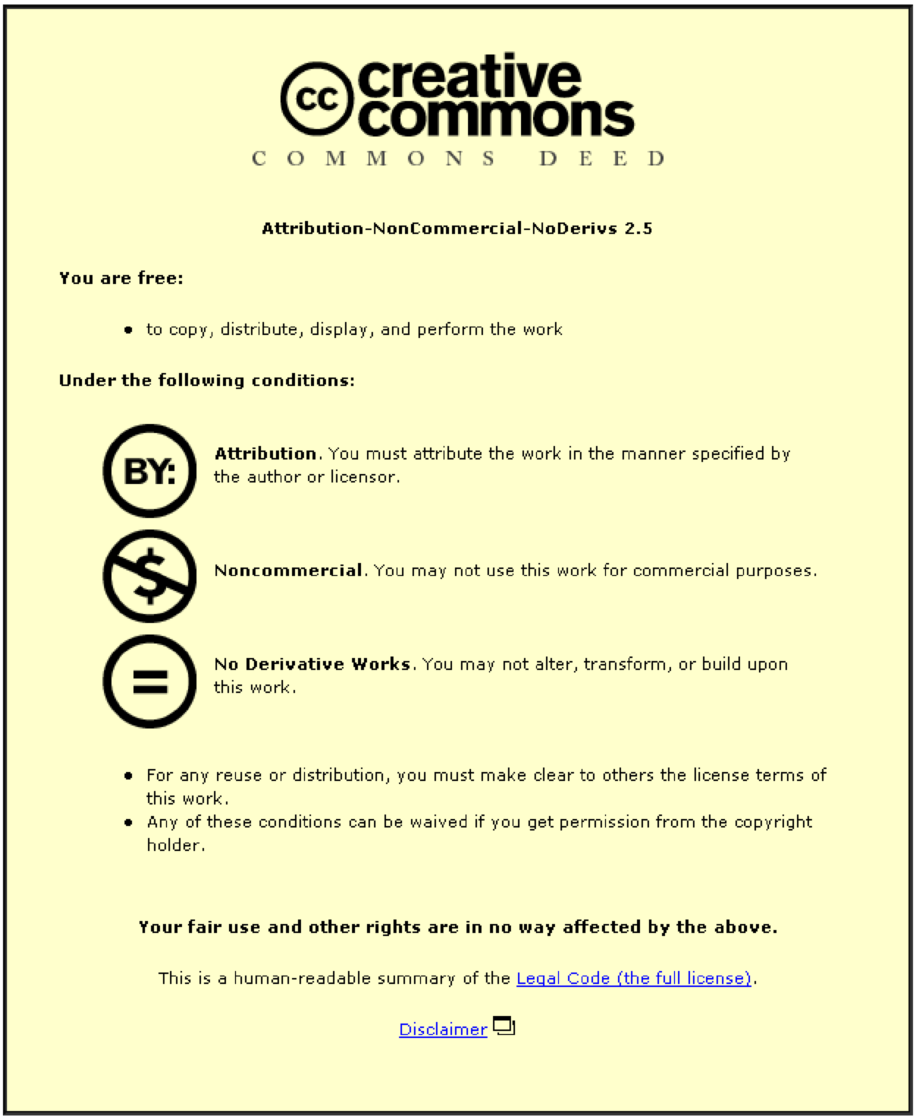

Incorporation of Therapeutic Effect of Daylight in the Architectural Design of In-patient Rooms to Reduce Patient Length of Stay (LoS) in Hospitals

By

Md. Ashikur Rahman Joarder

A Doctoral Thesis

Doctor of Philosophy of Loughborough University

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Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

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Dedicated to my parents and wife

Abstract

The biological need for lighting by an individual differs from the merely visual purpose, such as viewing objects and doing work or movement. Lack of adequate daylight for biological stimulation can lead to health problems, for e.g. imbalanced circadian rhythm. The importance of daylight is vital for hospital patients who are mostly physically and/or psychologically stressed. As, many patients stay indoors for 24 hours, they might be vulnerable to the lack of daylight which is necessary for health reasons. Hence, for hospital patients, daylight can be a strong therapeutic environmental design element to ensure good health and accelerate clinical recovery. The complex relationship between daylight environment and individuals' responses are not fully understood. Controversy results that are debated by the previous researchers, has made the implementation of daylighting strategies in the architectural design of hospital in-patient rooms critical, mainly for therapeutic purpose. Strong evidence needs to be established that can build confidence to both architects and policy makers to use daylight for therapeutic purpose and integration of therapeutic effect of daylight to in-patient room architecture is necessary as well. This thesis provides information to architects (with examples) for incorporation of therapeutic effect of daylight in the design of in-patient rooms to reduce patient length of stay (LoS) in hospitals.

A triangulation research method was applied in this work, where theories were developed qualitatively and tested quantitatively. Literature review was carried out to establish the potential effect of daylight on patient health. Retrospective field investigations were conducted to establish the quantitative relationship between daylight intensity and patient LoS inside in-patient rooms by developing Multiple Linear Regression (MLR) models under a general hospital environment. Using the daylighting goal to enhance therapeutic benefit for hospital patients, referred from literature and verified from field investigation data, a daylight design concept (sky window configurations) was developed and evaluated by prospective simulation study, and found better compared to traditional standard hospital window configurations, in order to enhance therapeutic benefit for hospital patients. A dynamic annual Climate-Based Daylight Modelling (CBDM) method that uses RADIANCE (backward) raytracer combined with a daylight coefficient approach considering Perez all weather sky luminance model (i.e. DAYSIM), was used for simulation analysis.

This thesis develops strategies for architects to incorporate therapeutic effect of daylight in the architectural design of hospital in-patient rooms, including guidelines to support architectural decisions in case of conflicting situations, and to identify the range of daylight intensities within which patient LoS is expected to be reduced. The strategies also consider the ultraviolet radiation (UVR) protections and discuss the challenges of climate change for daylight researchers for the incorporation of therapeutic effect of daylight in the design of hospital in-patient rooms.

The thesis provides a contribution to knowledge by establishing strong evidence of quantitative relationship between daylight and LoS, and by presenting new architectural forms for hospital in-patient room design as one of the possible ways to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms effectively. It is expected that the research will encourage and help architects and policy makers to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, efficiently.

Keywords: daylight, hospital, in-patient room, therapeutic environment, evidence based research, MLR model, CBDM simulation.

Acknowledgement

I would like to thank every people who have supported me for completing this PhD research.

In the first instance, I would like to thank my supervisor, Professor Andrew Price, for his advice, guidance, suggestion and support throughout the course of the study without which this thesis would not have been completed. It was a great pleasure to work with him and I have learned a great deal from him, in terms of both academic and practical life.

I am most grateful to Square Hospital Ltd. (SHL), Dhaka, Bangladesh, where my field data collection was took place. I want to express deep appreciation to Mr. Tapan Chowdhury, Managing Director, SHL, for extending his kind consent on conducting the study in the hospital; Dr. Amer Wahed, Associate Medical Director, SHL, for his tireless faith and support throughout the study beyond expectation; Engr. Md. Yousuf Ali Prodhan, Manager, Engineering Services, SHL, for giving his time and extend his support for collecting environmental data in hospital building and supplying all relevant information about hospital building, especially for his enthusiastic passion for research work beyond his official responsibility; Prof. Dr. Md. Aminul Islam Khan, Consultant, Pathology & Laboratory Services, SHL, and Dr. Mohammad Iqbal, Clinical Governance (Audit & Research), EMAS NHS Trust, Lincolnshire Divisional HQ, Lincoln, for their help and advice; Dr. M. Akhter Hossain, Consultant, Cardiac Surgery, SHL; Dr. Kamal Pasha, Specialist Cardiologist, SHL; Dr. Md. Moynul Islam, Resident Medical Officer, Cardiovascular Surgery, SHL; and Dr. Anu Shrestha, Resident Medical Officer, Cardiovascular Surgery, SHL, for giving me time in continuous discussions on health and medical issues; Engr. Seikh Nazmul Tariq, Co-ordinator Maintenance, SHL; and Sister Shanchita, Head Nurse, Cardiac In-patient Unit, SHL, for their cooperation at different times; Mohammad Nasimul Wahab and Md. Shah Jalal, Medical Record Officer, Medical Record Dept., SHL; and Mr. Ashfaq, Mrs. Monjila and Mr. Sukanto Adhikary, Medical Record Attendant, Medical Record Dept, SHL, who helped make the data collection of my research possible; and finally all unidentified patients who agreed to be a part of this study.

I owe a debt of gratitude to my M.Arch supervisor, Professor Zebun Nasreen Ahmed, Head of the Department of Architecture, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh to boost my research interest to daylighting.

I also express my thanks to a number of colleagues at the School of Civil and Building Engineering, Loughborough University for their support at various occasions. My warm thanks also go to many others living in Loughborough, as well as those living in Bangladesh for their assistance, suggestions and encouragements.

Finally, I am forever thankful to my family, in particular my parents and my wife for their understanding, endless patience, encouragement and love. I am indebted to my own daughter who had to endure my absence for most part of the duration of this PhD programme.

Thanks to Loughborough University, the Health and Care Infrastructure Research and Innovation Centre (HaCIRIC), and the Engineering and Physical Sciences Research Council (EPSRC) for funding this research project.

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List of Abbreviations

ADB	Activity Data Base
AGS	Architectural Graphic Standards
AIA	American Institute of Architects
ALOS	Average Length of Stay
AM	Ante Meridiem (before noon)
ARI	Art Research Institute
ARPNSA	Australian Radiation Protection and Nuclear Safety Agency
ASD	Atrial Septal Defect
ASTM	American Society for Testing and Materials
BMI	Body Mass Index
BMS	Building Management Systems
BST	British Summer Time
CABG	Coronary Artery Bypass Graft
CAD	Computer Aided Design
CBDM	Climate-Based Daylight Modelling
CBPD	Centre for Building Performance and Diagnostics
CCU	Coronary Care Unit
CCV	Cancer Council Victoria
CIBSE	Chartered Institution of Building Services Engineering
CICU	Cardiac Intensive Care Unit
CIE	International Commission on Illumination
CNS	Central Nervous System
CRF	Chronic Renal Failure
CRS	Creative Research Systems
CSICU	Cardiac Surgical Intensive Care Unit
CT ICU	Cardio-Thoracic Intensive Care Unit
CVD	Cerebral Vascular Diseases
DA	Daylight Autonomy
DAmax	Maximum Daylight Autonomy
DEFRA	Department for Environment, Food and Rural Affairs
DH	Department of Health
DM	Diabetes Mellitus
DSYs	Design Summer Years

EDC	Environmental Data Compendium
EF	Ejection Fraction
ER	Emergency Room
FBS	Fasting Blood Sugar
FNAC	Fine Needle Aspiration Cytology
FS	Finkelstein -Schafer
GABA	Gamma-Aminobutyric Acid
GHG	Greenhouse Gas
GMT	Greenwich Mean Time
HBN	Health Building Note
HEI	Horizontal Exterior Illuminance
HIV	Human Immunodeficiency Virus
HR	Heart Rate
HPA	Health Protection Agency
HTM	Health Technical Memoranda
HTML	HyperText Markup Language
ICU	Intensive Care Unit
IESNA	Illuminating Engineering Society of North America
IPCC	Intergovernmental Panel on Climate Change
IVF	Invitro Fertilization
LEED	Leadership in Energy and Environmental Design
LoS	Length of Stay
lx	Lux
LRC	Lighting Research Centre
MAP	Mean Arterial Pressure
MI	Myocardial Infarction
MLR	Multiple Linear Regression
MM	Malignant Melanoma
NHL	Non-Hodgkin’s Lymphoma
NHS	National Health Service
NICU	Neonatal Intensive Care Unit
nm	Nanometre
NMHA	National Mental Health Association
NMSC	Non-Melanoma Skin Cancers
OBGYN	Obstetrics and Gynaecology
OBS	Ott Biolight Systems
OPD	Outpatient Department

OR	Operating Room
PICU	Paediatric Intensive Care Unit
PM	Post Meridiem (after noon)
POV	Provision of Outdoor View
RERC	Renewable Energy Research Centre
RH	Relative Humidity
SAD	Seasonal Affective Disorder
SADA	SAD Association
SAS	Statistical Analysis System
SCN	Suprachiasmatic Nucleus
SGM	Solatube Global Marketing
SHL	Square Hospital Ltd.
SICU	Surgical Intensive Care Unit
SLL	Society of Light and Lighting
SPO2	Saturation of Peripheral Oxygen
SPSS	Statistical Package for the Social Sciences
SRES	Special Report on Emissions Scenarios
TCAs	Tricyclic Antidepressants
TIA	Transient Ischaemic Attack
TMY	Typical Meteorological Year
TMY2	TMY, version 2
TOMS	Total Ozone Mapping Spectrometer
TRYs	Test Reference Years
TTTA	Taylor Technical Talent Award
UDI	Useful Daylight Illuminances
UKCIP02	United Kingdom Climate Impacts Programme 2002
UKCP09	United Kingdom Climate projection 2009
UPF	Ultraviolet Protection Factor
UV	Ultraviolet
UVA	Ultraviolet A
UVB	Ultraviolet B
UVC	Ultraviolet C
UVR	Ultraviolet Radiation
WC	Water Closet
WCI	Weather Channel Interactive
WG	Weather Generator

CHAPTER 1
Introduction

1.1. Introduction

This chapter introduces the thesis and provides a brief background and justification of this PhD research. The aim and objectives of the research are stated in this chapter. An overview of the research methodology to achieve the aim and objectives is presented. Scope and limitations of the present research activities are mentioned. The chapter ends with a guide to the reader and key findings of the research are presented related to objectives, chapters and publications during the research period.

1.2. Background

In order to emphasise impact of buildings on people a former British Prime Minister Winston Churchill stated, ‘First we shape our buildings; thereafter, they shape us’ (White, 2006: p.14). Dr. Ilona Kickbush, former WHO's (World Health Organization's) director of Health Promotion further highlighted that ‘Health isn't created in hospitals or doctors' offices... We can create health by actually changing the institutions and environments in which people spend a major part of their day’ (Flower, 1994: paragraph 67). These are the simple concept of a therapeutic built environment which is often difficult to implement into practice.

In traditional healthcare design, functional efficiency, costs, sterilisation (Dutro, 2007), medical treatments and technology were most emphasized compared to psychological and social needs of patients. As a result, instead of calm surroundings, functional emphasis often produced hospital environment institutional, lifeless (Dutro, 2007), stressful and harmful for patient care (Eriksen, 2001; Ulrich, 2000, 1992; Horsburgh, 1995). With better realisation of the effects of healthcare architecture on medical outcomes, interest grows to treat hospital physical environment as ‘therapeutic environment’ (Gesler et al., 2004) and therapeutic design of hospital building become important, not only for architects, but to policy makers, investors and medical professionals (Ulrich, 2003).

The use of daylight for therapeutic environment design is relatively new and unexplored area of research (Pechacek, 2008). The importance of daylighting for hospital in-patient room design can be viewed from two major perspectives: energy perspective and health perspective (Rogers et al., 2006). Before the 1940s, daylight was the primary light source in buildings, and artificial light was used to supplement the natural light. In a short span of 20 years, electric lights were used to satisfy most lighting requirements of building occupants (Edwards et al., 2002). The arrival of fluorescent lighting and cheap energy allowed deep-planned, fully air-conditioned and mechanically ventilated buildings with sealed windows to be built within expensive, dense, noisy and polluted urban sites. Daylight, during this period, was no longer a critical design element and external walls usually had fewer windows, even no windows or, in case of glass curtain walls, full windows. Nevertheless, this phase was short-lived. Two factors that encouraged the return to natural light and ventilation in buildings were the 1970s energy crisis together with the realization of the damage to the biosphere by greenhouse gas (GHG) emissions (ERG, 1994), which became the main driving forces for daylight building design. The initial aim of daylight design was to reduce the use of electric lighting for energy conservation and get the environmental benefits.

Almost as a side issue, in the late ‘70s and early ‘80s human health and performance benefits of existing daylit buildings came to the focus (Ternoey, 1999). The health and performance of people in buildings became the major issue with the realisation that the costs of individuals (performance and/or productivity) in buildings are often 75 to 100 times greater than the cost of utility bills. These health and performance benefits developed into the main focus of 1990s daylighting research and experimentation (Ternoey, 1999). Due to the increasing realisation of the healing powers of nature on individuals’ health and wellbeing, daylight has become an important element for therapeutic environment design (Baker et al., 2002) and should be a prime concern when it is related to healthcare design and patient health.

Dr Mark Rea, of the Lighting Research Centre said that: “The last 25 years of research is now challenging our traditional definition of what constitutes ‘good lighting’. Vision-based lighting design neglects what recent research has found” (Beales, 2003: p.1). The major technical difference between lighting requirement for visual and health purposes states that, to make an object visible light is need to be incident on the object first and then needed to be reflected towards the eyes. On the other hand light is needed to be incident on individual’s body, for example eye and/or skin directly, to start biological stimulation inside human body (Wurtman, 1975). Requirements of daylight from health perspective (e.g. biological needs for lighting) are different from visual needs (Pechacek et al., 2008). Lack of adequate daylight for biological stimulation can lead to health problems, such as depression and imbalanced circadian rhythm (CIE, 2004; Begemann et al., 1997). It is important to ensure proper daylighting for physiologically and/or psychologically stressed hospital patients, as majority of them stay indoor for 24 hours for several days and likely to be affected by a lack of daylight needed in 24 hour diurnal cycle. Therefore, daylight can be a strong therapeutic environmental design element to ensure good health, and accelerate clinical recovery of hospital patients.

1.3. Justifications

Research in the therapeutic built environment indicates that hospital design has more importance to patient, staff and visitor experiences compared to the past (White, 2006). Global awareness developed among medical professionals and healthcare administrators for functional and supportive healing environments for patients (Ulrich, 1991), especially for visual environment. The U.S. Green Building Council Research Committee (2008) in their report titled, ‘A National Green Building Research Agenda’ described a number of subjects as priority topic for lighting research. One of the priority topics for lighting research was to quantify the impact and mechanism of daylight on individual occupants’ health and performance to develop architectural design guidelines for different daylight strategies that can maximize human health, comfort and performance.

In an update of the American Institute of Architect (AIA) Guidelines for Design and Construction of Health Care Facilities, the Environmental Standards Council of the Centre for Health Design drafted and submitted outlines for environmental factors that contribute to the satisfaction of patients, staff and visitors, and were unanimously accepted by the Committee (AIA, 2006). Because of these new additions, daylight is recommended for the positive health benefits of patients and staff in healthcare facilities (Smith, 2007).

The therapeutic environment depends on physical, social and symbolic design of hospital buildings (Gesler et al, 2004). Many studies, namely Park (2006) and Walch et al. (2005) have shown that built environment has an influence on anxiety, blood pressure and pain levels of individuals. Researchers also explored link between poor psychosocially unsupportive surroundings and negative effects, for example longer hospital stays, elevated depression, higher occurrence of delirium and greater need for pain drugs (Ulrich, 1991; 1992), however, the complex relationships between environmental stimulus and individual responses are not fully understood (Gesler et al, 2004; Leather et al., 2000; Canter et al., 1979) and many healthcare environmental design related questions are still unanswered (Dutro, 2007). The debate continues on the mechanism and evidence of health impact due to daylight (Loftness et al., 2006). To prove that better light could increase muscle strength, Ott (1982) used kinesiology tests, but Jewett et al. (1985) argued that light does not have this effect and Ott's method of testing altered the experimental results. Jewett et al. (1985) concluded that psychological effects could obscure any true effect of lighting (Edwards et al., 2002). Ulrich et al. (1984; 1991; 1993) completed three important studies on therapeutic environment, but his methodology of measuring the anxiety levels were questioned by other researchers (Weber, 1996; Devlin et al., 2003), because of the unpredictable recovery profile of critically ill patients and the number of variables analysed by Ulrich (HBN-04, 1997). The work of Ulrich (1984), Mendell (1991) and Kellert (2005) are equally debated to identify the link between importance of views of nature and reduction of patient stay time after surgery, sick building syndrome, overall emotional health and the importance of biophilia (Loftness et al., 2006). As the costs of medical treatment and healthcare construction are rising each year, key stakeholders demand to ensure that every design decisions should benefit the patients and total healthcare systems. Due to lack of strong evidence, some authorities and decision makers in healthcare community are least convinced on the effects of physical environment on the recovery process of patients (Mobach, 2004). Strong evidence need to be established that can build confidence to both architects and policy makers to use daylight for therapeutic purpose and then integration of therapeutic effect of daylight to building architecture is necessary.

In a study of hospital lightings in UK, it was found that the quality of hospital visual environment is poor due to concentration only on basic requirements for task illumination (Loe et al., 2000), without considering the other aspects of lighting, for example aesthetic and therapeutic. Some basic design guidance on the use of lighting is necessary to ensure optimal, functional, ambient, comfortable and therapeutic environment for patients and other users of hospital buildings (Dalkea et al., 2006). Non-professional decision-makers in the construction and refurbishment of healthcare building projects often require more guidance on lighting design strategies, however, guidelines and information for design of the luminous environment of hospital buildings are not available in a user friendly and accessible format (Dalkea et al., 2006). According to Dutro (2007: p.8), ‘Without research based data, the designer has no guidelines to direct the development of the design’. To generate a positive image of a particular hospital environment, e.g. daylight, the exact specification and configuration of the element in the design of building are necessary. Clear, authoritative and research based guidance on therapeutic lighting specification can improve health and productivity of individuals, and energy efficiency of the building that will reduce the running costs of hospitals (Dalkea et al., 2006), and will result benefits to the patients, medical staff, managers and owners of healthcare facilities (Dutro, 2007), however, the complete daylight requirement, to meet therapeutic need of patients effectively, that can be used as a guideline/reference for hospital design is still underway (Pechacek et al., 2008).

It is an established thought that daylight is an important issue for sustainable building design technique. Nevertheless, the versatility and far-reaching implications of daylight on occupants’ comfort and building energy system have made daylighting a more difficult strategy to implement in practice compared to other energy-saving technologies (Galasiu, 2008). The research on positive responses of daylight on individuals’ psychology (e.g. circadian systems and mental attitude) have been well-advanced and documented without application of the knowledge into architectural design (Pechacek , 2008) for example designing daylit hospitals to accelerate clinical recovery of patients in addition to save energy, is often missing (Beales, 2003). There is also lacking in acceptance and adaptation of daylight design solutions into the current practice, confirmed and recommended by leading practitioners (USGBCRC, 2008). There are several reasons behind this. One of the reasons is that the policymakers and grant givers were less comfortable in funding therapeutic environmental studies conducted by the academic researchers, due to the neglect of pharmaceutical company who are more interested on the development of medicines and medical instruments for treatment compared to development of hospital therapeutic environment. In principle, these practice is boldly against with patients' acceptance, and benefit with daylighting (Wirz, 1998). More research are needed for the improvement of existing hospital built environment to incorporate healing qualities and to define new healing qualities into an established environment based on the patient, staff and visitor experiences (White, 2006). Practical evidences and/or examples of incorporation of therapeutic effect of daylight in the design of hospital buildings are necessary to be established by researchers and professionals.

Human health in the built environment is one of the most critically needed research subject, requiring both extensive experimental and field research efforts. With field experiments, controlled laboratory experiments are needed to be carried out simultaneously to establish the correlations between daylight, as part of therapeutic environment, and health related concerns, e.g. respiratory, digestive, circadian, musculo-skeletal, circulatory and nervous systems (Loftness, 2006). Researchers and designers are not yet very specific about the many physiological impact and impressions of daylight on individuals’ performance (Durak et al., 2007). It is important to investigate the healing effects of daylight in healthcare buildings carefully and scientifically, rather than being the subject of anecdote, personal opinion and unsupported conjecture (Dutro, 2007; Leather et al., 2000).

Not only the environmental researchers but also the hospital authorities, policy makers and pharmacists should realise that architectural design can influence the rate of recovery of patients in hospital rooms. Clinicians should participate in studies related to the impact of architectural built environment on patient health and recovery rate. A finer and detailed objective measurement of the actual physical design of the environment and its relation with clinical recovery are needed to be investigated (Dutro, 2007). These objective measurements then need to be correlated with the subjective outcomes to identify the nature and relative importance of the design elements that are particularly salient in conveying architectural meanings (Leather et al., 2000). Social, political and scientific community should identify the ways and directions for the achievement and implication in this new, emerging, interdisciplinary area of research (Mobach, 2004).

As technology improves, the hospital environment itself should contribute to the patients' recovery. Daylight design can play an important role in this process and should be given careful consideration at the design stage by the architects, clients and policymakers (Brennan, 2007). There are constraints for incorporation of therapeutic effect of daylight in architectural design of hospital in-patients rooms. Following three major constraints were identified in this research as a summary of above discussion and further scopes exist to investigate on these three issues to minimise the research gap.

- Lack of strong evidence (i.e. quantitative relation between daylight intensities and patients stay in hospitals) that can build confidence to both architects and policy makers to use daylight for therapeutic purposes in hospital in-patient room design (Durak et al., 2007; Loftness, 2006; Mobach, 2004; Leather et al., 2000)
- Lack of comprehensive model to meet the therapeutic requirements of daylight (i.e. intensities of daylight that may support to reduce patients stay in hospitals) that can be used as a standard/reference for hospital in-patient room design (Pechacek et al., 2008; Dalkea et al., 2006)
- Lack of evidence or examples that can describe the possible ways to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms (USGBCRC, 2008; Galasiu, 2008; White, 2006).

1.4. Aim and objectives

The aim, objectives and methodology were developed in this research with a desire to overcome the following three constraints mentioned above. The overall aim of the study is to develop strategies for architects to incorporate therapeutic effect of daylight in the architectural design of in-patient rooms that will reduce patient length of stay (LoS) in hospitals. To achieve this aim the following five objectives were developed.

Objective 1: To understand the impact of daylight (positive and negative) on patients' psychological, physical, and physiological health.

Objective 2: To establish quantitative relationship between daylight intensities and patient LoS under a general hospital environment.

Objective 3: To identify the range of daylight intensities within which patient LoS inside in-patient room is expected to be reduced.

Objective 4: To develop a concept to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, effectively.

Objective 5: To conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose.

1.5. Overview of research methodology

A detailed description of the research methodology, used for this PhD research, has been discussed in Chapter 3. This section provides a brief overview of the research methodology for the thesis. A triangulation research method was applied in this research where theories were developed qualitatively and tested quantitatively. Figure 1.1 shows a flow diagram of the research process, which integrates the main research methods: literature review, retrospective field investigation and prospective simulation study.

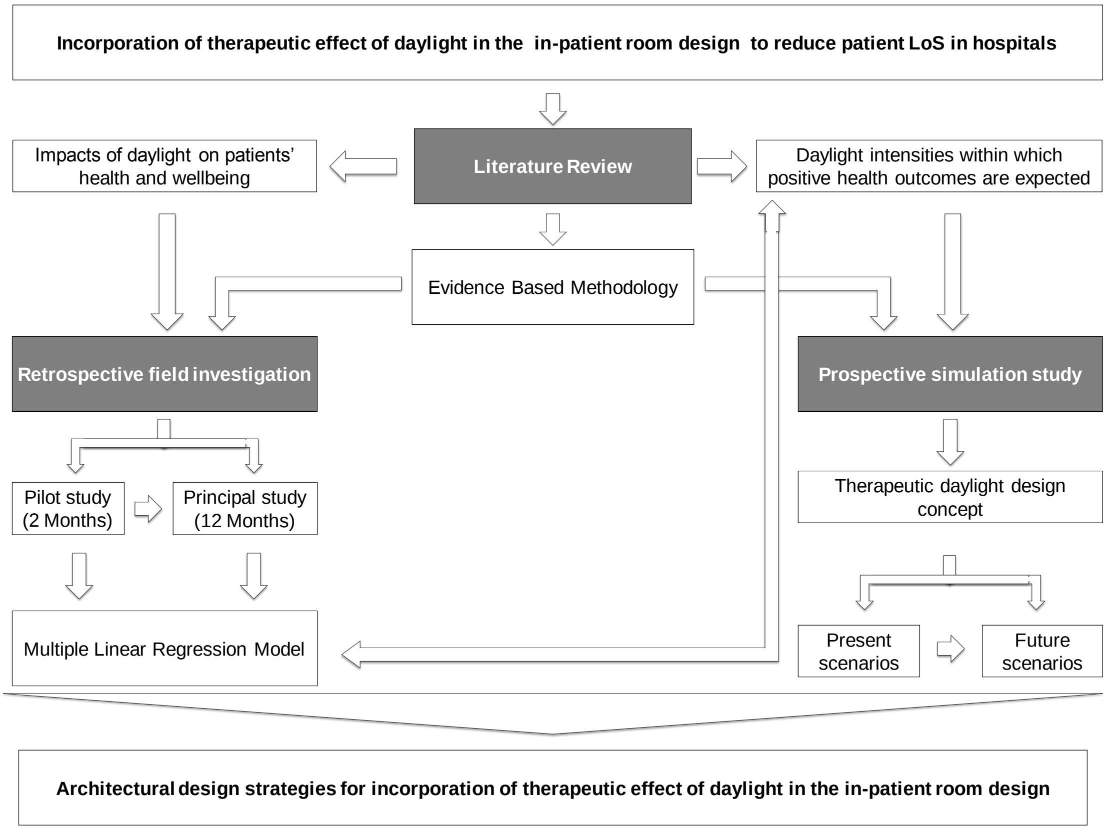


Figure 1.1: Flow diagram of the research process.

The research started with a literature survey. The compilation of primary literature (e.g. Rashid et al., 2008; Ulrich et al., 2004; Rubin et al., 1990) suggests that there is a lack of sound evidence on the impact of daylight on patients' physiological health. To implement daylight strategies within the therapeutic design of most of the hospital buildings, the impact of daylight on patients' physiological health needs to be established based on sound evidence from field, at the beginning. Based on the work of past researchers (e.g. Choi et al., 2012; Dutro, 2007; Park 2006 and Walch et al., 2005), an evidence based methodology was developed for retrospective field investigation to establish strong evidence of the relationship between daylight intensities and patient LoS, with the help of statistical (Multiple Linear Regression (MLR)) models. The developed methodology was successfully tested in this research from a two-month pilot study before starting a one year principal study. The data collected during principal study were also used to generate another MLR model to verify the range of daylight intensities within which positive health outcomes are expected, recommended from past literature before using the values (intensities) as a goal for prospective simulation analysis in this research.

To ensure therapeutic need of hospital patients effectively a conceptual design of window configurations was developed, evaluated and compared with traditional window configurations, located in a standard hospital in-patient room, by prospective simulation study, using the therapeutic goal defined under this research. The therapeutic potentiality of the concept was also evaluated with respect to the future climate change scenarios to conceptualise the impact of climate change on indoor daylight level and its contribution to daylit in-patient rooms, designed for therapeutic purpose. Finally, the experiences of prospective simulation study, the developed MLR models from retrospective field investigation data and findings of literature reviews were compiled to recommend architectural design strategies to incorporate therapeutic effect of daylight on the design of hospital in-patient rooms to reduce patient LoS in hospitals.

1.6. Scope and limitation of the research

The present work, given the time and resource constraints, focuses mainly on therapeutic effect of daylight on hospital patients. To make an objective assessment of the subjective issues related with therapeutic effect of daylight on hospital patients, some level of simplification is necessary (Pechacek, 2008). In the absence of any accepted scale for the measurement of therapeutic effect of daylight, contemporary research (e.g. Gochenour et al., 2009 and Pechacek et al., 2008) consider effective circadian rhythm (biological events that occur at regular intervals) as an indicator of therapeutic effect of daylight. It is also admitted that, in addition to circadian rhythm, multiple mechanism are engaged in improving performance of hospital patients under daylight environment (Lockley et al., 2006), and still researchers are struggling to identify those mechanism (Nelson et al., 2003). The exploration of the complete and accurate biological mechanism as the effect of daylight is somewhat outside of the scope of this research. As it is very difficult, if not impossible, to isolate the effect of daylight on circadian rhythm from other physiological and psychological mechanism, this research focuses on evidence than the mechanism to identify the therapeutic effect of daylight on hospital patients. This research considers reduction of patient LoS in hospitals as the therapeutic effect of daylight (evidenced from field survey of this research). In addition to daylight, to consider impact of other variables on patient LoS, this research considered 30 other variables during data collection of field surveys: 20 clinical variables (e.g. arterial pressure, heart rate, respiratory rate, body temperature, smoking habits, hypertension, dyslipidaemia and diabetes mellitus); five demographical variables (i.e. gender, age, weight, height and body mass index) and five environmental variables (e.g. room type, room temperature, relative humidity, rent of the room and outdoor view). However, several human factors (e.g. individual daylight preferences, physiological conditions and activities inside in-patient rooms) and non-clinical variables (e.g. related with patient's family, profession, social and cultural differences) might have impact on patient LoS; those were not considered due to limited access to patients, unavailability of information and time.

Due to the limited number of completed studies that measured the therapeutic effect of daylight on hospital patients objectively related to physiological diseases, critical review of this research was confined with few research (e.g. Pechacek, 2008; Dutro, 2007; Park 2006; Walch et al., 2005 and Choi, 2005) including some Masters research (e.g. Pechacek, 2008; Dutro, 2007 and Choi, 2005) to identify the status of current research design methodology and develop evidence based methodology for data collection and analysis, and simulation study. The fundamental outputs of some of these Masters research was published later in reviewed journals (e.g. Choi et al., 2012 and

Pechacek et al., 2008) and the references were updated accordingly in this PhD research.

Strategies and recommendations based on this research were made to be easily applicable for designing hospital in-patient rooms with simple passive technologies to save active energy (i.e. electricity). Most of the high-tech solutions such as Building Management Systems (BMS) and Intelligent Buildings in the control systems were not included in this research. The recommendations of this research may form the basis of further research to introduce automated high-tech solutions to incorporate therapeutic effect of daylight in the design of in-patient rooms based on these initial findings.

Besides improving the therapeutic environment of hospital rooms, daylighting is also associated with aesthetics, energy consumption (electric lighting, mechanical heating and cooling), heat loss and gain, ultraviolet radiation (UVR) gain, glare control, ventilation, sound transmission, costs, safety, security, and subjective concerns of privacy and view. The provision of outdoor view (POV) has been considered during field investigation, possibilities of discomfort have been analysed during simulation study and protection from UVR based on available technology has been considered in this thesis to recommend architectural design strategies. In the constraint of available time and other resources required for such an extensive investigation, the consequences of daylight inclusion on energy savings, heating, ventilation, cost benefit analysing and other variables/parameters associated with change of daylighting mentioned earlier were beyond the scope of present research. This study was limited to contend with the therapeutic daylighting potentiality inside in-patient rooms of hospital buildings. It is expected that the research would be used as a basis for further research to investigate the consequences of other effect of daylight inclusion inside hospital rooms (e.g. temperature and comfort level) in addition to the reduction of patient LoS.

1.7. Structure of the thesis

This thesis is organised into seven chapters. This section provides an overview of each following chapters.

Chapter 1 is an introduction to the thesis; describes the justification of this research with the aim, objectives, brief methodology and key findings under limitations.

Chapter 2 presents the outcomes of the literature review under three major concerns. The first part identifies the knowledge gap by relating the consequences of the direct and indirect effects of daylight with evidence of psychological, physical and physiological benefits of patients under healthcare settings. The second part presents the adverse impact of excessive daylight on health. The third part highlights, the possibilities of increasing the adverse impact of daylight due to climate change.

Chapter 3 contains the detailed steps of the methodology used in this research. The outputs of two methods applied in this research have been presented in Chapter 4 (retrospective field investigation) and Chapter 5 (prospective simulation study).

Chapter 4 reports the activities and findings of two field studies: pilot study and principal study. This chapter consists of three major parts. The first and second parts describe the activities of pilot and principal studies to explore the relationship between daylight intensities and patient LoS inside hospital rooms. The third part describes the experiment which was conducted to verify the intensities of daylight under which reductions in patient LoS are expected, recommended from previous literature identified in Chapter 3 and later used as goals for simulation exercises in Chapter 5.

Chapter 5 contains the descriptions and outputs of simulation exercises done during this PhD research. This chapter consists of major two parts. The first part shows how therapeutic effect of daylight can be incorporated in hospital in-patient room design by evaluating a concept developed in this research and compared with the standard typical window configurations for hospital in-patient rooms, using the simulation goal fixed in Chapter 4. The second part shows the performance of the concept under different climate change scenarios.

Chapter 6 discusses the architectural design strategies for incorporation of therapeutic effect of daylight in the design of hospital in-patient rooms to improve patients psychological, physical, and physiological health with respect to the extended outputs of the of the developed MLR models from retrospective field investigation data described in Chapter 4 and experiences of prospective simulation study done in Chapter 5 of this thesis with consideration of some issue, such as vitamin D metabolism and UVR protection, highlighted in the literature review of Chapter 2.

Chapter 7 concludes this thesis with a brief summary and discussion of the key findings of the research, strategies for therapeutic daylit hospital in-patient room design, key contributions to knowledge and recommendations for further research.

Figure 1.2 shows organisation of the chapters and structure of the thesis.

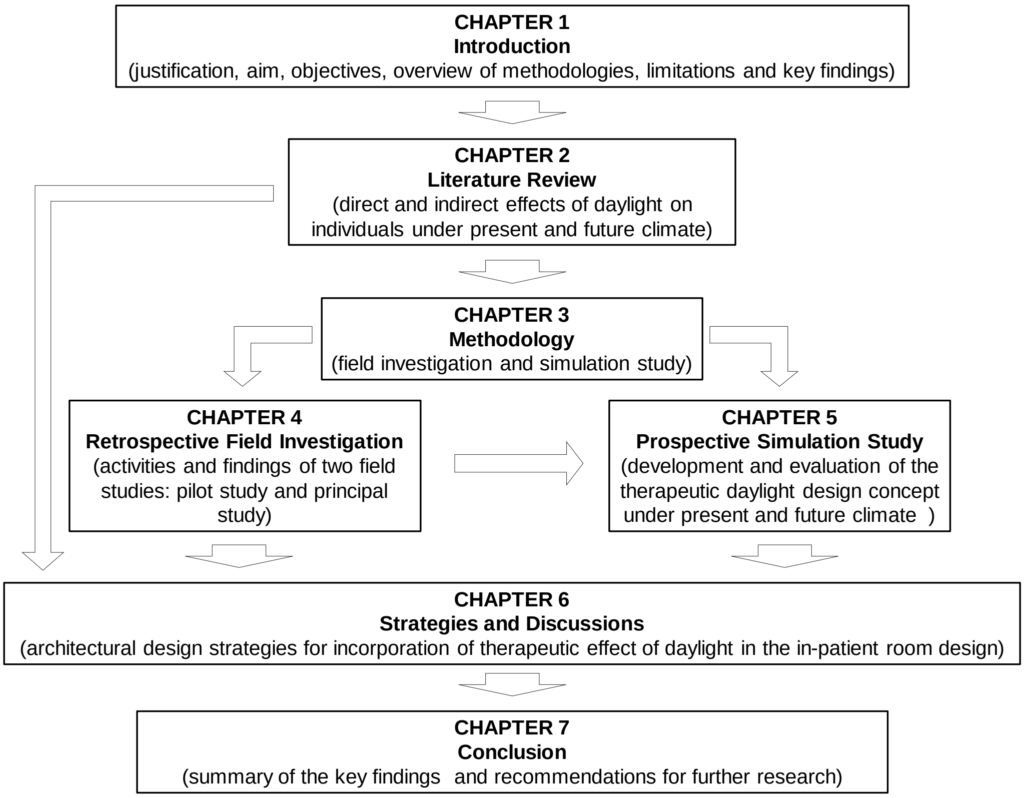


Figure 1.2: Organisation of the chapters and structure of the thesis.

1.8. Key findings

The research started to overcome some constraints mentioned at the end of Section 1.3. With the gradual development of the research from the literature review and incorporation of research findings at each stage made objectives, methodology and limitations of the research more defined, refined and detailed. The publications of the initial research outputs at different stages helped the researcher to get the blind review of some external experts and update the research, particularly the methodology, applied in different stages of this research. Presentations of papers and posters at major research events (see, Appendix G) and responses from audiences provided the opportunities to know the opinions of both academic and professional bodies about this research and to develop new ideas. Table 1.1 summarises the key findings of the research in relation to the objectives, methodologies, the concerned chapters and related publication outputs.

Table 1.1: Summary of the key findings of the research in relation to the objectives, methodologies, concerned chapters and related publication outputs.

Objectives		Methodology	Chapters	Key findings	PhD research time publications
1	To understand the impact of daylight (positive and negative) on patients' psychological, physical, and physiological health.	Literature Review	Chapter 2: Literature Review	For an overall progress of hospital patients' health, both psychological and physiological improvements are necessary. Impact of daylight on patients' psychology and physical diseases related to bones and cancers are well established. The physiological impact of daylight on patient LoS needs to be established based on sound evidence.	• Conference Paper (2009). A Systematic Study of the Therapeutic Impact of Daylight Associated with Clinical Recovery. HaCIRIC PhD workshop, 2nd Annual International Conference, 1–3 April, Brighton, UK, pp.25–31. • Conference Paper (2009). The Changing Perspective of Daylight Design to Face the Challenge of Climate Change. 3rd CIB International Conference, SASBE, June 15–19, Delft, The Netherlands.
2	To establish quantitative relationship between daylight intensities and patient LoS under a general hospital environment.	Field Investigation	Chapter 4: Retrospective Field Investigation	The coefficient estimates of MLR models derived from real-world field data suggest that while holding the other explanatory variables (e.g. POV and blood pressure) constant, the patient LoS reduced by 4-8 hours per 100 lx increase of daylight inside hospital rooms.	• Journal Paper (2012). Impact of Daylight Illumination on Reducing Patient Length of stay (LoS) in Hospitals after CABG Surgery. Lighting Research & Technology. [in press]. • Journal Paper (2010). Access to Daylight and Outdoor Views: A comparative study for therapeutic daylighting design. World Health Design, 3 (1), pp.62–69. • Journal Paper (2009). A Survey on Daylighting Potentiality in the offices of Dhaka Bangladesh. Global Built Environment Review (GBER), 7 (1), pp.5–22. • Conference Paper (2012). Therapeutic Daylight for Hospital Patients: A Search for the Benchmarks". European Conference on Design for Health, July, Sheffield, UK. [in press]. • Poster (2009). Implementation of Therapeutic Daylight on Hospital Design to Accelerate Clinical Recovery: A Search for Knowledge Gap and Development of an Evidence Based Methodology. ACHSE National Congress, 4-7 August, Gold Coast, Australia.
3	To identify the range of daylight intensities within which patient LoS inside in-patient room is expected to be reduced.			The patients, who experienced higher (above 2000 lx) and lower (below 190 lx) levels of daylight in the maximum time inside hospital in- patient rooms, needed significantly more time (extra 29-42 hours) to recover compared to the patients who experienced moderate levels of daylight (between 190 lx to 2000 lx) throughout their stay inside in-patient rooms .	

Table 1.1: (continued)

Objectives		Methodology	Chapters	Key Findings	PhD research time publications
4	To develop a concept to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, effectively.	Simulation study	Chapter 5: Prospective Simulation Study	A specially designed 45^0 inclined high window (Sky Window) configurations performed better than traditional typical standard hospital window configurations in order to enhance therapeutic effect of daylight inside in- patient rooms more effectively.	• Conference Paper (2012). Daylight Simulation in Architectural Practice: Shading Design for Hospitals in London". International Seminar on Architecture: Education, Practice and Research, 02 - 04 February, Dhaka, Bangladesh. [in press]. • Journal Paper (2012). Impact of Climate Change on the Constructed Luminous Environment: An Evaluation for the Hospital In-patient Rooms Located in London". The International journal of the Constructed Environment. [in press]. • Conference Paper (2009). A Simulation Assessment of the Height of Light Shelves to Enhance Daylighting Quality in Tropical Office Buildings under Overcast Sky Conditions in Dhaka, Bangladesh. 11th IBPSA Conference and Exhibition, 27–30 July, Glasgow, UK, pp. 1706 – 1713. • Conference Paper (2009). Daylight Simulation for Sustainable Urban Office Building Design in Dhaka, Bangladesh: Decision-making for Internal Blind Configurations. 2nd SUE-MoT International Conference, 22-24 April, Loughborough, UK, pp.218–241. • Poster (2011). Daylit Hospitals to accelerate clinical recovery. Health and Life Sciences Research Student Conference, Loughborough University, 14 March, Loughborough, UK. • Poster (2010). Use of Daylight to Accelerate Clinical Recovery. Poster Competition for PGRs, Loughborough University, 7 May, Loughborough, UK. • Poster (2009). Innovative Healthcare Design with Daylighting to Support Clinical Recovery. Engineering and Physical Sciences Research Council (EPSRC) Panel Review, University of Reading, Reading, UK, 23 September.
5	To conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose.			The average indoor illumination at test point (patients head) can raise a maximum 8% in the future (2080-2100) compared to the present (1983-2004). To protect the indoor from increased daylight levels, internal blinds will be needed to shut down more often/ time during day hours, which might create a negative impact on patient LoS due to lack of POV.	

CHAPTER 2
Literature Review

2.1. Introduction

The first chapter introduces the research. This chapter discusses the outcomes of the literature review to identify the positive and negative impacts of daylight on individuals' health under the present and the future climate change scenarios. This chapter consists of major three parts. The first part mapped a chain of consequences of the effects of daylight on human body starting from biological effects (chemical reactions inside the body), its impact on neuroendocrine systems, circadian rhythms, and Vitamin D metabolisms. This part also relates the findings of biologist about the influence of incident light on the eye and the skin with the evidence of the psychological, physical and physiological responses of individuals as direct and indirect responses to daylight. The first part ended with identifying the existing knowledge gap that needs to be reduced to incorporate therapeutic effect of daylight in the design strategies for hospital in-patient rooms. The second part presents the adverse impact of excessive daylight on health. The third part highlights the possibilities of increasing the adverse impact of daylight due to rapid climate change. The strategies under the references of the literature reviews of this chapter have been discussed in Chapter 6 and key findings have been presented in concluding Chapter 7.

2.2. Background

The idea of supportive hospital design to accelerate clinical recovery has a long history (Leather et al., 2000) from Florence Nightingale's (1863) observation that 'a variety of form and brilliance of colour in the objects presented to patients are an actual means of recovery' (Dalkea et al., 2006: p.343) to contemporary research by MIT Daylighting Lab (MITDL, 2011) to identify potential of daylight for individuals' biological needs.

In the arena of scientific research, in early 1980s, Ulrich (1984) first investigated the idea of architectural decision making for hospital design, based on medical evidence (Mobach, 2004). Ulrich (1984) reported that patients with a tree views spent less time in hospital rooms than those with views of a brick wall through their windows. This specific study formed the starting point for new research, termed ‘evidence-based design’ and also known as the design of ‘healing environments’ (Mobach, 2004) or ‘therapeutic environments’. As a follower, many researchers studied the impact of other variables on patient health and wellbeing such as noise, music, room brightness, and pictures on the wall (Donabidian, 1998).

To evaluate the status of research on therapeutic built environment, at the end of 1990s the Centre for Health Design commissioned an impartial group of researchers, led by Dr. Haya Rubin at the Johns Hopkins Medical School. The researchers examined 78,761 articles to search for different environmental variables that are related to patient health and recovery. The reviewers found only 84 articles published in the medical and design literature from 1970s that contain relevant data (Rubin et al., 1998), and rest of the articles were poorly designed from a methodological point of view (Devlin et al., 2003). Their review presents an idea of the status of the research on therapeutic built environment at a glance. Based on 84 selected studies the investigators concluded that there is enough evidence exists to rationalize that the built environments impact significantly on patient clinical recovery (Ulrich, 2000).

In 2004, a research team from Texas A&M University and Georgia Tech published a review report on impact of built environment on health outcomes (Ulrich, 2004). The team went through several thousand scientific articles including more than 600 studies from top peer-reviewed journals. The team found scientific evidence of the impact of design variables such as room type (single-rooms versus multi-bed rooms), noise, lighting, ventilation, ergonomic designs, supportive workplaces and plan layout linked with reduction of errors, stress, sleep, pain, drugs, and other hospital and health outcomes for patients. Scientific literature confirmed therapeutic built environment is an important issue to make hospitals safer, more healing and healthier place for patients’ then the conventional ways of hospital design (Ulrich, 2004).

As a summary of the above mentioned studies, it can be said that the concept of designing therapeutic built environment is not at all new (Francis et al, 1999). A significant number of articles and research reports have been published on therapeutic built environment, though there are questions about the outcomes. Different fields of therapeutic environmental variables (e.g. noise, lighting, ventilation and view) are not equally developed and researched.

In particular about daylight research, evidence suggests that patient visualisation and perception of the hospital environment impact on health and wellbeing, however, the complex relationship is not yet fully understood (Gesler et al., 2004). The number of evidence based scientific research, focused only on the effect of daylight on patients' recovery as a part of therapeutic built environment is few in number (Rubin et al., 1998) due to the versatility and far-reaching and complex implications of daylight (Galasiu et al., 2008) on patients comfort and recovery. In most of the studies, the effect of daylight on patient health was considered as a secondary observation within wider research on natural views, aesthetics or artificial lighting with higher intensity. The information related to daylight in hospitals are spread over a wide range of articles, papers and research reports published in architecture, medicine, ergonomics, psychology and lighting design books, journals and periodicals. It is difficult for daylight related research to build upon these fragmented sources. The purpose of this chapter is to understand the impact of daylight on patient health and wellbeing, suggested from previous literatures. It was found from past literature that, some reviews were done either from a biological point of view narrating the inner body mechanism due to the incident of daylight on the eye or the skin (e.g. Wurtman, 1975), or from a therapeutic research perspective compiling the evidence of psychophysical impact of daylight on human mind and health (e.g. Ulrich, 2004; Delvin et al., 2003; Edwards et al., 2002; Rubin et al., 1998). This chapter compiles those diverse research sources and combines the findings of biologists and researchers of therapeutic lighting environment in a line to explore how daylight influences patient health and recovery, gradually from light incident on patients to the evidence of patient health outcomes. The following sections present the impact of daylight on individual health and wellbeing.

2.3. Effect of (day)light on human body

British Standard (BS 8206, 1992) treats daylight as two distinct sources of light: skylight, the diffuse light from the whole sky; and the sunlight, the direct solar beam. However, many research, mostly conducted by clinicians, consider daylight and sunlight as synonyms and describe the effect of daylight as the effect of sunlight. For example, Walch et al. (2005) and Beauchemin et al. (1998) describe the effect of sunlight on patient health, but measured the illumination inside hospital rooms by light meters, which are unable to distinguish between sunlight and skylight and provide the sum of sunlight and skylight measurement. This PhD research describes ‘daylight as the sum of sunlight and skylight’ (Littlefair, 2007: p. 84; Phillips, 2004: p.200; Phillips, 2000: p.223; IEA, 2000: p.8-3; Ganslandt et al., 1992; p. 274), therefore, reviews the effect of daylight/sunlight with its actual meaning, rather than the term used by the previous researchers in their articles.

Daylighting, the technique that optimises the use of natural light to illuminate interiors, is becoming increasingly popular; not only for its ability to transform the visual environment of the room dramatically, but also for its natural healing qualities (SGMI, 2004). The quality and quantity of daylight have major impact on human body. As the effects are less quantifiable, benefits of daylight are often overlooked (Edward et al, 2002). Physiological and psychological impact of daylight is the outcomes of either some hormonal (e.g. serotonin/melatonin) activities or chemical reactions in the blood or skin (e.g. pigmentation). The impact of daylight on the psychological diseases are mostly due to lights incident on the retina of the eye and cause modification of individual endocrine, hormone, and metabolic state (Wurtman, 1975).

With the progress of lighting research, nowadays the impact of daylight has been recognized more than only psychological. Light improves health and recovery rate by affecting the human body chemistry. Terman, et al. (1986) claimed that increased light intensity could reduce the common subclinical problems on hospital patients such as oversleeping, overeating, energy loss and disturbance in concentration. The impact of light on the physical diseases are mostly due to lights incident on the skin that results in production of vitamin D, skin tanning and dissociation of bilirubin (Wurtman, 1975; Kovats, 2008). When daylight incident on the eye and/or the skin of human body, collectively it regulates circadian rhythm, improved motor skills, less physiological fatigue, and the overall improvement of task performance (Joseph, 2006; Clanton et al., 2004), those are vital for patient recovery under hospital environment.

It has been found from several studies that bright daylight has positive impact on health (Ulrich et al., 2004). On the other hand, inadequate lighting can cause moodiness and cravings for carbohydrates (NHS, 2006). Ott identified light as a nutrient for body similar to water or food for metabolic processes (OBS, 1997) and Wurtman (1975) claimed that some of these important biological effects of light on body could be measured in a laboratory. The effects of incident light on body can be categorised in two levels (Edwards et al., 2002; Wurtman, 1975).

a) Indirect effect: when light incident on the eye and generate neural or neuroendocrine signal by the photoreceptor cell.
b) Direct effect: when light incident on the skin and cause photochemical reaction within the tissue.

2.3.1. Indirect impact of light incident on retina

Light is an active neurobiological agent (Zullo, 2007). The indirect responses to light is the actions of chemical signals generated by neurons and the actions of chemical messengers (hormones) delivered by circulation of the blood (Wurtman, 1975). Light is converted into electrical signals when it falls on the retina of the eye. With the help of retinal photoreceptors, the rod and cone, sense of vision is generated when these electrical signals are transmitted by the optic nerve and reach to the visual cortex of the brain. A small part of nerve fibres split off immediately from the optic nerve that transmits the signals received by specialized retinal photoreceptors located in the ganglion cell layer, and send signals to that area of the brain known as hypothalamus (LRC, 1998). There are two major zones in hypothalamus, one stimulates hormone production by controlling the sympathetic nervous system, and the other inhibits hormone production by controlling the parasympathetic nervous system.

The endocrine system that is the body’s major regulatory system is also controlled by the information received by the hypothalamus and significantly affects secretions of the pituitary gland. The chemical and physiological processes involved in metabolic system of human body and the rates of chemical reactions within the cells are regulated by the endocrine systems. Endocrine systems regulate secreting of hormones directly as chemical messengers into the blood stream. Once in the blood stream, hormones reach to the heart and heart circulate these chemical messengers to different parts of the body. Certain specific target cells at different parts of the body catch the message and translate the message for action (Liebermann, 1991). Messages conveyed by hormone regulate mechanisms for example pubescence, ovulation and a wide variety of daily rhythms (SGMI, 2004). Based on the indirect response of light due to fall on retina, the impact of light can be divided into two circumstances (Clanton et al., 2004).

a) Exposure to light produces serotonin, dopamine and Gamma-aminobutyric acid (GABA).
b) Exposure to darkness produces melatonin, norepinephrin and acetylcholine.

a. Activity of serotonin

Serotonin is a neurotransmitter that regulates emotions including desire, body temperature, sleep, appetite and metabolism. In 2002, The Lancet reported that exposure to high-intensity daylight increases concentration of serotonin in the central nervous system (CNS), while dark and cloudy days depleted serotonin levels (Zullo, 2007). Serotonin in low levels can increase depression, carbohydrate cravings, trouble sleep patterns and pain sensitivity. High serotonin levels are responsible for elevated mood, subsidisation of carbohydrate cravings, improved pain tolerance and more restful sleep (Somer et al., 1999).

b. Activity of melatonin

With introduction of darkness or the absence of light, serotonin starts to convert into melatonin. That means serotonin levels decrease with the increase of melatonin levels (Somer et al., 1999). The natural control of melatonin production fails when daylight (SGMI, 2004) and artificial lighting in the interior of buildings are inadequate during the day (Edwards et al., 2002; Lewy et al., 1985). Individuals' activity and energy level are significantly controlled by melatonin levels in the body. High melatonin level is responsible for drowsiness and depression, while an alert state of consciousness is associated with lower levels of melatonin (OBS, 1997). Proper regulation of melatonin level will not only maintain physiological functioning, but also reduces stress and fatigue (Kirby et al, 1999). The simple and easy way to balance the melatonin level in the body is to expose individuals to adequate natural light during daytime (NHS, 2006).

2.3.2. Evidence of indirect impact of light on health outcomes

a. Regulating circadian cycles

The circadian system is a pervasive physiological regulatory mechanism that is organized neurologically to drive bodily functions up and down every day. The effects of light on circadian rhythms can be studied by observing daily patterns of core body temperature, alertness, urine production, cortex activity and other physiological variables (LRC, 1998). Light controls individuals' circadian rhythms by synchronizing internal clock to 24 hours when it falls on the retina and send signals to a small nucleus within the hypothalamus called the suprachiasmatic nucleus (SCN) where the main clock for the human body is located (Samuels, 1990). The hormone melatonin works to control the body's "internal clock", or circadian rhythm, which is set externally by visible light and regulates many human bodily functions (Clanton et al., 2004). Little or no light can disrupt the standard melatonin levels; hamper the natural cycle between night and day (Karolides et al., 2005).

Human circadian rhythm has an average internal period of 24.2 hours (from 23.5 to 24.7 hours) for adults (Cajochen et al., 2000). The period of circadian rhythms, does not depend on the knowledge or perception of external timepieces (Edwards et al., 2002). In absence of periodic environmental signs, the internal clock produces a "subjective" day length that may usually differ from 24 hours. Under experimental isolation conditions, the lengths of cycling has found greater than 24 hours (called infradian rhythms) or less than 24 hours (called ultradian rhythms) (LRC, 1998). It becomes difficult to adjust a daily correction in circadian rhythm when continuous deviation is occurred from 24 hours cycle (Terman, et al. 1986).

Studies also confirmed strong evidence between exposure to bright light and circadian rhythms with improved sleep. In a study, the daylight intensity was increased in different living spaces of a dementia unit where visually intact and impaired patients were stayed. It was found that the stability of the rest-activity rhythm increased in patients with intact vision, but not in visually impaired patients during increased illumination periods (Someren et al., 1997).

b. Treating seasonal affective disorder (SAD)

SAD is one of the most researched subjects among the psychological effects of light (Edwards et al., 2002). SAD is a kind of mood disorder which is related to seasonal variations of light and results depression episodes (NMHA, 2005). Lack of daylight in winter and shortening of daylight hours, cause biochemical imbalance in the hypothalamus (SADA, 2005). Circadian rhythm is affected by lack of sufficient amount of light and susceptibility to SAD increases. Estimation shows 90% of humans suffer from seasonal mood changes during the winter months and among them 10% suffer in

SAD, characterised by depression, anxiety, fatigue, insomnia, fitful sleep, change in appetite, gloom and weight gain. The severity can vary with individuals, but everybody is influenced to some extent by the decrease of daylight (SGMI, 2004).

The popular effective treatment for SAD symptoms is to expose individuals to more daylight. Uses of bright light exposures have been proofed as an effective treatment for reducing SAD by the outcomes of as many as eleven strong studies (Ulrich et al., 2004). In other experimental study, morning light was found twice effective than evening light in treating SAD (Lewy et al., 1998).

Positive response of light therapy includes winter weight gain, increased appetite, hypersomnia and complete remission of symptoms in summer, however, the activities such as feeling worse in the morning (possibly a phase-shift phenomenon) and eating a lot of sweet foodstuffs late in the day, have been found under less predictable levels (Eagals, 2004).

c. Reducing depression

Light is very effective to eliminate some of the root causes of depression. Bright light causes an anti-depressant response, activates the production of brain serotonin. One reason people become depressed is the malfunction of body clock that controls hormone cycles. The body clock can easily become imbalanced by stress, age, surgery, trauma, or due to the lack of light. When the body clock becomes imbalanced it produces the inappropriate hormones; causing mood problems, energy problems and insomnia. Researchers discovered in early ‘80s that the effective treatment for winter depression is specialised bright light (20 times brighter than normal light) and recently, experiments confirm that this light is also capable to treat non-seasonal depression (Zullo, 2007).

At least seven studies confirmed that morning light exposure is more effective in reducing depression compared to exposure to evening light (Ulrich et al., 2004). Severe depressed patients’ hospital stay time reduced 2.6 days on average while allocated to a sunny room compared to a dull room with shadow surrounding spaces (Beauchemin and Hays, 1996). Exposure of light also reduces depression of women during pregnancy (Oren et al, 2002). On the other hand, treatment of depression by medications can cover only some symptoms and cause a multitude of unwanted side effects. Nevertheless, light causes no long-term side effects. Additionally, individuals’ response to light is faster (less than a week) and do not need any readjustment compared to several weeks treatment by a number of medications (Zullo, 2007).

d. Reducing agitation

It has been found that exposure to bright morning light can reduce agitation among elderly patients with dementia. Agitations were reduced to elderly patients with dementia when they were exposed to 2,500 lx light for two hours in the morning for two segments of ten-day periods. During non-treatment days, patients were agitated significantly (Lovell et al., 1995).

e. Reducing length of stay to bipolar disorder patients

Daylight influences length of hospital stay among hospitalized patients (Ulrich et al., 2004). Psychologically disturbed patients in brightly lit rooms have a shorter length of stay then patients in dull rooms (Zullo, 2007). It was found from a study of the length of hospitalization between bipolar disorder patients in different rooms with varying daylight intensities that patients assigned randomly to the brighter, eastern rooms (exposed to direct morning daylight) had a mean 3.67-day shorter stay compared to patients stayed in west-facing rooms (Benedetti et al., 2001).

f. Reducing physiological pain reduction

Concentration of serotonin increased with light exposure. In the CNS, serotonin works as an inhibitor of pain pathways (Guyton et al., 2000). Data from over 40 controlled trials showed that pain perception of patients are reduced by serotonin (Lynch, 2001) when tricyclic antidepressants (TCAs) block the removal of serotonin from the synaptic cleft (Fields, 1984). In a study, two groups of patients undergoing elective cervical and lumbar spinal surgeries were compared. The patients were admitted postoperatively either at the bright or at the dim sides of the same hospital building. The patients' pharmacy costs as well as the standard morphine equivalent of used opioid postoperative medication were measured. This study found that patients, exposed to an average 46% higher intensity of daylight, experienced marginally less pain, less perceived stress, took 22% less analgesic medication per hour and had 21% less pain medication costs (Walch et al., 2005).

g. Reducing post-operative delirium

Psychological improvement during hospital stay accelerates patients' physiological recovery process. Studies confirm that post-surgical units with daylighting improve patients' psychological status. Intensive Care Unit (ICU) facilities in hospitals can be very stressful for both patients and staff. In this stressful environment, patients can develop "post-operative delirium", which affects patients' intellectual ability. Daylight can help to reduce the stress in this environment. Study on ICU patients confirmed that the ICU without window is responsible to raise twice post-operative delirium and depression among patients (Collins, 1975). Windows provide a psychological release that reduced the stress level for patients. Ulrich (1984) reported that patients who could see trees through their windows spent less time in hospital than those with views of a brick wall: 7.96 days compared with 8.70 days per patient. In addition, the former group also took fewer doses and had slightly lower scores for minor post-surgical complications.

2.3.3. Direct impact of incident light on skin

When daylight incident on body, the radiation is absorbed directly by the skin and starts to stimulate biochemical reactions in the blood and other tissues just under skin (Joseph, 2006). Direct exposures to daylight increase the amount of pigment in the skin and the skin remains darker for a few hours due to the photooxidation of a colourless melanin precursor. This reaction is caused by most of the wavelengths of daylight (Wurtman, 1975). Different wavelengths of light also regulate the chemical reactions in the body (OBS, 1997) and affect individuals physiologically and psychologically. Human photobiologic actions are most sensitive between the ranges of 290-770 nm. Vitamin D synthesis and skin reddening occur in the range of 290-315 nm. Pigmentation or tanning of the skin and dental cavities reduction occur in response of 280-400 nm range. Degradation of bilirubin occurs in response to light in the ranges of 400-500 nm (blue light). Vision is the most sensitive to light in 500-650 nm ranges (yellow-green light) (Hathway et al., 1992). Daylight has a continuous spectrum of colours, ranging from the short wavelengths of invisible ultraviolet light through blue, green, yellow, and into the infrared waves (Liberman, 1991) (Figure 2.1) and necessary to run many biological functions properly.

2.3.4. Evidence of direct impact of incident light

a. Vitamin D metabolism

Daylight initiates photochemical and photosensitization reactions that have an effect on blood compounds, fluid space between the cells or in the cells themselves. Research shows that most of the vitamin D in the blood can only be derived by exposure to daylight (Wurtman, 1975). A vitamin D deficiency will occur in absence of some direct or diffused solar radiation exposure on skin for long periods, which may result physiological disorders, weakened body defences and a provocation of chronic diseases (SGMI, 2004).

b. Diseases related to bones and skeleton

In 1919, daylight was discovered to be the key of curing rickets, a disease of young children characterized by a deformation in the developing bones (Edwards et al., 2002). In 1985 two independent studies claimed that vitamin D generated by the daylight in the skin can prevent or cure rickets (Hathaway et al., 1992). In absence of daylight, the amount of calcium required for normal growth and development of the bones will not be absorbed by skin. This shortage of vitamin D actually leads to rickets in children and osteomalacia in adults, characterized by a porous, weak, and malformed skeleton (Edwards et al., 2002); therefore, for the development and maintenance of healthy bones, proper exposure of daylight is necessary in different ages.

c. Diseases related to blood and cancer

Lighting Research Centre at Rensselaer Polytechnic Institute revealed that exposure to direct daylight in a moderate level can slow non-skin cancer cell development (Bullough et al., 2006). In the early stages of some forms of cancer, psoriasis and genital herpes can be treated with UVR (Liberman, 1991). Exposure to daylight reduces mortality from lung and breast cancer (Lim et al., 2006). It has also been suggested that daylight may reduce the risks of some cancers, including colon, prostate and breast cancers (Freedman et al, 2002), although the epidemiological evidence in support of this is weak and controversial (de Gruijl, 1997). Exposure to light is also used for neonatal hyperbilirubinaemia treatment (Zullo, 2007). In hyperbilirubinemia condition, the red blood cells die and release haemoglobin, which soon degrades into the yellow compound bilirubin. An increase in the concentration of bilirubin in the blood, due to excessive production of the compound or to failure of the liver to remove it, results jaundiced colour to the skin (Wurtman, 1975).

d. Reduction of the length of stay to myocardial infarction patients

Daylight reduced hospital mortality and length of stay in myocardial infarction (MI) patients in cardiac intensive care unit (CICU). In a study in the CICU, a total number of 628 MI patients who treated in sunny and dull rooms were retrospectively compared for length of stay and fatal outcomes. The study found shorter stay time in the sunny rooms, particularly for women patients (2.3 days in the sunny rooms compared to 3.3 days in the dull rooms). Fatality for both men and women was consistently higher in dull rooms (among 335 patients 39 patients died in dull rooms and among 293 patients 21 patients died in sunny rooms) (Beauchemin et al, 1998).

2.3.5. Existing knowledge gap

Based on the above literature review, the significant findings of light-related research in connection with hospital patients for last 20 years were separated to identify the existing knowledge gap, and presented in Table 2.1. The impact of light on patients have been categorised in three groups: psychological impact of light; impact on diseases related to bones and cancers and impact on physiological diseases.

It is evident from Table 2.1 that the relationship between daylight and psychological benefit of hospital patients (e.g. reducing depression and SAD), and the impact of daylight on some specific physical diseases related to bones and cancers (e.g. rickets and breast cancer) are well established and supported by robust research. Research on the impact of daylight on physiological diseases (diseases originated from the malfunctions of physiological organs of human body e.g. heart, lungs, stomach, kidney, spinal cord, and not generated from psychological pressure) are few in number; three out of 23 articles listed in Table 2.1. Among 16 empirical research on psychological impact of light on patients (e.g. depression and SAD) presented in Table 2.1, six research identified the impact under bright artificial light sources. In a cohort study, Wirz-Justice et al. (1996) get evidence for the use of outdoor daylight exposure as a potential alternative or adjuvant to conventional bright artificial light therapy for SAD patients, for the first time. It is expected that the impact of daylight exposure on patients

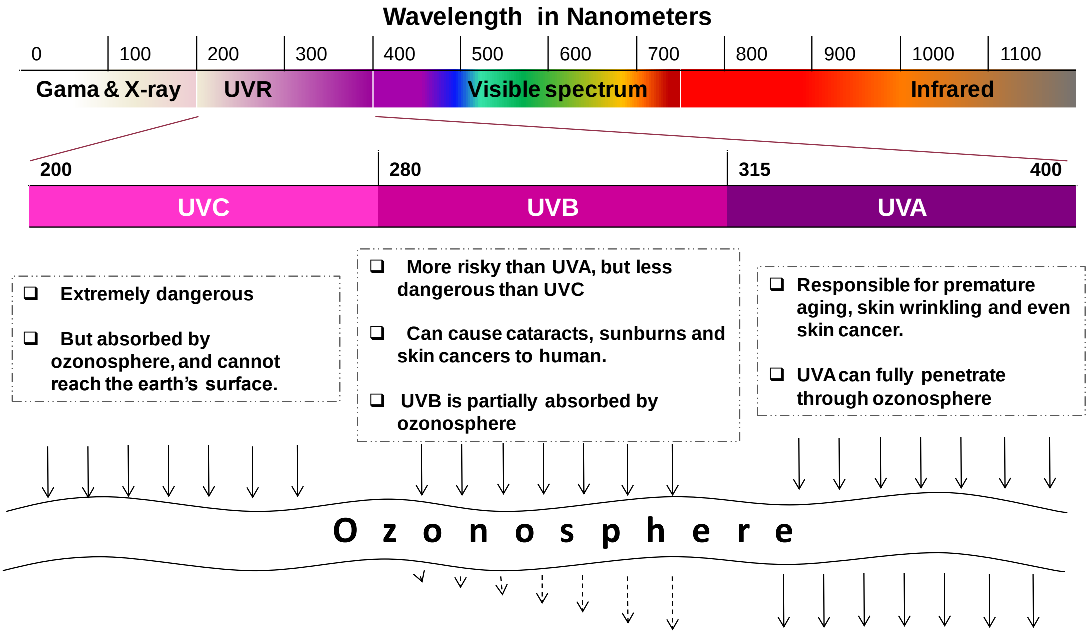
Table 2.1: The significant findings of light related research on patients.

Impact	Author	Year	Findings
Psychological impact of light	Burgess et al.	2006	Daylight exposure at morning determines human circadian phase.
	Lahti et al.	2006	Daylight influences the duration of sleep.
	Roenneberg et al.	2003	Duration of daylight exposure influences the timing of sleep.
	Ljubicic et al.	2007	Duration of daylight exposure is associated with depression of patients.
	Beauchemin et al.	1996	Patients hospitalised for severe depression reduced their LoS by an average of 2.6 days if assigned to a sunny rather than a dull room overlooking spaces in shadow.
	Oren et al.	2002	Light (artificial) treatment in morning has an antidepressant effect during pregnancy
	Kecskes et al.	2003	Daylight exposure reduces LoS of female patients with unipolar major depressive episode.
	Benedetti et al.	2001	Bipolar patients randomly assigned to the brighter, eastern rooms had a mean 3.67-day shorter LoS in hospital than patients in west-facing rooms.
	Someren et al.	1997	Exposure to bright light (artificial) improves rest activity rhythm disturbances in demented patients.
	Lovell et al.	1995	Exposure to bright light (artificial) reduces agitated behaviour in institutionalized elderly patients.
	Lewy et al.	1998	Light (artificial) treatment in morning is twice as effective as evening light treatment for SAD patients.
	Wirz-Justice et al.	1996	This is the first study to provide evidence for the use of outdoor daylight exposure as a potential alternative or adjuvant to conventional artificial light therapy in SAD.
	Bauer et al.	1994	Bright light (artificial) impact on patients' mood and behaviour.
	Kripke et al.	1992	Bright light (artificial) is beneficial for patients with non-seasonal depression.
Impact on diseases related to bones and cancers	Lim et al.	2006	Exposure to daylight reduced mortality from breast and lung cancer patients.
	Whyte et al.	2005	Deficiencies of UV-B can increase the risks of rickets in childhood and of osteomalacia and fractures in adults.
	Holick	2004	Deficiencies of UV-B have been associated with increased risks of rheumatoid arthritis.
	Hughes et al.	2004	Exposure to daylight reduced the risk of non-hodgkin lymphoma (NHL).
	Freedman et al.	2002	Exposure to sunlight reduces mortality from prostate and colon cancer.
	Lefkowitz et al.	1994	Exposure to sunlight reduces mortality from ovarian cancer.
Impact on physiological diseases	Choi et al.	2012	Daylight reduces average LoS for hospital patients in different wards: internal, otolaryngology, surgery, and gynecology wards.
	Walch et al.	2005	Elective cervical and lumbar spinal surgery patients exposed to an increased intensity of daylight (46% higher) experienced less perceived stress, marginally less pain, took 22% less analgesic medication per hour and 21% less pain medication costs.
	Beauchemin et al.	1998	Daylight reduced hospital mortality and LoS for women MI patients (2.3 days in sunny rooms compared to 3.3 days in dull rooms) in CICU.

psychological health will be similar to the impact of bright artificial light which will help to reduce patient LoS in hospitals. Table 2.1 shows that, there are at least five evidences confirmed that higher daylight intensities reduce patient LoS. Three of the studies examined LoS related to patients with psychological problems e.g. SAD (Beauchemin et al., 1996), unipolar (Kecskes et al., 2003) and bipolar (Benedetti et al., 2001) disorders; the other two research studied LoS related to patients with physiological problems e.g. myocardial infarction (Beauchemin et al., 1998) and other (e.g. internal, otolaryngology, surgery, and gynecology) diseases (Choi et al., 2012). Research on the impact of daylight on physiological diseases, that could be measured objectively (i.e. LoS of hospital patients), are necessary for the incorporation of the therapeutic benefit of daylight in the design of in-patient rooms, as it is applicable for most of the hospitals. The researcher identified that some parts of the methodologies, as well as the outcome of the two research, studied LoS related to patients with physiological problems (i.e. Beauchemin et al., 1998 and Choi et al., 2012), are questionable (discussed in Section 3.4). Defined knowledge about the impact of daylight on patients physiological developments was identified as weak and controversial from the outcome of the review of the literature related to therapeutic environment, conducted by previous researchers such as Devlin et al. (2003) and Edwards et al. (2002), and the results are well debated (HBN-04, 1997; Loftness et al., 2006); therefore, suggests that it is necessary to further investigate the impact of daylight on patient LoS in a general hospital environment scientifically. The particular interest of this PhD research is to quantify the impact of daylight intensity on LoS of patients with physiological diseases.

2.4. Adverse impact of excess daylight on health

The adverse impact of daylight on health are due to prolong exposure to UVR (wavelengths between 200 - 400 nm, see Figure 2.1). UVR of daylight that reaches the earth surface has potentiality to damage biological organisms (Gibson, 2008). Shortwave radiations of different wavelengths are not equally penetrable to ozonosphere and not equally harmful to individuals. UVR is divided into UVA (wavelengths between 315 - 400 nm), UVB (wavelengths between 280 - 315 nm) and UVC (wavelengths between 200 - 280 nm). UVA is responsible for premature aging, skin wrinkling and even skin cancer and can fully penetrate through ozonosphere. UVB is more risky than UVA, but less dangerous than UVC. UVB can cause cataracts, sunburns and skin cancers to human. UVB is partially absorbed by ozonosphere. UVC is extremely dangerous, but completely absorbed by ozonosphere, and cannot reach the earth surface (Gibson, 2008; MacDonald et al., 2006). As a result, the most critical part of UVR is UVB which is partially absorbed by ozonosphere and has a possibility to increase in the future due to the impact of climate change (discussed latter in Section 2.5). Figure 2.1 shows the spectrum of solar radiation with classification of UVR, and summaries the findings relating to the major negative health effects of prolong exposure to UVR. The major negative health effects of prolong exposure to UVR are described below.



- ❑ Extremely dangerous
- ❑ But absorbed by ozonosphere, and cannot reach the earth's surface.

- ❑ More risky than UVA, but less dangerous than UVC
- ❑ Can cause cataracts, sunburns and skin cancers to human.
- ❑ UVB is partially absorbed by ozonosphere

- ❑ Responsible for premature aging, skin wrinkling and even skin cancer.
- ❑ UVA can fully penetrate through ozonosphere

Figure 2.1: Distribution of UVR and summary of the findings about major health effects of exposure to UVR (adapted from: Gibson, 2008; MacDonald et al., 2006).

a. Immune suppression

There is a possibility that UVB exposure can cause suppression of the immune response to animal and human body (Kovats, 2008; Longstreth et al., 1998). Human infectious diseases have shown an effect of UVB exposure in animal models for herpes, tuberculosis, leprosy, trichinella, candidiasis, leishmaniasis, listeriosis and lyme disease (HPA, 2002). UVB can also activate viruses such as herpes, HIV and human papilloma and could adversely affect the course of some infectious diseases in humans as well as the effectiveness of some vaccinations (Kovats, 2008). UVB exposure can reactivate latent infections (Rooney et al., 1991), and with induced immune suppression may cause some cancers, such as squamous cell skin cancer. Evidence support that the incidence of Non-Hodgkin's Lymphoma (NHL) shows a positive association with UVB levels in most developed countries including England and Wales (Bentham, 1996) and worldwide. Studies from the USA do not show the same association (Freedman et al., 1997) and daylight exposure could exacerbate HIV infections were not supported in a USA study (Saah et al., 1997). Epidemiological evidence of immune suppression on the potential impact on human health remains sparse and insufficient (Longstreth et al., 1998; de Gruijl, 1997) and researchers are accumulating information on the mechanisms by which exposure to UVR causes immune suppression, but direct evidence on what the implications are for human health is still indefinable (UNEP, 2003).

b. Breast cancer

Studies have found a potential link between light pollution and hormone production, specifically related to melatonin and estrogen levels in women (Coyle, 2004). The presence of light exposure at night time reduces melatonin levels, which elevate estrogen levels in women who did not sleep at night often, and increases responsiveness of estrogen-dependent tissues to cellular proliferation. As a result, the risk of breast cancer increased (Davis et al., 2001). Schernhammer et al. (2001) conducted a 10 years follow-up study on nurse's health study cohort and revealed that breast cancer risk increased moderately among female nurses who frequently work in rotating night shifts.

c. Skin cancers

As the depth of penetration of UVB is very short, skin and eyes of human body are more in risk to damage by UVB exposures. Studies confirmed that increased UVB exposures are expected to raise skin cancers (Kovats, 2008; UNEP, 2003). There is strong evidence that exposure to UVB is a major aetiological factor for both non-melanoma skin cancers (NMSC) and malignant melanoma (MM) (HPA, 2002). The different types of skin cancers show important differences in the relationship between solar exposures and risk levels (Longstreth, et. al., 1998).

Increased temperature may also enhance the carcinogenic potential of exposure to daylight, although the evidence is speculative. Study estimates that a 2°C increase in ambient temperature might result in 21% increase in the incidence of skin cancer, which is substantially greater than any anticipated effects of ozone depletion alone. This estimation is based on extrapolation from the results of experiments on mice and there is, yet, no direct evidence for humans (Kovats, 2008).

d. Eye damage

Exposure to daylight is associated with a variety of eye disorders. Among them, the most significant one from a public health perspective is cataract. The lens affected by cataract gradually loss its transparency to frequently blindness. The treatment is to replace the affected lens by surgery. Several epidemiological studies have shown an association between cortical cataract incidence and individual UV exposure levels (Taylor et al., 1988). There is uncertainty about which part of the solar spectrum (UVA or UVB) is responsible for cataract (de Gruijl, 1997). As ozone depletion would affect UVB levels but have little influence on UVA, the doubts about the action spectrum has made it difficult to estimate the effects of UVR on cataract incidences (HPA, 2002).

Although there were some uncertainties remained about the role of daylight exposure in the formation of cataract, new studies from Australia (Neale et al., 2003), France (Delcourt et al., 2000) and a review of 22 published studies (McCarty and Taylor, 2002), supported an association between exposure of daylight and cataract with animal models (UNEP, 2003) particularly implicating UVB.

e. Sunburn

Prolonged exposure to UVR will turn skin either brown (a suntan) or red (a sunburn) and over prolonged exposure will break chemical bonds of skin tissue, may cause skin wrinkle. Sunburn is the most obvious effect of exposure to UVR from the sun (erythema) (Kovats, 2008). Over exposure of the sun can cause pain and blister to skin and may take several days to resolve. Severity depends on the intensity and duration of exposure. A general response to UVB exposure is thickening of the skin and in many individuals (depending on skin type), the development of a tan provides some protection (HPA, 2002).

2.5. Impact of climate change on UVR

It is evident from above discussion that the most of the adverse effects of daylight are associated with exposure to UVR. There is a possibility to increase the adverse impact of daylight due to climate change. The rapidly accelerating climate change, which is mainly associated with GHG emissions, is responsible for many dangerous regional and global environmental events. GHG-related climate change can deplete the stratospheric ozone layer (HPA, 2002). The atmospheric ozone layer acts as a filter against part of short wave radiation (Figure 2.2). As a result, there are possibilities that more downward shortwave radiation will reach to the earth in the future. As, shortwave radiation contains UVR there is a possibility to increase the UVB levels in the future due to the impact of climate change.

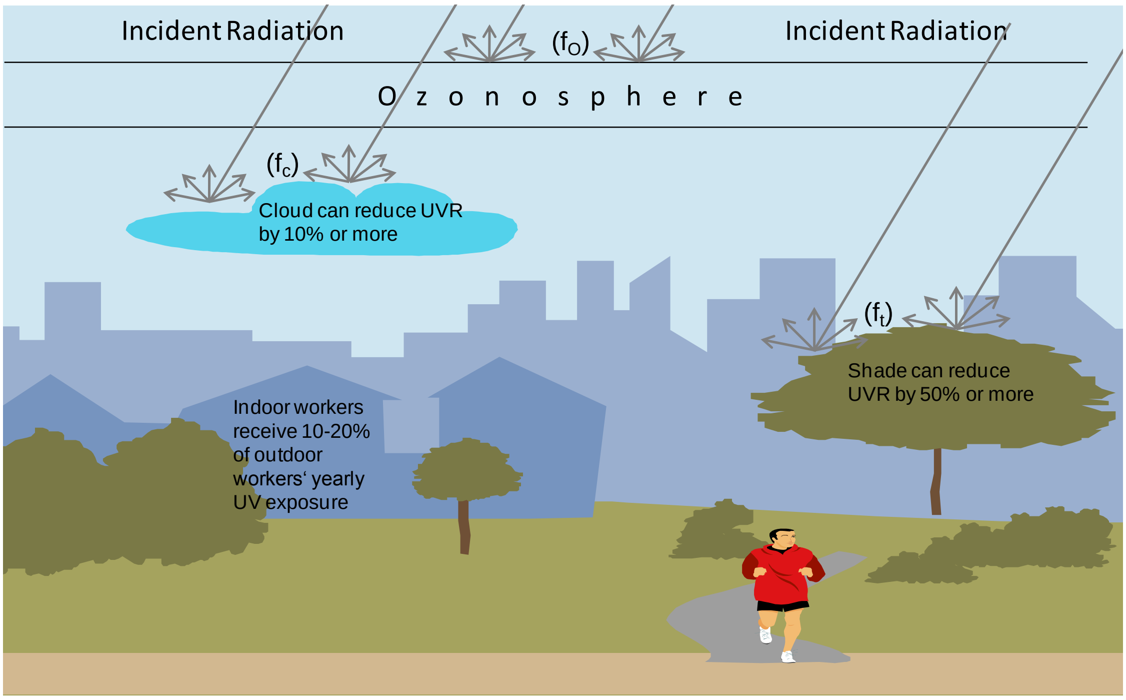


Figure 2.2: Natural elements that affect the transmission of solar radiation to the earth surface (adapted from: Gibson, 2008; CCV, 2004).

There are some natural elements in the environment that affect the transmission of UVB to the earth surface. Figure 2.2 shows different natural elements in the environment, which are responsible for reducing UVB exposures such as ozone layer (f_O), clouds (f_C) and trees (f_t) (Gibson, 2008). UVB is partially absorbed by Ozonosphere in first instance. Light cloud can reduce UVB by 10% and heavy cloud can reduce more. Shades and trees can reduce UVB by 50% or more, however, individuals who stay inside indoor environment have a risk to receive 10-20% of UVB radiation in a year through windows and openings, compared to individuals who are engaged in outdoor works (CCV, 2004) (Figure 2.2).

Rapidly accelerating climate change may also cause decrease of cloud cover and reduction of green. The decrease of cloud cover is proportional to the increase of UVR levels in environment for example if the cloud cover decreases by 4%, the ambient UVR levels can be expected to be increased by ~2% (Diffey et al., 1994). According to United Kingdom Climate projection 2009 (UKCP09), the changes in mean cloud amount during summer can be decreased up to – 18% (-33 to - 2%) in some parts of UK (southern) which will result an addition of + 16 W/m^2 (-2 to + 37 W/m^2) in downward shortwave radiation over the 21st century (Jenkins et al., 2009). Therefore, it can be assumed that the amount of incident UVR on earth will be increased in the future. Longer summers and permanent changes in cloud cover may lead to changes in the levels of personal exposure to UVR both outside and inside of the buildings. Therefore, 10-20% of outdoor UVR received by indoor occupants can be a threat for some particular geographical location in particular periods of the year.

The amount of UV exposure depends on the geographical location of the place (altitude and latitude) for example a country located in the southern hemisphere is closer to the sun in summer due to the earth’s oval shaped orbit and will receive more UVR during summer compared to a country located in similar latitudes in the northern hemisphere. On the other hand, the depletion of ozone layer due to climate change is not uniform over the globe. As a result changes in UV-levels sometimes vary significantly under same hemisphere between two adjacent locations. Slaper et al. (1998) estimates location specific changes in UV-levels for European countries by using satellite data on ozone depletion. Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) was used to measure ozone, and UV-transfer model (Slaper et al., 1992) was used to estimate changes in ground level (Bordewijk et al., 1997) over the period 1980 to 1991 (Figure 2.3). Figure 2.4 shows the changes in UV radiation in Europe over 1980 to 2000 (EDC, 2000). From Figure 2.3 and 2.4, it is evident that relative changes in UV level were largest (8%) in north-west Europe considering 10 years from 1980 and in Central Europe (7-8%) considering 20 years among European countries. If the increase ratio of Figure 2.3 continues over a life time, the excess skin cancer risk at 52^0 north latitude are shown in

THIRD-PARTY CONTENT

Figure 2.3: The increase in UV radiation in Europe over 1980 to 1991 due to change in ozone layer (source: Slaper et al., 1992).

THIRD-PARTY CONTENT

Figure 2.4: The changes in UV radiation in Europe over 1980 to 2000 (source: EDC, 2000).

Figure 2.5 till 2100, derived from an improved integrated source-risk model (Slaper et al., 1992) to measure excess skin cancer risks caused by depletion of ozone layer due to various halocarbon emission scenarios. Assuming a population of 160 million in North-West Europe, the number of excess skin cancer cases that can be avoided by complying with the California Scenario amounts to more than 500,000 cases per year. Roughly 2% of the cases are fatal (Slaper et al., 1998). However, it is assumed that the enhanced depletion of ozone layer will not continue for prolonged period and there are also uncertainty lies in accurate prediction of future skin cancer risks.

THIRD-PARTY CONTENT

Figure 2.5: The excess skin cancer risk at north-west Europe caused by depletion of ozone layer due to various halocarbon emissions scenarios (source, Slaper et al., 1992).

2.6. Summary

This chapter has achieved the first objective by mapping a chain of consequences of the effects of daylight on human body starting from light incident on different parts of the body (eye and skin) and then linking daylighting with evidence of physiological and psychological outcomes to individuals. The impact of daylight has been described under two segments: indirect and direct.

It was summarised from the evidence of direct and indirect impact of light exposure on patients that the impact of daylight on psychological diseases (e.g. SAD and agitation), as well as on specific physical diseases related to bones and cancers (e.g. rickets and skin cancer) are well established, but few and controversial research exists on the impact of daylight on physiological diseases. To reduce the existing knowledge gap, Chapter 3 of this research describes the methodology to investigate the impact of incident daylight on the LoS of heart surgery patients based on real world data collected from field and Chapter 4 presents the outcomes.

In contrast, excess daylight has possibilities to do more harm than good. There is also a risk of increasing the adverse impact of daylight due to climate change. The analysis of Slaper et al. (1998) shows that UK fall in the region where the increase of UV radiation was the maximum (6-8%) during 1980 to 1991 among European countries due to the changes in ozonosphere (Figure 2.3). It is necessary for daylight designers to consider UVB protection when design with daylighting and windows for UK and other regions of the world. Available techniques to protect patients from UVB when inside the hospital in-patient rooms have been discussed in Chapter 6 and key strategies based on literature review have been presented in concluding Chapter 7.

CHAPTER 3
Methodology

3.1. Introduction

Chapter 2 identifies an existing knowledge gap. To reduce the knowledge gap, this chapter contains the detailed steps of the methodology of this research which integrates field investigation and simulation study. A suitable methodology to conduct field investigation to establish statistical relationship between daylight intensities and patient LoS in a hospital in-patient room was developed at the beginning of the research. The methodology was also developed for verification of the benchmarks of daylight intensities within which reductions of patient LoS in hospitals are expected, using real world field data. These benchmarks were later used as a goal for simulation study in Chapter 5. The concept of single-bed in-patient room design, to incorporate therapeutic benefit of daylight, and the methodology for evaluation of the concept, under the present and the future climate scenarios by prospective simulation study, were developed in this chapter. The outcomes of field investigation and simulation study are presented in Chapter 4 and Chapter 5.

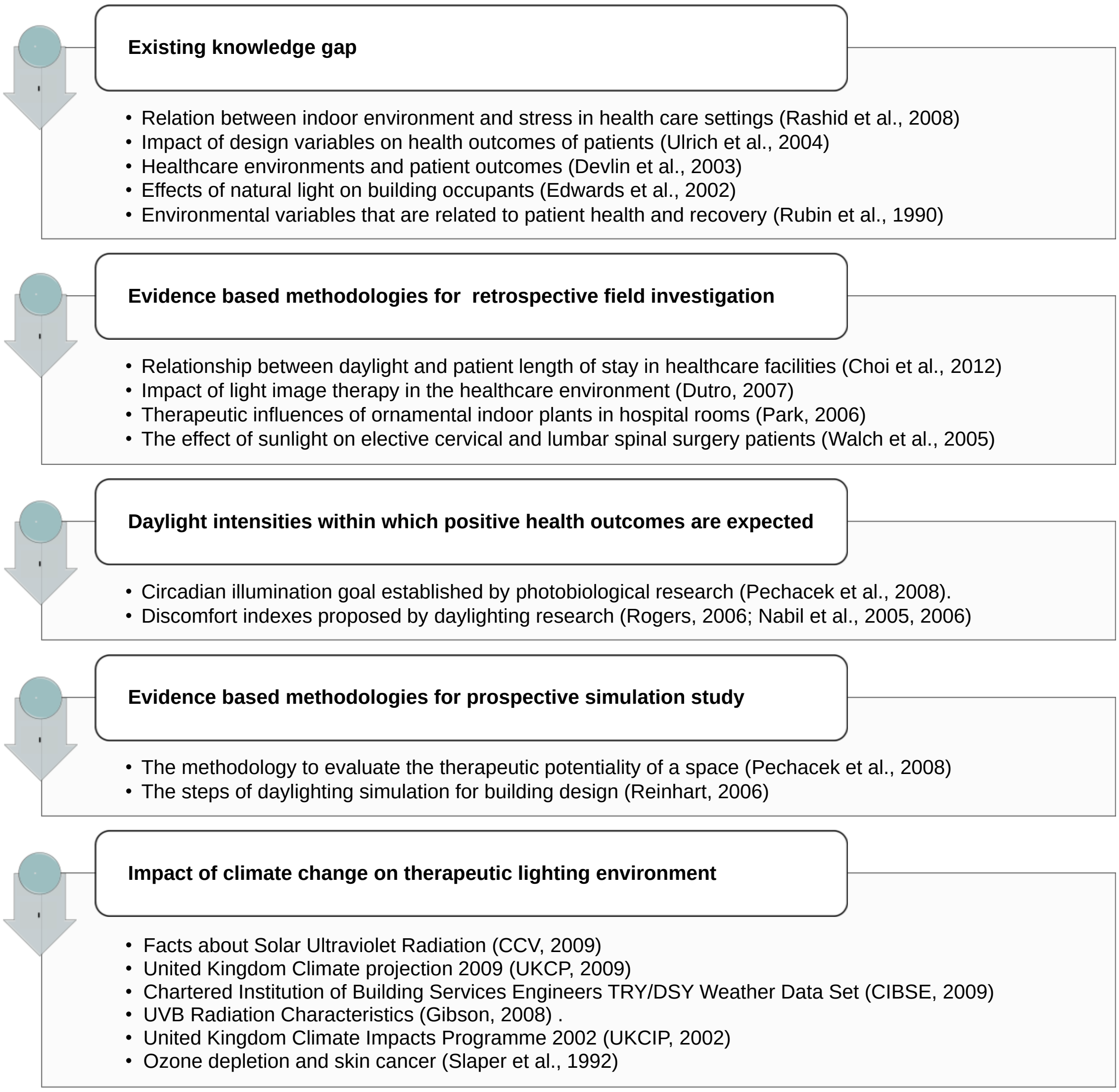
3.2. Background

Early research into daylight design was focussed on the physical characteristics of daylight, for example: depth of daylight penetration into the buildings without additional support and how the penetration could be increased passively; the nature and availability of daylight at different geographical locations; the changing quantity and quality of daylight with orientation, time of day and seasons; and how daylight can be made comfortable for users by ensuring radiation and glare free light. The subjective nature of daylight such as impact of daylight on health, performance and activity has not been fully resolved; moreover controversy results revealed and equally debated by the researchers (Loftness et al., 2006). Liberman (1991: p.22) stated that, ‘the major control centres of the body (the nervous system and the endocrine system) are directly stimulated and regulated by light to an extent far beyond what modern science, until recently, has been willing to accept’. With the development of knowledge, the subjective issues of daylight get the interests of the researchers, while difficulties rose to incorporate these subjective issues in the physical design of hospital buildings.

Three major constraints were identified in Chapter 1 (Section 1.3) for the implementation of therapeutic effect of daylight on the architectural design of hospital in-patient rooms. Methodology in this chapter was developed to overcome those three constraints. Due to the versatile and complex relationship between daylight and patient recovery process (Galasiu et al., 2008), the number of evidence based scientific research focused only on the effects of daylight on patients' recovery is few in number (Rubin et al., 1998). Completed and current research has weakness in estimation of daylight levels and patient recovery rate. It was not sensible to follow one specific research methodology from past for this PhD research. Under these circumstances, the researcher tried to develop an updated methodology based on the works of previous researchers.

It was difficult to get consent to conduct survey in hospital environment and reach patients clinical data (due to ethical issues) without impeding the regular treatment and care of the patients to figure out the impact of daylight objectively. Researcher under these conditions needed to be flexible in research design methodology and have to keep alternative/backup methodology in mind (for example use of outdoor data loggers in case the hospital authority objects to install indoor data loggers inside patient rooms) to achieve the aim and objectives of the research. The suitability of achieving each objective was assessed against literature review at the beginning and the outcome of literature review directed to conduct field investigation and/or simulation study. Once, further study become essential, the concern of the literature review was to develop evidence based methodology for the study. Figure 3.1 shows how the methodology for field investigations and simulation studies were developed with respect to the outcomes of literature review. Along with the development of the methodology from literature review for field investigation, the test of the methodology was sometimes necessary (by pilot study) to ensure the suitability of the methodology for an extensive field investigation (i.e. principal study).

Unlike many environmental variables (e.g. temperature and humidity), daylight intensity differ significantly in two points in the same room (e.g. near window and near back/corridor wall opposite the window), even illumination changes rapidly with time at the same point with the change of the sun position and cloud cover in the sky throughout the day and whole year. Therefore, the estimations of daylight inside patient rooms with reference to historical climate data (i.e. use of weather file during simulation study) were not reliable. In this research outdoor horizontal exterior illuminance (HEI), measured by an outdoor data logger from site, was taken as a reference to estimate indoor daylight level by simulation study during pilot survey, and indoor data loggers were installed inside the in-patient rooms of the case unit to record indoor daylight data directly during principal survey to incorporate the effect of rapid change of outdoor daylight on indoor daylight level.



Existing knowledge gap

- Relation between indoor environment and stress in health care settings (Rashid et al., 2008)
- Impact of design variables on health outcomes of patients (Ulrich et al., 2004)
- Healthcare environments and patient outcomes (Devlin et al., 2003)
- Effects of natural light on building occupants (Edwards et al., 2002)
- Environmental variables that are related to patient health and recovery (Rubin et al., 1990)

Evidence based methodologies for retrospective field investigation

- Relationship between daylight and patient length of stay in healthcare facilities (Choi et al., 2012)
- Impact of light image therapy in the healthcare environment (Dutro, 2007)
- Therapeutic influences of ornamental indoor plants in hospital rooms (Park, 2006)
- The effect of sunlight on elective cervical and lumbar spinal surgery patients (Walch et al., 2005)

Daylight intensities within which positive health outcomes are expected

- Circadian illumination goal established by photobiological research (Pechacek et al., 2008).
- Discomfort indexes proposed by daylighting research (Rogers, 2006; Nabil et al., 2005, 2006)

Evidence based methodologies for prospective simulation study

- The methodology to evaluate the therapeutic potentiality of a space (Pechacek et al., 2008)
- The steps of daylighting simulation for building design (Reinhart, 2006)

Impact of climate change on therapeutic lighting environment

- Facts about Solar Ultraviolet Radiation (CCV, 2009)
- United Kingdom Climate projection 2009 (UKCP, 2009)
- Chartered Institution of Building Services Engineers TRY/DSY Weather Data Set (CIBSE, 2009)
- UVB Radiation Characteristics (Gibson, 2008) .
- United Kingdom Climate Impacts Programme 2002 (UKCIP, 2002)
- Ozone depletion and skin cancer (Slaper et al., 1992)

Figure 3.1: Development of the methodologies for field investigations and simulation studies based on literature.

Only intensity of light was measured with time as lighting variable during field investigation. It was found from literature that along with intensity of light as a key factor (Baker, 2000) other lighting variables might have also impact on health for example spectrum and photic history (Lockley, 2008; Veitch et al., 2004), therefore, it was essential to estimate if a correlation exists between incident daylight illumination and patient LoS within a group of environmental and clinical variables. It was also necessary to develop an intensity based goal for prospective simulation study as widely available simulation tools are based on capabilities to evaluate photopic visual response (e.g. illuminance and luminance) but unable to measure radiometric spectrum (Pechacek et al., 2008). The range of daylight intensities within which positive health outcomes are expected recommended from past daylighting literature were based on non-healthcare facilities (i.e. schools and offices), and needed to be verified against field data before using the values (intensities) as a goal for prospective simulation study for hospital in-patient rooms.

Predicting actual daylight intensity by simulation is beyond the capabilities of all but the most advanced computer modelling software (Pechacek et al., 2008). It was difficult to overcome the limitations of daylight simulation analysis experienced by past researchers. The design concept for hospital in-patient rooms presented in this thesis was developed and evaluated to present an example on how daylight can be incorporated in the design of in-patients room to meet the therapeutic needs of hospital patients more effectively. Due to the climate change, any idea/concept needs to be evaluated both under the present and the future climate scenarios. The impact of climate change on visible radiation (light) inside in-patient rooms was analysed by prospective simulation study. Finally, the experiences of prospective simulation study, the developed MLR models from retrospective field investigation data, and findings of literature review were compiled to recommend architectural design strategies to incorporate therapeutic effect of daylight on the design of hospital in-patient rooms to reduce patient LoS in hospitals. The following sections briefed research designs and methods followed by description of the detailed steps of each methodology applied in this research.

3.3. Research designs and methods

To reduce the research gap identified in Chapter 2 (Section 2.3.5), quantitative relationship between daylight intensities and patient LoS in hospitals was needed to be established based on evidence from real world patient data. The study of data collection could be done under laboratory setup and/or existing hospital environment. Experimental study with randomised control to make comparison between different groups of patient with similar health status, who stay in rooms with different daylight levels, was not practical in a laboratory setup under this PhD due to inadequate research facilities. This type of experimental study was also not feasible in a hospital environment due to ethical issue as it was expected that patients who will stay under lower level of daylight will suffer in their recovery process (i.e. increased LoS). Under these circumstances patients data collection from field (i.e. hospital) by observational study under historical controls, where the patients assigned themselves to the different sample groups and the researcher observed the impact, is more appropriate from ethical perspective under available research facilities. Therefore, retrospective field investigation in an existing hospital building, which will be observational in nature, was selected to collect data to establish quantitative relationship between daylight intensities and patient LoS. The detailed steps of retrospective field investigation have been described in Section 3.4.

To develop and evaluate a design concept to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, several methods are available such as full scale model, scaled model and daylight simulation analysis. The construction and modification of full scale model for different design options are too expensive and time consuming for the present research. To evaluate the annual performance of an option with scaled model, the model is needed to be remained in outdoor environment for one year and to develop and evaluate another design option, incorporating the result of the previous analysis, will take years. Evaluation of the models (full scale and/or scaled) under controlled artificial sky conditions in laboratory might be quicker, but unavailable under present PhD research facilities. Therefore, daylight simulation, which is a widely accepted research method, was selected to develop and evaluate a design concept developed by the researcher. Parametric simulation also allows study of the exclusive effect of one single element or the small modification of the element on daylighting, keeping other element constant which is difficult to achieve in real world studies, due to the simultaneous influence of combined impact of different environmental and artificial aspects (e.g. maintenance). Another significant contribution of parametric simulation study is that, it is possible to analyse the daylighting condition under the future climate scenarios within a short time by simply assigning simulation parameters, which is not presently possible under full scale and/or scaled model analysis. The detail steps of prospective simulation study have been described in Section 3.5.

3.4. Methodology for retrospective field investigation

In this section, an evidence based research methodology was developed to correlate daylight intensity with patient LoS in hospital rooms under physiological diseases, based on past research. Among 23 studies mentioned in Table 2.1, three studies conducted by Walch et al. (2005), Choi et al., (2012) and Beauchemin et al. (1998) identified correlation between daylight intensities and patients' physiological developments. The researcher found the outcome of Beauchemin et al. (1998) questionable. Beauchemin et al. (1998) studied LoS in CICU, where patients stay senseless or sleep under high doses of drugs. It is difficult to justify that shorter LoS is the result of therapeutic daylight (Choi et al., 2012), which vastly need to fall on patient retina to start and to continue biological stimulation inside body. The researchers calculated the average LoS of two groups of MI patients treated in north (dark) and south (bright) CICU rooms and reported that women in bright rooms stayed an average of one day less than the women in dark rooms. Choi et al., (2012) took samples from wards (not a particular type of patient or diseases) e.g. medical wards or orthopaedics wards. In the same ward, the level of complications among admitted patients may vary from minor to severe and LoS may vary for two patients due to the severity of the diseases. In terms of methodology, the research conducted by Walch et al. (2005) and Choi et al., (2012) had potentialities for reviewing to develop evidence based methodology for field investigation of this research. The Centre for Building Performance and Diagnostics (CBPD) identified 16 international case studies linking access to the natural environment (i.e. daylight, window and natural ventilation) to improved health outcomes: LoS, headaches, colds and sick building syndrome (Loftness et al., 2006). CBPD's findings also indicated the outcome of the same two studies (i.e. Walch et al., 2005 and Choi et al., 2012 (Master's research completed in

2005 and available as Choi, 2005; revised and republished in 2012 as a Journal paper)) on physiological diseases that studied the relationship between daylight and patient LoS till 2006.

In the reviewing process of this PhD research, two further studies conducted by Dutro (2007) and Park (2006) were identified who objectively analysed the therapeutic impact of visual elements on hospital patients, applying robust field investigation methodology. Due to the limited number of completed studies that measure the therapeutic effect of daylight on hospital patients objectively, the four research (Choi et al., 2012; Dutro, 2007; Park 2006 and Walch et al., 2005) relating to the therapeutic environment of hospital building on physiological diseases were selected as key pieces of research for critical review to identify the status of current research design methodology and to develop evidence based methodology for data collection and analysis of this research. Table 3.1 presents a brief description of four studies, focussing on the sample and variables selection, and tools for statistical analysis as well as the key findings.

Based on critical reviews of the key pieces of research presented in Table 3.1, guidelines for selection of samples, primary variables and statistical model for data analysis were identified. The hypothesis of the field study was that the increase of daylight intensity inside hospital rooms may reduce patient LoS. To test this hypothesis, data collection and analysis were done in three phases.

- The first phase continued for two months as a pilot study to explore the statistical relationship between average daylight intensity of the in-patient rooms and patient LoS inside hospital in-patient rooms.
- In the second phase, a more precise and extensive study was done as a principal study for 12 months (one year), to establish a stronger evidence (than pilot study) of the statistical relationship between daylight intensity at a particular point above patients' head and patient LoS inside hospital in-patient rooms.
- In the third phase, some additional experiments were done, using the data collected during principal study, to test the range of daylight intensities within which patient LoS are expected to be reduced referred from literature.

The steps of the methodology developed from literature review for pilot and principal study have been illustrated in Figure 3.2 and described below.

Table 3.1: Summary of the four key pieces of research.

	Park, 2006	**Dutro, 2007**	**Choi et al., 2012**	**Walch et al., 2005**
Sample (No.)	1. Thyroidectomy surgery patients (80). 2. Appendectomy surgery patients (90). 3. Hemorrhoidectomy surgery patients (90).	Pediatric outpatient (80).	1. Internal ward (6-34).* 2. Otolaryngology ward (14-32).* 3. Surgery ward (10-23).* 4. Gynecology ward (18-36).*	Elective cervical and lumbar spinal surgery patients (89).
Period	July 2005 - January 2006.	May - December 2007.	Spring, Fall and Winter, 2005.	12 March - 7 August 2003.
Place (Hospital)	1. Gyeongsang National University Hospital, Korea. 2. Bando Hospital, Korea.	East Tennessee State University Pediatric Clinic, Johnson City, Tennessee.	Inha University Hospital, Inchon, Korea.	Montefiore Hospital, New York, U.S.A.
Environmental Variables	Presence of ornamental indoor plants in hospital rooms.	1. Picture with backlight. 2. Picture with no backlight. 3. Black square ceiling. 4. No changes to the ceiling.	1. Luminance ratio (LR) on the TV Wall. 2. LR between patient eyes and TV. 3. Horizontal illuminance level across a patient room. 4. Diversity of illuminance (DI). 5. Physical environment of patient rooms.	1. The intensity of daylight.
Psychological Variables	1. Ratings of Pain intensity, Pain distress, Anxiety and Fatigue (PPAF). 2. The State-Trait Anxiety Inventory form Y-1 (STAI-Y1). 3. The Environmental Assessment Scale (EAS). 4. The Patient’s Room Satisfaction Questionnaire (PRSQ).	1. Duration of examination by the physician. 2. Characterization of the exam assessed by the physician. 3. Stress of the attending parent or guardian.	No psychological data were collected.	1. Stress. 2. Depression. 3. Anxiety. 4. Severity of pain.
Demographic Variables	No demographic data were collected.	No demographic data were collected.	No demographic data were collected.	1. Age. 2. Sex. 3. Race/ Ethnicity. 4. Education. 5. Income.

*the number of sample varied in different seasons e.g. spring, fall and winter.

Table 3.1: (Continued)

	Park, 2006	**Dutro, 2007**	**Choi et al., 2012**	**Walch et al., 2005**
Clinical/ Physiological Variables	1. LoS. 2. Blood pressure. 3. Temperature. 4. Heart rate. 5. Respiratory rate. 6. Analgesics used for postoperative pain control.	No physiological data were collected.	Patient average LoS.	1. LoS. 2. Systolic blood pressure. 3. Diastolic blood pressure. 4. Heart rate. 5. BMI. 6. Mean oral morphine consumption. 7. Pain medication cost per hour. 8. Prior analgesic medication use. 9. Diagnosis procedure. 10. Surgical complications. 11. No. of levels fused. 12. Operating room (OR) morphine. 13. Post-anesthesia care unit (PACU) morphine. 14. Pain rating at PACU discharge. 15. Optimism level on postoperative day one.
Statistical analyses	1. Analysis of covariance (ANCOVA) and Chi-square test using SAS.	1. Kruskal- Wallis non-parametric method using SPSS and SAS. 2. Regression analysis and Tukey's Standardized Range Test using SAS.	1. One-way Analysis of Variance (ANOVA) and two-sample T-test using SPSS.	1. Parametric (t- Test for independent samples) or nonparametric equivalents (Mann-Whitney test or chi-squared) tests were carried out using Minitab statistical software program.
Findings	Patients exposed to plants experienced shorter LoS in hospital; took fewer intakes of postoperative analgesics; responses more positively to physiological conditions and express less pain, anxiety, and fatigue than patients in the control group.	Although a statistical difference was not determined between the room with the backlit image and positive and negative control rooms, patients in rooms containing nature art tended to exhibit less anxiety.	Patients average LoS was shorter by 16% to 41% in hospital rooms located in brighter orientations, south-east area, compared to north-west area.	Patients exposed to an increased intensity of daylight (46% higher) experienced less perceived stress; marginally less pain; took 22% less analgesic medication per hour and 21% less pain medication costs

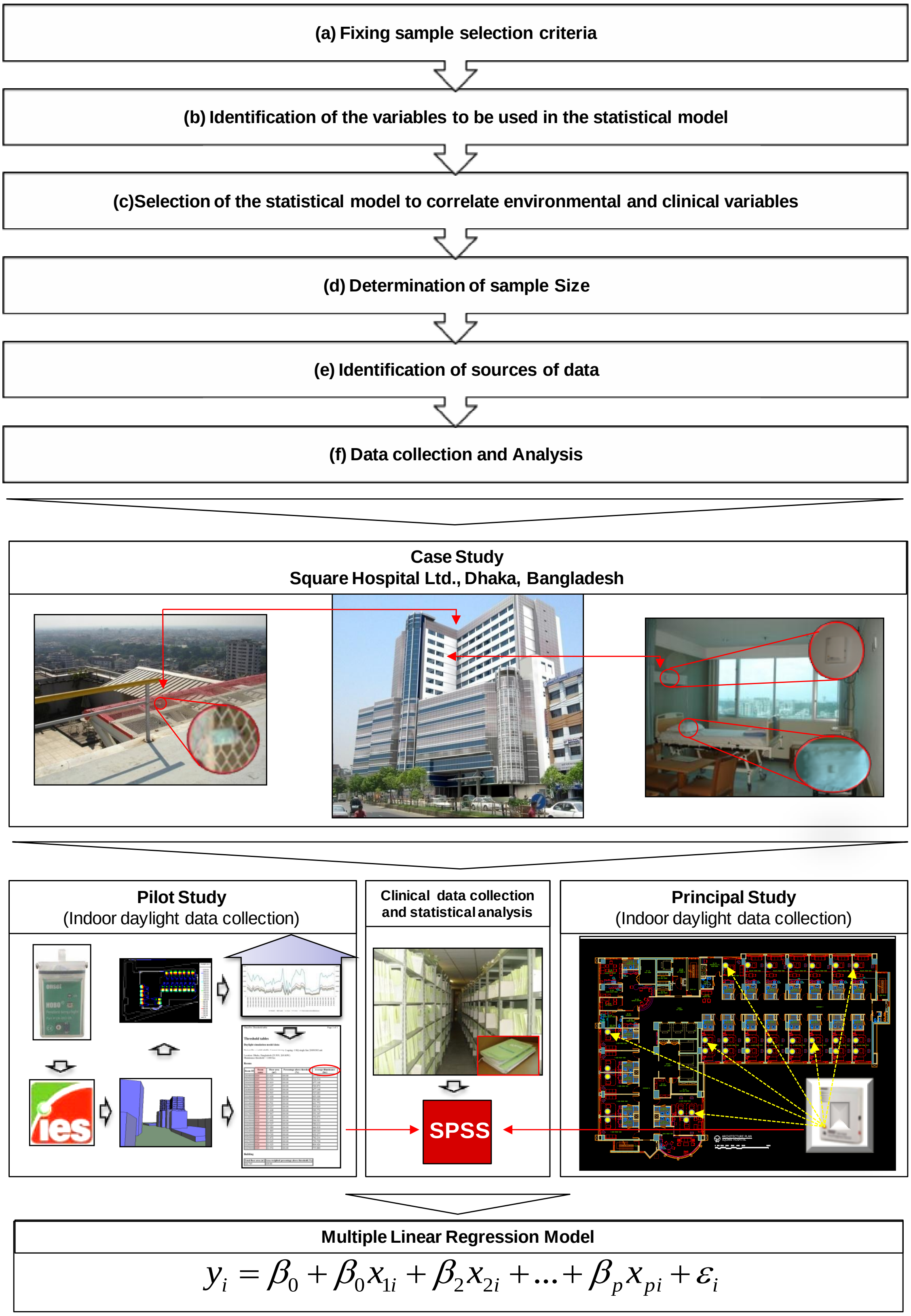


Figure 3.2: Flow diagram of retrospective field investigation.

a. Selection of samples

Reviewing four key pieces of research for sample selection (Table 3.1), it was found that effects of daylight on clinical improvement have been analysed on different patient groups (for example thyroidectomy surgery, appendectomy surgery, gynaecology, haemorrhoidectomy surgery, otorhinolaryngology, orthopaedics, elective cervical and lumbar spinal surgery patients) without very clear or definite criteria for particular sample choice. The possible reasons, identified after analysing individual researcher's background, were availability of data in hand and researcher's easiness in access to hospital premise and clinical data. More intensive research works (e.g. Park, 2006; Walch et al., 2005 and Ulrich, 1984) considered surgery patients as the sample for the studies. In most of the cases surgical patients have to undergo a standardized medical procedure before and after surgery. Without exception or complicated cases, usually the surgery patients are in a nearly equal state of physiological condition after surgery when they come back to wards from post-operative care unit. It is sensible to compare the impact of therapeutic elements on the patients of equal physiological health status after surgery. To build a reliable model, the following criteria for sample selection were fixed for this study.

- For sampling, take a uniform patient population (e.g. patients undergoing a particular type of surgery/procedure).
- It is logical not to take sample of a particular disease or the entire ward, where the area of physiological problem is the same but due to the varying levels of complication in the disease, clinical recovery or patient LoS may differ.
- It should be a non-psychological disease and should not be related to bones and cancers (as sufficient positive impact of daylight on these diseases already exists in literature, see Table 2.1).
- Selected samples admitted in the hospital should be in an equal or nearly equal stage of the disease at the beginning of the study.
- To recover, selected patients should undergo a standard procedure of treatment.
- The disease should carry both physiological and psychological (usually accompanied with physiological diseases) stress to patients.
- The patients should be free from other major health complexities.

- To recover from the problems, the patients must have to stay in hospital rooms for at least 48 hours to receive treatment. So that, the investigator have enough time to observe the patient's progress before release (very short stays cannot be regarded as being influenced by daylight).

Following the above criteria, a number of patients, who had undergone a major open heart surgery, were taken as sample for this research. Open-heart surgery generally means an operation in which a heart-lung machine is used to support the patient's blood circulation while the surgeon opens the chest and makes changes to the heart or the arteries on the surface of the heart (Parks, 2008). After surgery, the patients are moved to a bed in the Cardio-Thoracic Intensive Care Unit (CTICU). With gradual improvement to satisfactory levels, the patients are transferred from the CTICU to the Cardiac Surgery In-patient Unit (CSIU). When the patients are assigned to hospital rooms in CSIU they were ready for the observational study.

b. Selection of the variables

Selection of variables is important for successful statistical analysis. For statistical analysis different variables were considered in four studies shown in Table 3.1. The variables could be grouped into four major classes: environmental variables, physiological variables, demographic variables and psychological variables. Among four studies one research considered demographic variables (Walch et al., 2005). Park (2006) balanced his study with six physiological variables and four psychological variables. He investigated how patients are able to utilize plants for their recovery using a multi-modal combination of medical and psychological measurements. As the therapeutic influences of ornamental indoor plants on patients, recovering from surgery, are mostly psychological, and physiological health improvement is the output of psychological acceptance of plants by the patients, his variable selection was sensible. In Dutro's (2007) study no physiological data were considered but he admits physiological data (i.e. blood pressure, blood, and saliva tests) would yield the most accurate quantitative data to test his postulation. Because this testing would compel using an invasive procedure on children, it was determined that for his experiment these type of tests were not feasible. Choi et al. (2012) did simulations to identify five lighting variables in his study but considered only one physiological variable that is patient average LoS and no other clinical variables were considered. Choi et al. (2012)

correlation research between only two variables (the average LoS and simulated indoor daylight environments of patient rooms) made his result less reliable from clinical point of view. On the other hand Walch et al. (2005) being clinicians, considered as many as 15 clinical variables but has limitation on measuring the intensity of daylight inside hospital rooms that was the only environmental variable in his model (discussed in Section 3.4.1).

It was emerged from literature that the views of variable selection are different, when analysed by clinicians and non-clinicians. Clinicians try to consider more clinical variables and non-clinicians tend to focus on environmental and/or architectural variables. There are some common variables selected by both groups. Reviewing the past works on variable selection and considering open heart surgery patients as sample group, the following variables were recommended for this research for a single case investigation.

- **Environmental variables:** illuminance (daylight intensity in lx), room temperature, relative humidity (RH), room type (e.g. suite, single deluxe, single standard, semi private-double bed room) and POV.
- **Clinical variables:** LoS, blood pressure, body temperature, heart rate, respiratory rate. Clinical variables also depend on the selected sample groups; this means the type of patients or diseases that will be investigated. After a discussion with hospital medical staff, additional variables that may be considered for open heart surgery patients and can be included in the model were identified. Those were patients' smoking habit, hypertension, dyslipidaemia, myocardial infarction (MI), transient ischaemic attack (TIA), stroke, bronchial asthma, cerebral vascular diseases (CVD), diabetes mellitus (DM), chronic renal failure (CRF), ejection fraction (EF) value, saturation of peripheral oxygen (SPO2), fasting blood sugar (FBS) and fluid balance.
- **Demographic variables:** gender, age, weight and body mass index (BMI).
- **Psychological variables:** it was evident from previous studies that psychological variables are correlated with clinical variables; therefore, the direct/indirect psychological impact of daylight on patients' physiological health can be observed by analysing clinical variables mentioned above. To make the research more objective, emphasis was given on the parameters of patients'

physiological health indicators in this research and no psychological variable were recommended separately in this research. There are also possibilities of multicollinearity, if psychological variables are included in the same statistical model with clinical variables.

c. Statistical model

The four studies selected for critical review (Table 3.1) have a common ground in methodology, that the therapeutic effects were assessed by statistical analysis. Hypothesises were supported by t-Test, chi-square test, ANCOVA, ANOVA, Kruskal-Wallis test, Mann-Whitney test, Tukey's Standardized Range test and regression analysis using Minitab statistical software program (Walch et al., 2005), SAS (Park, 2006; Dutro, 2007) and SPSS (Choi, 2012; Dutro, 2007). Most of the research considered lighting (or indoor environment) as a categorical or ordinal variable, and only two variables at a time (e.g. daylight level/orientation and LoS). But, to establish the complex relationship between daylight intensity and LoS, a group of variables (both continuous and categorical) are needed to be considered to measure the effects of several environmental (e.g. daylight and view) and clinical (e.g. LoS and blood pressure) factors concurrently.

The intention of field investigation in this research was to compare the LoS of patients who experienced varying daylight intensities and POV during their treatment in hospital rooms. To fill the research gap, evidence based relationship needed to be developed which can correlate the daylight intensities and other environmental variables (for example POV and room type) with clinical variables (for example blood pressure, body temperature, heart rate and respiratory rate) to predict patient LoS, therefore, the purposes of statistical analysis of field data were:

- to understand the functional relationship between the patient LoS and other (environmental, clinical and demographic) variables mentioned in Section 3.4(b), to observe what might be causing the variation in the patient LoS; and
- to estimate patient LoS corresponding to a set of daylight intensities.

As there were more than two continuous variables needed to be analysed to predict patient LoS as a function of other (environmental, clinical and demographic) variables grouped under a "hidden" nominal variable (patient name), after analysing 33 statistical tests for biological statistics recommended by McDonald (2009), MLR test was found suitable to satisfy the purpose of the statistical analysis of field data. MLR analysis is a method for measuring the effects of several factors concurrently. MLR attempts to model the relationship between two or more explanatory (independent) variables and a dependent (response) variable by fitting a linear equation to observed data. Every value of the independent variable x is associated with a value of the dependent variable y. Formally, the MLR model for p observations can be expressed as Equation 3.1:

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_p x_{pi} + \varepsilon_i \tag{3.1}$$

where, y_i is the true dependent, β_0 is the constant or intercept, β_1 to β_p are the coefficients relating the p explanatory variables to the variables of interest, and ε_i is the error term reflected in the residuals. It should be noted that whether it is for a single variable or for multiple variables, the relationship predicted is always linear. In the least-squares model, the best-fitting line for the observed data is calculated by minimizing the sum of the squares of the vertical deviations from each data point to the line (if a point lies on the fitted line exactly, then its vertical deviation is 0). Because the deviations are first squared, then summed, there are no cancellations between positive and negative values. The ordinary least-squares estimate β_0 to β_p, are usually computed by statistical software packages (e.g. SPSS).

The null hypothesis in this study states that an increase of daylight inside patient rooms will have no effect on the patient LoS. The dependent variable of the model (y_i) was the patient LoS in the hospital in-patient rooms in hours, and primarily, the explanatory variables (x_i) were the rest of the variables. To determine the multicollinearity between explanatory variables, that may bias the standard error, generate wrong sign and implausible magnitudes in the coefficients (Chin et al., 2003), Pearson Correlation among the primary selected explanatory variables were analysed and the most significant variable from the correlated variables was separated to develop a suitable statistical model. After that, a stepwise regression analysis was conducted among the short listed non-correlated variables to select the “best” set of explanatory variables and insignificant variables were eliminated from the model. The analysis of field study data established evidence based relationship between the amount of daylight, and patient

LoS, while controlling other factors such as type of patient, hospital type, quality of treatment, room basic geometry, furniture layouts and colour schemes.

The elasticity (η_y), degree to which patient LoS (dependant variable) changes in response to a change in daylight level (independent variable) was calculated by using Equation 3.2:

$$\eta_y = b\left(\frac{\overline{X}}{\overline{Y}}\right) \tag{3.2}$$

where, the slope coefficient for daylight in MLR model is b . $\overline{Y}$ is the average value of the dependent variable (LoS) and $\overline{X}$ is the average value of the independent variable (daylight).

d. Sample size

In a statistical relationship, the larger the sample size, the higher the confidence level that the results truly reflect the population and the result is significant. In other words, for a given confidence level, the larger the sample size, the confidence interval will be smaller (CRS, 2010). In statistics, a result is significant if it is unlikely to have occurred by chance and the level of significance is reported by *p-value*. Conventionally, the level of significance of 0.05 (5%) is used for statistical analysis. Considering other factors such as the number of samples and risk associated with the interpretation of the result, other levels may also be used. In this research, the level of significance of 0.10 (10%), 0.05 (5%) and 0.01 (1%) have been considered as marginally significant, significant and highly significant, respectively (Stigler, 2008).

Among the four studies presented in Table 3.1, the sample number varied from six (Choi et al., 2012) to 90 (Park, 2006). According to Vittinghoff et al. (2005: p.43), 'If the outcome is uniformly distributed... confidence intervals may be valid with as few as 30–50 observations. However, with long-tailed outcomes, samples of at least 100 ... may be required for hypothesis tests and confidence intervals to be valid.'

Considering the time constraints and reviewing the sample numbers of previous researchers (Table 3.1), a minimum 30 samples were targeted for pilot study (duration two months) and above 100 samples were targeted for principle study (duration 12 months). Finally, 40 samples were possible to include in pilot study model and 263 samples were included in principal study model.

e. Sources of data

The research started with an aim to develop some strategies for the incorporation of therapeutic effect of daylight in hospital in-patient room design, generic in nature, which can be applicable to most of the regions of the world and not specific to a location or climate. In this research, emphasis was given on the patients' physiological attributes which are common in individuals' inner body mechanism, rather than on the psychological attributes that vary with cultural and/or racial backgrounds. The design of the retrospective field study was developed in such an objective manner that, if the sample from a standard hospital satisfies the criteria of Section 3.4(a), the hospital can be selected for case study to establish quantitative link between daylight intensity and patient LoS.

Dhaka, the capital of Bangladesh (the origin and country of birth of the researcher), where the researcher spent more than 12 years, before starting his PhD at Loughborough University, UK, and have experience of daylighting survey (for office buildings) during postgraduate level research (Joarder, 2007) was selected as the place to find out a suitable hospital building for field investigation to collect data for this research.

In August, 2007 nearly 50 hospitals in Dhaka city were surveyed by the final year students of Professional Practice Course, offered by the Department of Architecture, Bangladesh University of Engineering and Technology, and the outcomes were reported in the daily newspaper (Joarder, 2008). Reviewing the physical data of the survey, three standard hospitals in Dhaka city were found suitable for conducting survey and approached for the approval: Square Hospital at Panthapath, United Hospital at Gulshan and Apollo Hospital at Bashundhara. Square Hospital responded very quickly and positively, and agreed to allow conducting pilot and principal surveys that in total took nearly two years to complete. This research ensures compliance with the Data Protection Act 1998 and was checked by an Ethical Advisory Committee. The objectives of the research were informed to the hospital authority and researcher took approval prior to start survey.

Retrospective field study was performed in the cardiac inpatient unit, located at 10th floor of 15 storey Square Hospital building with a number of open heart surgery patients who were assigned to hospital rooms and experienced varying lighting conditions at their stay time during the study periods of pilot and principal survey. At the beginning of field investigation, sources of clinical data which will be used as variables in MLR model were identified. Clinical data (e.g. LoS, blood pressure, body temperature, heart rate and respiratory rate) and demographic information (e.g. age, gender and BMI) were collected by case hospital staff from patient record files, analysing discharge summary, patient evaluation form, vital signs record, pre-procedure checklist for general anaesthesia, operation record, outpatient department (OPD) clinical record, 2d M- mode/colour doppler echocardiography report, integrated progress notes, fluid balance chart: intake and output record, medication chart, insulin chart, diabetic chart and other medical reports with doctors' consultations. Environmental (light, temperature and R.H.) data of the hospital were collected by installing indoor data loggers (U12-012, Temp/RH/Light/Ext Data Logger, 12 bit) and outdoor data loggers (UA-002-64, Pendant Logger Temp/Light, 64k memory), inside and outside of the hospital building. Average illumination values inside patient rooms were calculated by daylight simulation programme, using actual HEI obtained from outdoor data loggers installed at the top of the hospital roof.

f. Data collection and analysis

The procedure of clinical data collection and statistical data analysis were the same for both pilot and principal study. To eliminate bias, the experiment was run double blind. That is, neither the patients nor the doctors were concerned about the actual daylight situations of the rooms, and there was no verbal interaction between the researcher and the observed patients. The study was observational in nature where the patients were assigned themselves to the different sample groups and the researcher observed the impact. Historical controls were applied in this study since randomised control is not feasible in a hospital environment. In this research patients treated with varying daylight intensities in the past were compared with each other once they came back from CTICU to cardiac in-patient unit. During this time, more tests were usually conducted to assess and monitor the patient's physiological development. Recorded test results were used for statistical analysis to predict about patient LoS inside hospital in-patient rooms. Data collection and analysis were done in following three stages, described below.

3.4.1. Pilot study

One of the constraints of daylight research is the estimation of daylight levels which change rapidly with time with the change of cloud cover in the sky. In Walch et al. (2005) research, the measurements of daylight intensities were taken by a light meter twice daily in the observed patient rooms at approximately 9:30 AM and 3:30 PM. These measurements were multiplied by the number of AM and PM daylight exposure hours and summed to determine the cumulative daily daylight exposure in lux-hours. The measurement of daylight intensity only twice a day does not represent the actual daylight levels that the patients experienced during their stay time in hospital, because of the rapid change of daylight intensity throughout the day. A more continuous measurement of daylight intensities for patient rooms was necessary for reliable outcome. This measurement could be done by either installing several data loggers in each patient room, or using simulation software to identify the average daylight levels. As it was not possible and practical to fix several data loggers on the test plane of the each patient room in a running hospital environment to calculate the average daylight intensity of each room (for e.g. 60 data loggers will be required to place on 850mm height with 500mm interval/grid in each room which is not possible to continue under the presence or treatment of patients), application of daylight simulation programme was preferred for pilot study to calculate the average room illumination.

To analyse the daylighting environment Choi (2005) used lighting simulation program, RADIANCE, to identify the illuminance level in his study. To verify the output data from RADIANCE, the calculated data produced by RADIANCE were compared with the data from the site and scale model measurement. The discrepancy between RADIANCE and on-site measurements was 2% to 47% and RADIANCE and the scale model was 9% to 50%. Choi (2005) suggested that as daylight is very much sensitive to sky conditions, this dependency can result in large discrepancies due to the difference between CIE sky condition (defined by International Commission on Illumination (CIE)) and the actual sky condition. CIE intermediate sky condition does not cover the various amount of cloud on sky and it is not the same with the actual sky condition. Thus, the HEI of RADIANCE is not identical with the actual HEI values. One HEI value cannot cover the diversity of the intermediate sky that covers 30% to 70% of the sky with clouds. Figure 3.3 shows the variation of averaged HEI from 19 November 2008 to 21 January 2009 for Dhaka, Bangladesh. So, during pilot study, one outdoor data logger was installed at the top of helipad above case hospital roof about 66m from ground level (Figure 3.4) to measure HEI with five minute interval. The output of data logger was used to simulate average interior daylight intensity of the studied rooms considering the CIE standard overcast sky model with a full progressive radiosity inter-reflection method using FlucsDL of IES (Virtual Environment 5.5).

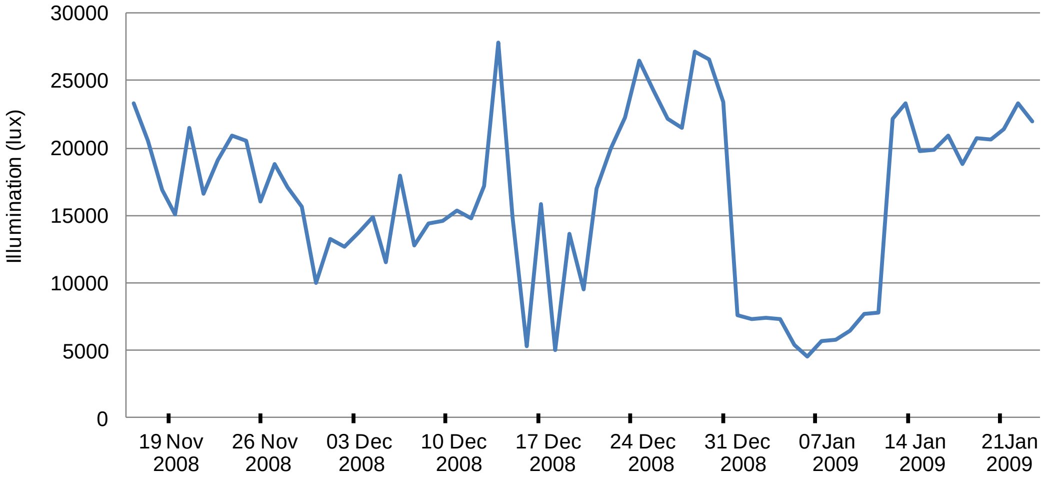


Figure 3.3: Averaged HEI from five minute interval data recorded by outdoor datalogger for Dhaka, Bangladesh.

Figure 3. 4: Location of outdoor data logger.

During pilot study, the hospital building and its surroundings were surveyed (Section 4.4 and 4.5; and Figure 4.6 and 4.7), and as-built drawings and material specifications were collected from the Engineering Division of the hospital to use the information to build 3D model for daylight simulation study. Acquired building information and HEI obtained from outdoor data logger were entered into an integrated whole building simulation program (i.e. IES). Instead of the daylight data of Typical Meteorological Year (TMY), actual outdoor HEI, measured from site was used to consider the unpredictable nature of outdoor daylight intensity. The final output of IES was the threshold tables for average interior daylight intensity for each of the studied room in Hyper Text Markup Language (HTML) format for each day, with respect to particular patient stay time. These indoor average daylight intensities from daylight simulation programs were correlated with clinical variables (e.g. LoS, blood pressure and heart rate) to predict about patient LoS in hospital rooms. The data collected during pilot study were used to develop a MLR model to explore the relationship between average daylight intensity of the in-patient room and patient LoS in hospitals. The coefficient estimates of MLR model showed that while holding the other explanatory variables (POV, mean arterial pressure, heart rate, diabetes mellitus, SPO2 and FBS) constant, the increase of 100 lx of average daylight inside in-patient room reduces patient LoS by, on average, 4 hours. The major limitation of pilot study was that it was based on simulated average indoor daylight data that could not accounted many aspects, such as patients' behaviour on blinds adjustment and overhead lighting control.

Considering the time limit of pilot study and probable risk associated with uncertainty of the output of the analysis of collected data, it was preferred to do a quick statistical analysis with simulated lighting data at the beginning. It was also planned that a successful completion of pilot study and statistical analysis of collected data with expected outcomes will lead to do an extensive principal study for one year with an updated methodology with a higher number of data loggers to cover the entire cardiac in-patient unit of Square Hospital, located at tenth floor.

3.4.2. Principal study

During principal study, 31 indoor data loggers were fixed at the back wall of each patient bed (head side) at the same cardiac inpatient unit studied for pilot study (Figure 3.5). The indoor data loggers were fixed on the wall at 2000mm height from floor level to avoid shadow on sensors due to movement of patients and hospital staff during work. To predict patient stay times in hospital rooms, the daylight level with one hour interval obtained from the indoor data loggers were used directly in the MLR model to correlate daylight intensities with clinical variables, therefore, no daylight simulation was required/done during principal study. The data collected during principal study were used to develop a stronger MLR model compared to pilot study model to explore the relationship between daylight intensity at a particular point above patient’s head (Figure 3.5) and patient LoS. The coefficient estimates of MLR model showed that while holding the other explanatory variables constant (POV, rent of the rooms, mean arterial pressure, heart rate and diabetes mellitus), the patient LoS reduces 7 hours per 100 lx increase of daylight intensity near a point above patient’s head (i.e. location of indoor data loggers).

Figure 3.5: Location of indoor data logger.

3.4.3. Daylight intensities for health

To incorporate therapeutic effect of daylight in the architectural design of hospital in-patient rooms, it is important to know the characteristic of light objectively (e.g. intensity and duration) that may support to reduce patient LoS in hospitals, therefore, review of the existing lighting standards and recommendations for hospital in-patient rooms are necessary. Table 3.2 presents a comparison of some current recommendations (ADB, 2009; SLL, 2008; CIBSE, 2002 and IESNA 2000) on general internal lighting for hospital wards and single bedrooms.

Table 3.2: Recommendations for lighting for hospital words and single bedrooms.

Lighting purpose	**Maintained illuminance (lx)**			
	ADB (2009)	**SLL (2008)**	**CIBSE (2002)**	**IESNA (2000)**
General lighting	100		100	75-200
Local lighting for reading	150	300-520	300	200-350-500
Lighting for simple examination		300-520	300	
Lighting for examination and treatment		1000	1000	
Night lighting, observation lighting	5	5-10	5	
Lighting for bathroom and toilets for patients			200	

Most of the lighting and photobiology publications are focused on artificial lighting sources (Pechacek et al., 2008) to meet the visual needs, including the recommendations presented in Table 3.2. It is recognised that, even artificial light and daylight might have the same intensity level; the properties of artificial light and daylight are different with respect to human perspective. Individuals accept less daylight compared to artificial light to do the same visual activities (MIT IAP, 2008). The physiological and psychological effects of lighting are especially different (Choi, 2005) from these two sources of light. The standard for daylight and artificial light should differ for both visual and health purposes. In this research, the benchmarks of daylight intensities within which patient LoS inside in-patient rooms are expected to be reduced have been identified by following two steps.

a) Identification of the benchmarks from literature.
b) Verification of the benchmarks, using the data collected during principal study.

a. Identification of the benchmarks from literature

Threshold values defined by the outcomes of photobiology research can be used as goals for daylit in-patient room design to ensure circadian illumination in terms of intensity, timing and spectrum of light incident on human eye (MITDL, 2011). Pechacek et al., (2008) research first attempted to provide some objective characteristics of daylight for circadian efficacy applicable for healthcare facilities. Pechacek et al. (2008, p.7) developed this system of equivalencies where ‘an inferred radiometric spectrum of a known light source is multiplied by the circadian action spectrum [C(λ)] curve to determine a circadian weighting [W-C(λ)]'. To account for the variability of the changes of daylight in apparent colour temperature with time of day, orientation and weather conditions, D65 (ASTM, 2006) was assumed for south, east, and west orientations, and D75 (ASTM, 2006) for north orientations in their research. Pechacek et al. (2008) validated that the same circadian power will be achieved with 190 lx daylight for south, east, and west orientations and 180 lx for north orientations with an uncertainty of ±10 to 20 lx, when daylight will be transmitted through a double-pane, clear, low-E window. The timing and duration of daylight exposure is also important for circadian system. The timing was fixed from 06:00 AM to 06:00 PM with duration of 12 hours average daylit period (applicable for most of the locations) on patients' eyes. The details of the system are available in Pechacek et al., (2008). The paper (Pechacek et al., 2008) later received the Taylor Technical Talent Award (TTTA, 2009) from the Illuminating Engineering Society of North America (IESNA). Gochenour et al. (2009) also applied the proposed index to evaluate the circadian potentiality of daylit space in residential building.

Although, Pechacek et al., (2008) work is a great advance on the evaluation of the therapeutic effect of daylight, it is not beyond limitation and criticism (Gochenour et al., 2009). Pechachek et al. (2008) derived the action spectrum from the response of fixed doses of monochromatic light based on the studies of night-time melatonin suppression. The response to polychromatic light, for example daylight during the daytime, is still not entirely understood. There is still gap in knowledge to set appropriate values for regulating individuals' circadian rhythms, and other physiological and psychological systems from photobiology. Pechacek et al., (2008: p.5) admitted that their method, presented, uses off the shelf technology and the findings should not be taken as an absolute measure of circadian efficacy or health potential because 'the precise definition of the human circadian action spectrum [C(λ)] is still underway' and the model predictions needs to be tested. The test of Pechacek et al., (2008) recommendations (if a minimum 180/190 lx of daylight around patients head can provide circadian stimulation to patients) is beyond the scope of this thesis, however, If 180/190 lx daylight can be considered as lower limit of daylight for therapeutic purpose to reduce patient LoS in hospitals, and could be used as a goal for simulation study for Chapter 5, is one of the interests of this research.

Nabil et al. (2006: p.905) provided a more detailed classification of daylight intensities after reviewing the published findings, based on the data from field studies on occupant preferences and behaviour that considers the 'propensity for excessive levels of daylight that are associated with occupant discomfort and unwanted solar gain'. Table 3.3 shows a summary of the findings. Nabil et al. (2006) concluded that, daylight illuminance in the range 100–2000 lx are potentially useful for the inhabitant of a room.

Table 3.3: Classification of daylight intensities based on occupants' preferences and behaviour (Nabil et al., 2006).

Daylight illuminances (lx)	**Occupants' preferences**
less than 100	insufficient daylight as sole source and needs significant amount of additional artificial light
100–500	effective daylight as sole source and can be used in conjunction with artificial light
500–2000	desirable or at least tolerable level of daylight
higher than 2000	likely to produce visual and/or thermal discomfort

Rogers (2006: p.13) proposed that the threshold of potentially glary conditions depends on the design illumination of a space and 'a patch of illuminance at least 10 times greater than the design illuminance typically represents an occurrence of direct daylight that could potentially cause glare and other visual comfort problems in a daylit space'. ADB (2009), CIBSE (2000) and Nabil et al. (2006) proposed a minimum 100 lx; IESNA (2000) recommends 75-200 lx for general lighting and Pechacek et al., (2008) proposed a minimum 180/190 (±10 to 20) lx on patients' head for circadian support. Based on different sources, according to Roger's (2006) proposal, glary conditions could vary from above 750 lx to 2000 lx. Many researchers suggest that much higher light levels – in excess of 1000 lx – are needed to stimulate biological systems compared to the visual systems (Middleton et al., 2002; Baker, 2000; Zeitzer, 2000; Muneer 2000), therefore, above 2000 lx which is the level that likely to produce visual and/or thermal discomfort found by Nabil et al., (2006) is more acceptable as the upper limit of therapeutic daylighting goal. The discomfort indexes proposed by Nabil et al. (2006) and Rogers (2006) are based on office and classroom environments and the values are needed to be further verified before use as a simulation goal for hospital environments.

b. Verification of the benchmarks using the data collected during principal study

The samples and data collected during the principal study were used to generate another MLR model to verify the upper (2000 lx) and lower (190 lx) limits of daylight, primarily identified from above discussion that can be considered effective to reduce patient LoS in hospitals. During observational studies, the researcher noticed that most of the heart surgery patients were lying with their spine on hospital beds after coming back from CTICU to the cardiac surgery unit. The doctors also advised that the patients are instructed to lie on back without creating any pressure on their chest and not to rest on their sides, particularly on left sides. To identify the amount of daylight that a patient receives on his/her retina, in this stage, it was planned to keep additional data loggers on vacant beds at the location of patients' heads for 24 hours at the same cardiac in-patient unit studied during pilot and principal studies (Figure 3.6).

Figure 3.6: Placement of additional data loggers on a vacant bed.

It was difficult to find an empty bed for 24 hours in a running and busy hospital: Square Hospital. Analysing the hospital's in-patient admission record for previous years (2008 and 2009), it was identified by the researcher that during and after the periods of Eid-ul-Fetur (an annual and biggest religious festival for Muslims, similar to Christmas for Christians) very few hospital beds are occupied by the patients and most of the beds remain vacant for two to seven days. Admissions and discharges of patients become rare, except for very emergency cases. So, the researcher targeted the period of Eid-ul-

Fetur (took place on 11 September in 2010) for this particular part of experimentation. During this time, additional data loggers were kept by rotation (as there were only 31 data loggers and there were always some patients at the in-patient unit) on vacant beds at the location of patients' heads for 24 hours. In absence of patients, the data loggers on beds recorded the amount of daylight that a patient might get while lying on the bed. An average ratio between two data loggers (one on the bed and the other on the wall) was estimated for each bed of the cardiac in-patient unit. The estimated ratio for each in-patient bed was multiplied with the reading of the data loggers installed on the wall for one year to calculate the amount of daylight that a particular patient might experience on head during his/her stay in the hospital bed. Based on this calculated amount of daylight, the sample patients of principal study were grouped in three categories. The first group contained the patients who had experienced lower levels of daylight (below 190 lx) in the maximum time of their stay inside in-patient unit. The second group contained the patients who had experienced moderate levels of daylight (between 190 lx to 2000 lx) in the maximum time of their stay inside in-patient unit. The third and last group contained the patients who had experienced higher levels of daylight (above 2000 lx) in the maximum time of their stay inside in-patient unit. The second group was taken as reference and their stay time was compared with other two groups during statistical analysis. It was found that the stay time for other two groups were significantly higher (extra 29-42 hours) than the reference group who experienced moderate levels of daylight in the maximum time of their stay inside in-patient unit. The specific limitation of this part of the study was that, the ratio between two data loggers was calculated from one day data but considered for the whole year. As the ratio was calculated in absence of patients, hence, the effect of patients' behaviour on blind adjustment and artificial light control was not possible to include. As, the estimated values of daylight were not directly used in the MLR model similar to the earlier study and only used to group the sample patients under three categories, the deviation from exact value have little impact on grouping patients (for example, the patients experienced average 500 lx or 1500 lx will fall in the same moderate daylight group). As the benchmarks of daylight intensity to ensure therapeutic effect of daylight identified from literature (Pechacek et al., 2008; Nabil et al. 2006) validate field data, it was finalised to be used as a goal for prospective simulation analysis in Chapter 5.

The detailed description of the findings of retrospective field investigation has been provided in Chapter 4 of this PhD thesis.

3.5. Methodology for prospective simulation study

In this PhD research, prospective simulation study was chosen to identify the design parameters that can help to improve the therapeutic potentiality of daylit in-patient rooms. The steps followed in the methodology of simulation in this research were a generic one and practiced by many researchers (for e.g. decision tree defined by Reinhart, 2006 shown in Figure 3.7) for the use of daylighting programs during building design or performance evaluation.

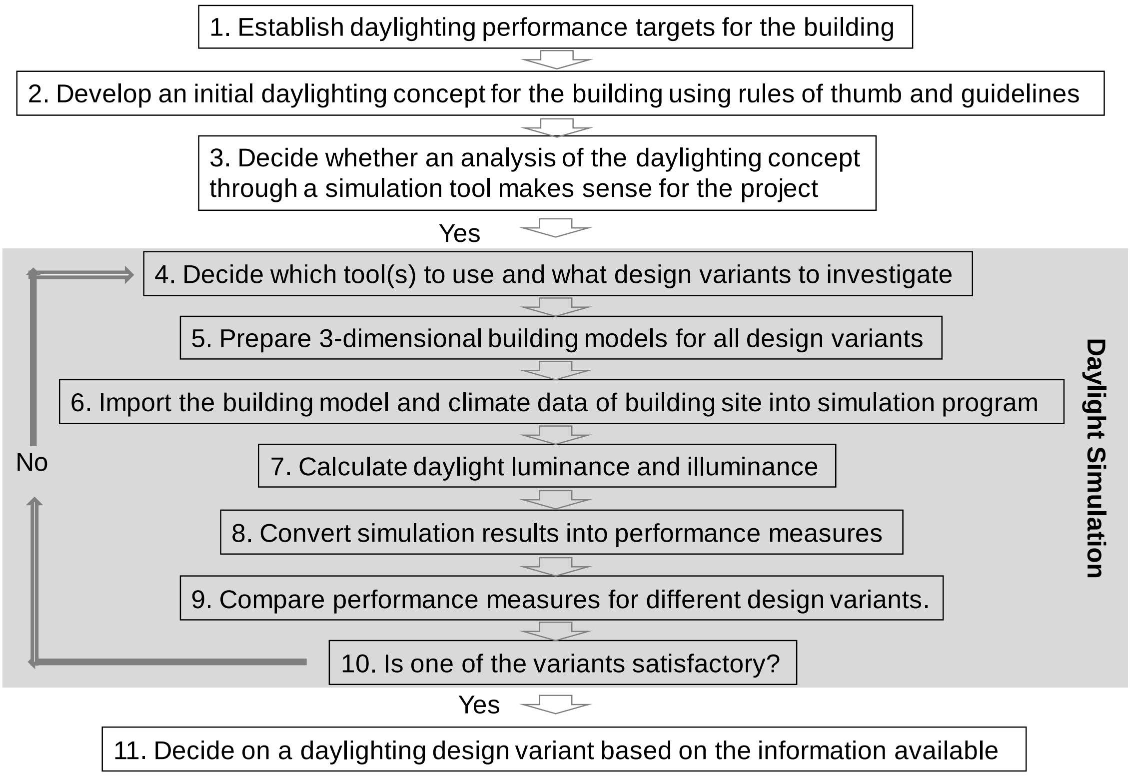


Figure 3.7: Decision tree for the use of daylighting simulation programs during building design (after, Reinhart, 2006).

The methodology to evaluate the probabilistic therapeutic potentiality of a daylit space to reduce patient LoS inside in-patient rooms was based on a dynamic annual daylight simulation method first used by Pechacek et al., (2008) using annual Daylight Autonomy (DA) metrics (Figure 3.8). Pechacek (2008) prospective analysis consisted of major three steps: development of a criterion, evaluation of a space and comparison between criteria and a space's characteristics. Pechacek et al., (2008) described the approach as a relative one and can be applied to analyse the impact of key architectural decisions on achieving effective circadian illumination for example window size, orientation, and glazing material (MITDL, 2011).

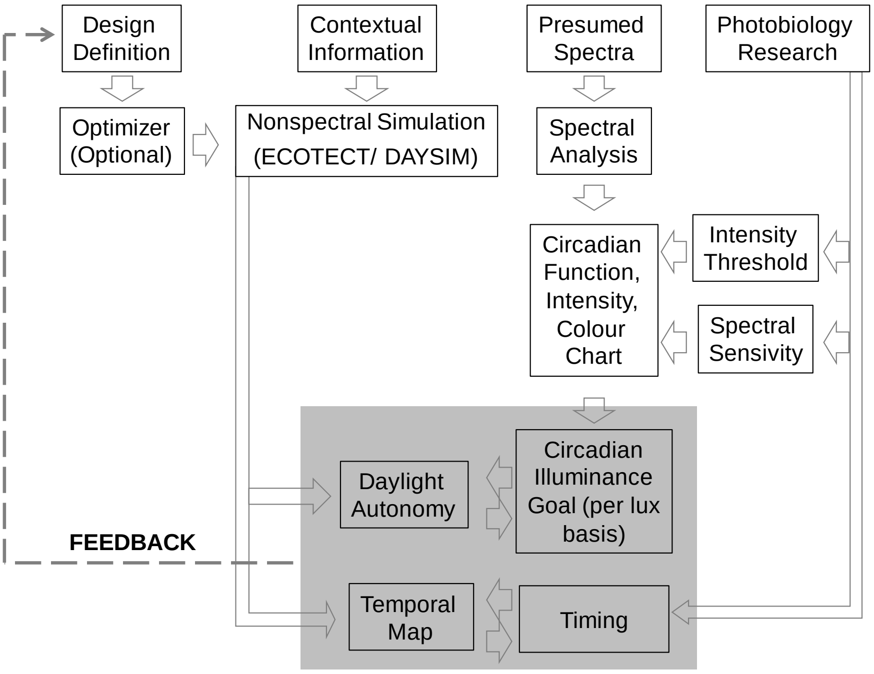


Figure 3.8: Circadian efficacy evalation process (after, Pechacek et al., 2008).

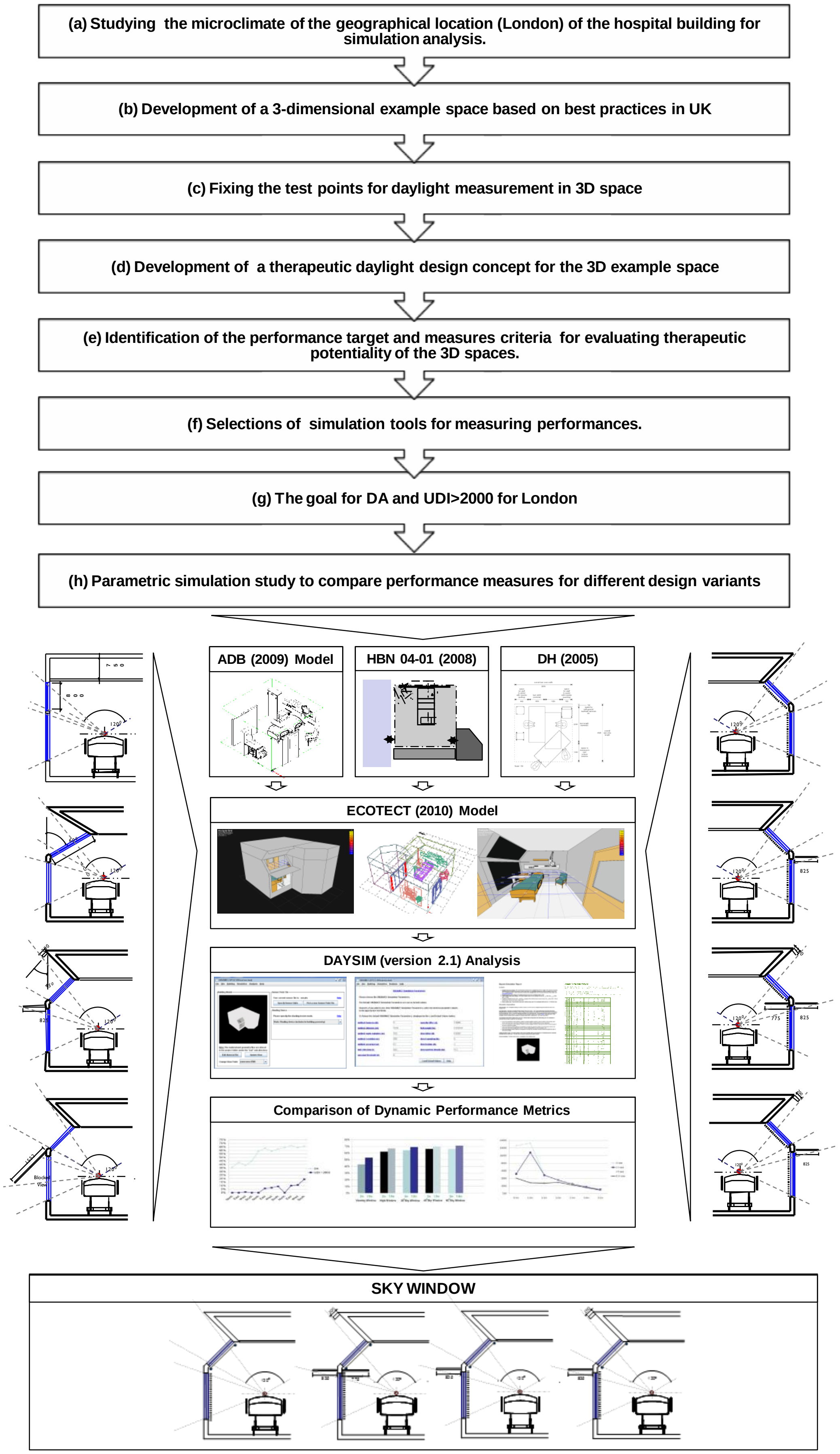
It has already been mentioned that Pechacek et al., (2008) method was the first and very preliminary on evaluating circadian potentiality of a space and need further development and verification (Gochenour et al., 2009). The researcher did not take the assumptions of Pechacek et al., (2008) research without questioning. One of the major differences between Pechacek et al., (2008) method and this research method is that in Pechacek et al., (2008) experiment the illuminations were measured, and the results were displayed on a vertical plane, located approximately at patient's head. The vertical plane was perpendicular to the window surface and the sensors were faced towards the partition wall. It is difficult to assume the room overall lighting situation (including excess light and glare) from a spatial distribution of illumination levels on a vertical plane go through patient head and mostly incident on the back wall of patient bed. Except the light on retina, the rest of the light presented on this vertical plane has little or no scope to be experienced by the patients. There are possibilities that the patients might rest with their spine and look forward to the ceiling. Many researchers emphasised that bedridden patients are forced to look at a monotonous white ceiling of hospital rooms and suggested decorative ceiling for hospital rooms (Dutro, 2007; Horsburgh et al., 2001). The impact of decorative hospital ceiling design on patients' choice and performance was found as a positive distraction from many studies (Dutro, 2007; Eriksen, 2001; Ulrich 1991; Cintra 2001). In this research more emphasis were concentrated on illumination distribution on horizontal planes with sensors upwards (which is widely practiced in daylight simulation analysis) to develop the design of daylit in-patient rooms for therapeutic purpose, and to support a design decisions (for example depth of sunshade). In addition, to compare therapeutic potentiality, illuminations on patients' heads from both horizontal and vertical directions were considered. The steps of the previous research methodologies (Figure 3.7 and 3.8) were rearranged, modified and updated to match with the progress and findings of this research (Figure 3.9 and 3.26).

Prospective simulation study was done in two phases to evaluate the performance of the daylight design concept:

- under current Typical Meteorological Year (TMY); and
- under the future climate defined by United Kingdom Climate Impacts Programme 2002 (UKCIP02).

3.5.1. Simulations under current TMY

The benchmarks, recommended from literature (190 lx to 2000 lx) to ensure therapeutic effect of daylight effectively, were universal based on human biological system, and once confirmed with the data collected from Dhaka, Bangladesh, that was objective in nature; the suitability of using the benchmark to other geographical locations were justified. The benchmarks were used to evaluate the therapeutic potentiality of an imaginary in-patient room located in central London by prospective simulation study. The principles of trial-and-error method were followed in the parametric simulation analysis to support a decision. The eight steps shown in Figure 3.9 were followed to develop and compare therapeutic daylit space to support hospital patients' recovery.



(a) Studying the microclimate of the geographical location (London) of the hospital building for simulation analysis.

(b) Development of a 3-dimensional example space based on best practices in UK

(c) Fixing the test points for daylight measurement in 3D space

(d) Development of a therapeutic daylight design concept for the 3D example space

(e) Identification of the performance target and measures criteria for evaluating therapeutic potentiality of the 3D spaces.

(f) Selections of simulation tools for measuring performances.

(g) The goal for DA and UDI>2000 for London

(h) Parametric simulation study to compare performance measures for different design variants

Figure 3.9: Flow diagram of prospective simulation study under TMYs.

a. Microclimate of the geographical location (London)

The potentiality of achieving any daylighting goal primarily depends on the geographical location of the building site. The coordinates of Central London are 51°30′29″N and 00°07′29″W. London uses Greenwich Mean Time (GMT) + 0, for less than half of the year. During summer time (daylight saving time), London uses GMT+1, also known as British Summer Time (BST). London has a temperate marine climate (Koppen climate classification), similar to much of the British Isles. Extremely high or low temperatures are rare in London. The city has mainly four distinct seasons: summer, winter, spring and autumn. Summers are warm with 11°C – 20°C average temperatures. Winters are chilly with daytime highs around 4°C – 10°C, but rarely below freezing. Spring has mild days and cool evenings. Autumn is usually mild but often unsettled as colder air from the north and warmer air from the south meet (CIBSE Guide J, 2002).

The weather of London is mostly dry with regular but generally night precipitation throughout the year, with an average of 583.6mm every year. Snows are relatively uncommon, particularly because, heat from the urban area can make London up to 5 °C warmer than the surrounding areas in winter. Table 3.4 shows the monthly average climatic condition of London.

Table 3.4: Average climatic conditions of London, UK (BBC, 2006).

Month	Average sunlight (hours)	Temperature				Relative humidity		Average precipitation (mm)	Wet days (+0.25 mm)
		Average		Record					
		Min	Max	Min	Max	AM	PM		
Jan	1	2	6	-10	14	86	77	54	15
Feb	2	2	7	-9	16	85	72	40	13
Mar	4	3	10	-8	21	81	64	37	11
Apr	5	6	13	-2	26	71	56	37	12
May	6	8	17	-1	30	70	57	46	12
Jun	7	12	20	5	33	70	58	45	11
Jul	6	14	22	7	34	71	59	57	12
Aug	6	13	21	6	38	76	62	59	11
Sep	5	11	19	3	30	80	65	49	13
Oct	3	8	14	-4	26	85	70	57	13
Nov	2	5	10	-5	19	85	78	64	15
Dec	1	4	7	-7	15	87	81	48	15

London has an average 4 hours of sunshine a day and the sky is predominantly overcast (Figure 3.10) all over the year (Schepers et al., 2009). The CIE defined standard overcast sky as, steep luminance gradation towards zenith and azimuthal uniformity (CIE, 2004). Figure 3.11 shows the sun path diagram of London. London sun angle exists below 45^0 for 90% of the year with a highest solar altitude of 62^0. The daylight hours for London vary from 8 hours (during December) to 16.5 hours (during June) throughout the year. Analysing the sunrise - sunset data of London, it was found that the earliest sunrise time was recorded at 04:43 AM and late sunset time at 09:22 PM on June 21 with a daylight hour of 16 hour 39 minutes. The late sunrise time recorded at 08:04 AM and earliest sunsets at 03:54 PM on December 21 with a daylight hour of 7 hour 50 minutes (WCI, 2010b). Though the data is for 2010, the sunrise and sunset times can be applied for any year (LW, 2009). Figure 3.12 shows the hourly solar radiation averaged by month for TMYs, London and Figure 3.13 presents the calculated hourly HEI of the 21st of each month for TMYs, London. Based on ECOTECT Weather File, 2010, the highest HEI was 72,596 lx on June 21 at 12:5 PM and lowest HEI at 12:5 PM was 6,313 lx on November 21. Considering the daylight situations, it can be concluded that it will be difficult to achieve sufficient daylight for therapeutic purpose for a typical hospital building located in London.

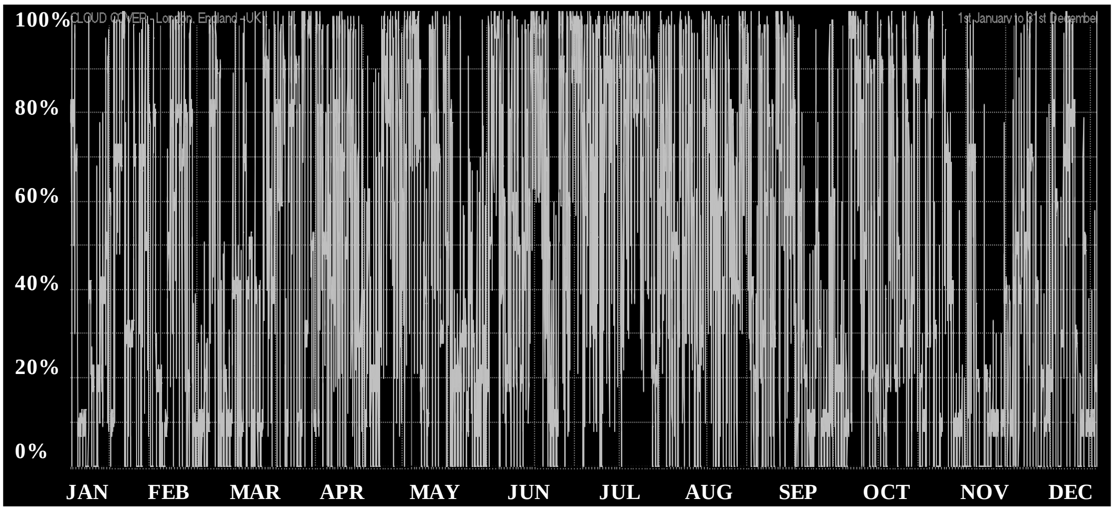


Figure 3.10: Cloud cover for TMYs, London (source of data: ECOTECT weather file, 2010).

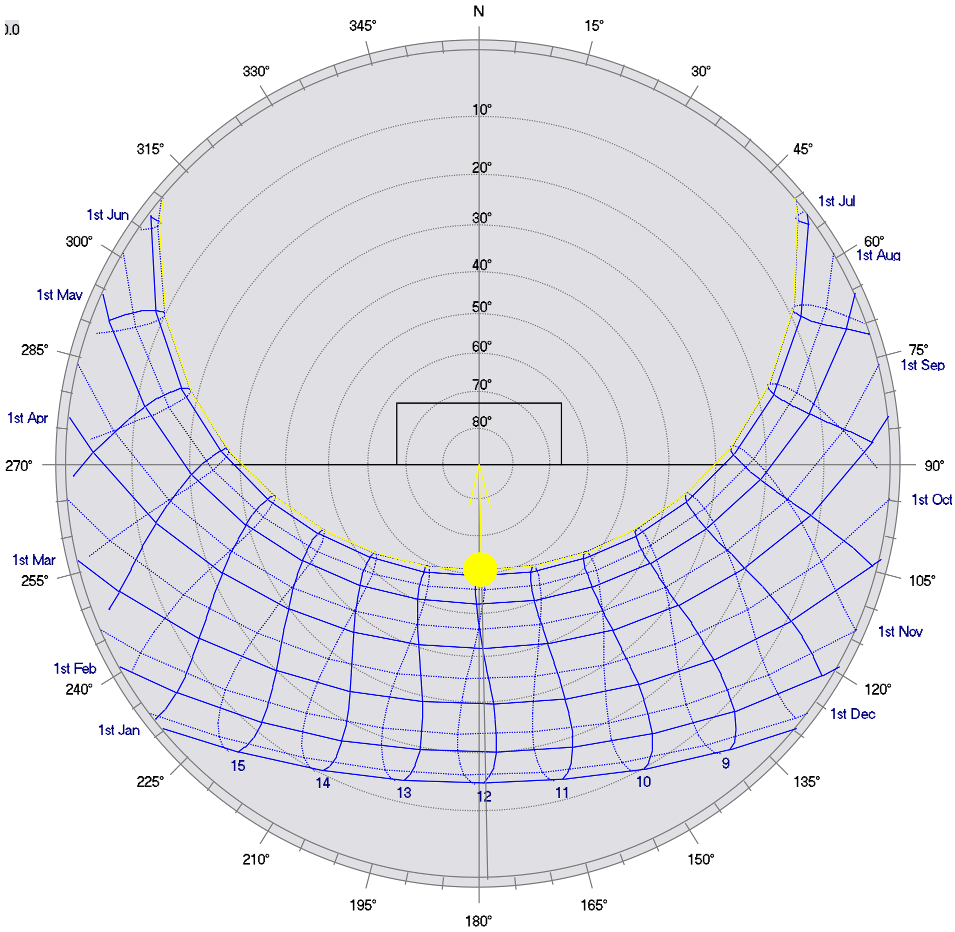


Figure 3.11 :The sun path diagram of London, UK (source: SUNTOOL - Solar Position Calculator, 1998).

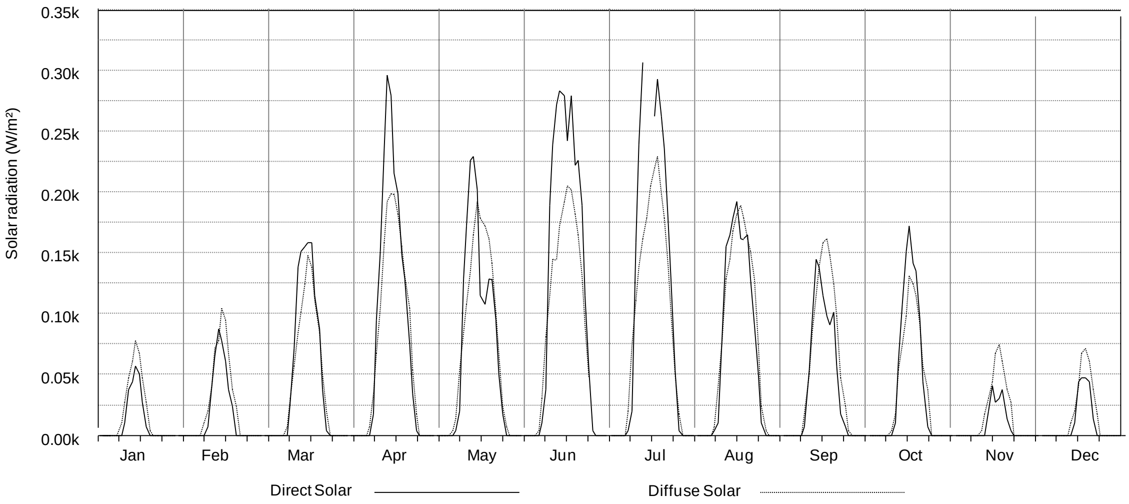


Figure 3.12: Hourly solar radiation averaged by month for TMYs, London (source of data: ECOTECT weather file, 2010).

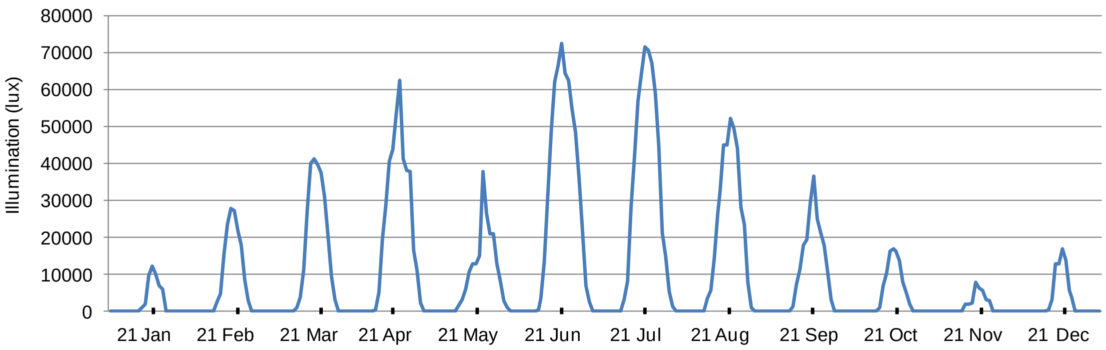


Figure 3.13: Calculated hourly HEI of the 21st of each month for TMYs, London, based on ECOTECT weather file, 2010.

b. 3-dimensional example space

Historically, in-patient accommodations have been the central part of hospital buildings and still occupying the significant proportion of space in a hospital (HBN 04-01, 2008). To ensure therapeutic benefit of daylight for hospital patients, it is sensible to ensure sufficient daylight inside in-patient rooms where the patients are largely stationary. Ne'eman (1974) also emphasise the necessities of daylight, for health purpose, inside in-patient rooms in healthcare facilities, as patients have low mobility compared to staff and others who have options to leave the premises and enjoy daylight more easily. Nowadays, patients are more concerned and have higher expectations of the quality of the space where they are getting treatment. In this regard, the option of single-bed room with provision of high-quality indoor facilities is likely to be the influencing factor in creation of patient-led NHS in near future (HBN 04-01, 2008; DH, 2005a). The majority of patients prefer single-bed rooms due to improved quality of sleep, greater privacy, opportunity for family members to stay, reduced noise, reduced embarrassment, and avoidance of upsetting other patients (Douglas et al., 2002; Kirk, 2002; Pease et al., 2002; Reid et al., 1973).

The current trend in hospital design is to promote patient-centred care and family participation in the patient curative process, where the patients are treated in universal rooms or acuity adaptable rooms consists of private rooms only (AIA, 2006). Studies showed that patient falls, medication errors and procedural problems can be reduced in acuity adaptable rooms (Hill-Rom, 2002; Gallant et al., 2001; Bobrow et al., 2000; Spear, 1997). In the publication titled, 'Guidelines for Design and Construction of Hospital and Health Care Facilities (issue: Single versus multiple bedroom occupancy)', AIA (2006) addressed several key issues on the advantages of single-bed rooms on reduction in the risk of cross infection, improvements in patient care, and greater flexibility in operation. Operating costs are less in single-bed rooms due to higher bed occupancy rates, reduction in transfer cost, and reduction in labour cost with comparison to multi-bed rooms (Hill-Rom, 2002; Ulrich, 2003). Single-bed rooms increase patients' control over personal environment with opportunities to discuss their needs with friends and family (Bobrow et al., 1994; Burden, 1998; Morgan et al., 1999), and more private and thorough consultation with healthcare stuff (Ulrich, 2003). Considering the advantages and acceptances of single-bed in-patient unit to patients, an example module of high quality single-bed in-patient room was developed as case space for the simulation exercise in this research.

The 3D in-patient single-bed room used in the simulation exercise was developed according to the guideline described in Health Building Note 04-01 (2008), published by the Department of Health (DH), UK. HBN 04-01 is a planning and design guideline for adult in-patient facilities. It describes bed, patient support spaces, stores, utilities, sanitary facilities, administration areas and staff facilities. HBN 04-01 gives the "best practice" guidance for new healthcare buildings and extension/adaption of existing facilities. The guidelines are applicable to in-patient rooms in most of the settings, including day surgery, acute and community facilities. HBN 04-01 principally provide information to brief and support the NHS projects.

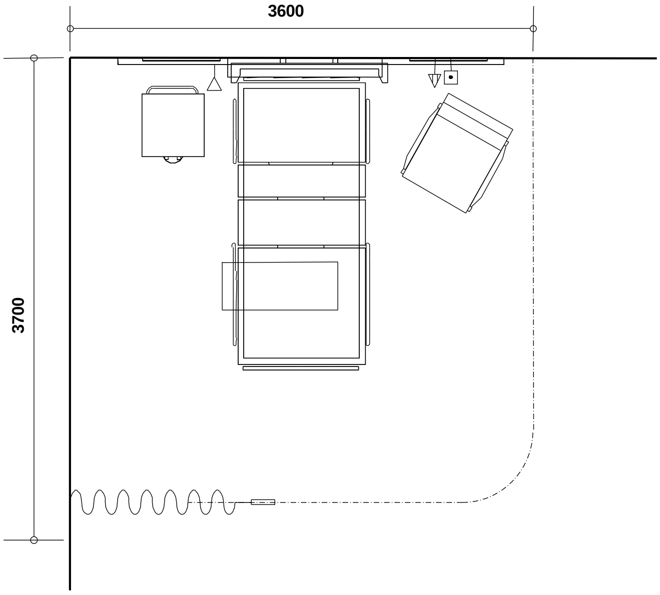
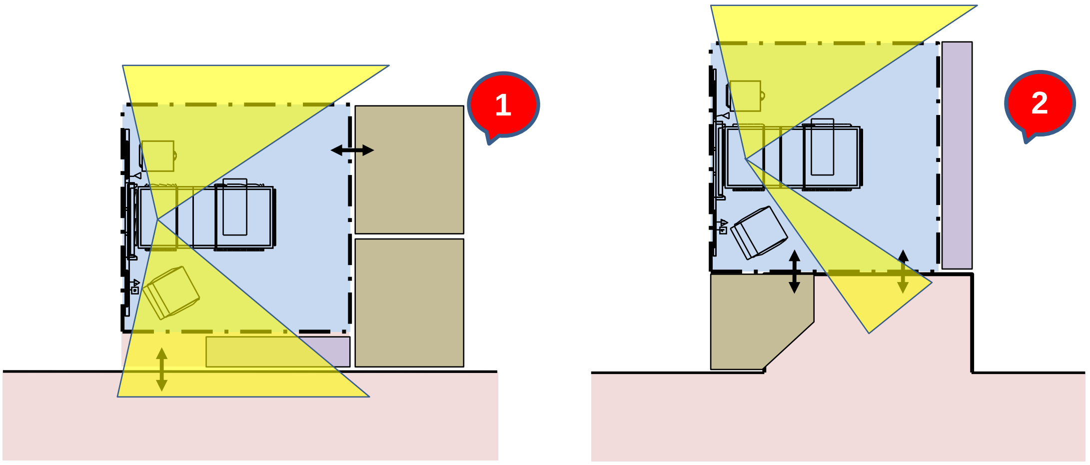


Figure 3.14: Core bed area (after, HBN 04- 01, 2008).

The most important part of an in-patient accommodation is the clinical area of the core bed space. The minimum clear space to carry out most activities around bedside can be accommodated within 3600mm (width) x 3700mm (depth) space established by ergonomic studies (Figure 3.14). This space is required to access around the bed for manoeuvring equipment including the bed in and out of the room; transferring patients into and out of bed; moving and handling of patients; and clinical activities including resuscitation. This area does not include space for fixed furniture, storage, preparation and worktops but can include space for door swings. A clinical support zone is required for built-in storage, hand washing, and space for movable equipment (e.g. supply or disposal trolleys). This space should not overlap clear bed space. In HBN 04-01 (2008), 19m^2 area was recommended for single-bed rooms [2.5m^2 of area increased from HBN 04 (1997)). The height of the space should be 2700mm. The depth and width of the single-bed rooms can vary according to the layout and arrangement of core bed space and clinical support zone. Clinical support zone can be placed in either corridor wall or partition walls.

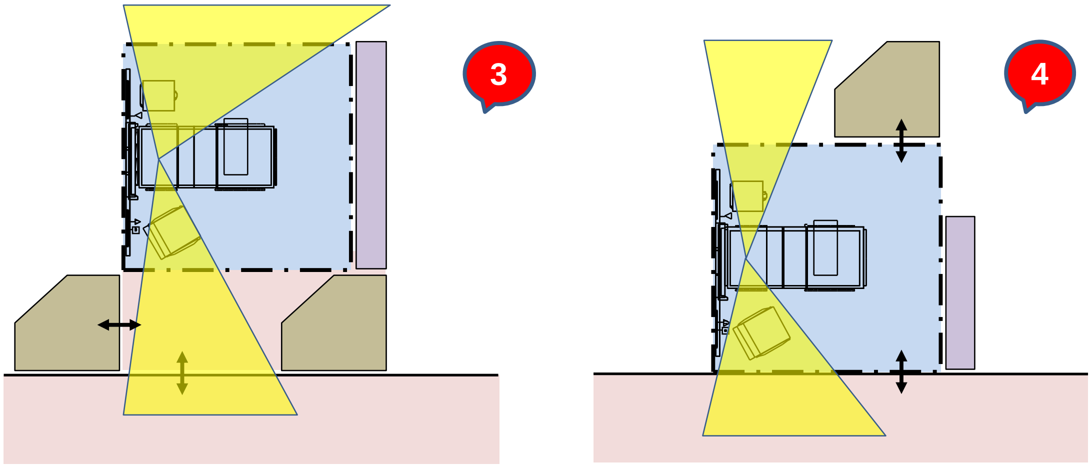
Each single-bed room should have an en-suite with WC, Shower and wash basin facilities (HBN 04-01, 2008; AIA, 2006). The size of the en-suite illustrated in HBN 04-01 (2008) is 4.5m^2 (2285mm x 2100mm) with a chamfered profile (Appendix B). Temporary manoeuvring space to assist a patient from both sides of the WC should be provided and can overlap the bed space and go beyond the enclosed area. The location of the en-suite has a major influence on the in-patients room access point, floor area, privacy, views to and from the bed, and daylighting potentiality of the rooms. Based on the best practice, NHS recommended four example layouts of en-suite location in combination of an in-patient room (Appendix B). According to the suitability of layout, in terms of viewing and daylighting potentiality, four example layouts illustrated in HBN 04-01 (2008) were ranked from 1 (best) to 4 (worst) for this research (Figure 3.15) and are described below.

1. **In-between en-suite:** this is the best location of the interlocking en-suites, as the en-suites do not block corridor and outside view of the patients. The width of the room can be kept the minimum by placing the clinical support zone in a partition wall. The degree of privacy for the patients can be made flexible by reducing the size of corridor window and/or introducing venetian blinds.



a) In-between en-suite

b) Internal en-suite



c) Internal adjacent en-suite

d)External en-suite

Figure 3.15: Four example layouts of en-suites illustrated in HBN 04-01 (after, HBN 04-01, 2008).

2. **Internal en-suite:** in this layout, the depth of the room is the minimum and therefore ensures better distribution of daylight over the room towards the corridor wall. Views of the bed from the corridor are restricted but the maximum outdoor view is possible. Partition walls can be used to accommodate clinical support zone.

3. **Internal adjacent en-suite:** the depth of the room has increased in this layout but has minimised corridor spaces. Views of the bed from the corridor have been improved in comparison to the inboard option. There is no restriction to

outdoor views. Partition walls can be used to accommodate clinical support zone.

4. **External en-suite:** this is the worst location of en-suite among the four alternative locations mentioned, considering daylighting potentiality and outdoor view of the in-patient rooms. The en-suite has blocked approximately 50% of external wall, and kept only half of the external wall free for placing a window. Views of the bed from the corridor have been maximised. The depth of the room can be kept the minimum by placing the clinical support zone to the partition wall with a minimum corridor width.

Among four example layouts, the external en-suite (Figure 3.15(d), option 4) was selected for simulation analysis which the worst en-suite layout is. The performance of a window for external en-suite layout will be the minimum one, which must be possible to be achieved by other three example layouts. It was assumed that the performance of the same window to increase therapeutic effect of daylight inside the rooms will be better for other three options.

c. Test points in 3D space

The Activity Data Base (ADB, 2009) provides detail specification data and software for healthcare environment design including space requirements and graphical layouts of the rooms. ADB software is also capable to generate and load full 3D computer-aided design (CAD) drawings (Figure 3.16). The data is based on the guidance given in the Health Building Notes (HBN), Health Technical Memoranda (HTM) and Health Technical Memorandum Building Component series (see, Appendix C). For the simulation studies, the room dimensions were fixed 4800mm (depth) x 3960mm (width), based on the recommendation of AIA (2006) that matches with the 3D CAD drawings generated by ADB (2009). A kings fund bed system (with variable height, two-way tilt, three adjustable backrest, bed stripper, and on castors) measures 1000mm wide and 2400mm deep, was placed at the middle of the room satisfying the recommendation of DH (2005b) for single-bed in-patient room with space for visitor in easy-chair/wheelchair (including electric wheelchair) (Figure 3.17) with approximately 1500mm space on each side of the bed satisfying the ADB’s 3D CAD drawing (Figure 3.16). Figure 3.18 shows the final room dimensions and primary location of bed. The distance of patient’s head will be approximately 2000mm from window surface. As patients are assumed to be largely stationary in a hospital room, it allows the consideration and evaluation of daylight intensity in one location (Pechacek et al., 2008). When patients are on bed, the location of patients’ heads might vary according to the bodies’ ergonomic gesture and posture e.g. lying with their spine, inclined and upright on back. The location of head may vary on a vertical line perpendicular to the floor above the bed. The adjustable height of the Kings Fund bed can vary from 410mm to 840mm without mattress (Adler, 1999). The minimum height of the patient head can be calculated as the minimum height of the mattress surface plus 200mm, and the maximum height of the patient head can be calculated as the maximum height of the mattress surface plus 600mm. In the absence of specific dimensional data on variable patient head heights (where the height is also adjustable for most of the hospital beds), the vertical location of patient head can vary from 850mm to 1450mm from finished floor level (SLL, 2008). This research recommends the height of the test point at 1150mm from floor level, calculated as the midpoint between the maximum and the minimum heights of patient heads (Figure 3.19). With the changes of the height of patient head, the direction of looking is also changed. For example, if the patients lay with their spine, the directions of the eyes are upward towards the ceiling, and if the patients are in upright position resting on their back, the directions of the eyes are towards the wall. The direction of the eyes may vary up-to 90 degrees in angle (parallel to the floor to perpendicular to the ceiling) based on different inclined position of the patient body resting on tilting back of the beds. The researcher found that measurement of illumination on a horizontal plane, with sensor points upward to the ceiling, is more advantageous compared to the measurement on a vertical plane where the sensor points were towards the partition wall (discussed earlier in Section 3.4). During field survey, the researcher also found that, most of the heart surgery patients were lying with their spine on hospital beds after coming back from CTICU to the cardiac surgery unit (discussed earlier in Section 3.4.3(b)). The situation might differ for other categories of patients. The researcher has also interest to observe the differences of therapeutic potentiality of incident daylight on patient retina between two positions (vertical and horizontal) to identify the changes with previous findings (i.e. Pechacek et al., 2008), therefore, illuminations on patients’ heads from both horizontal and vertical directions were considered in this research.

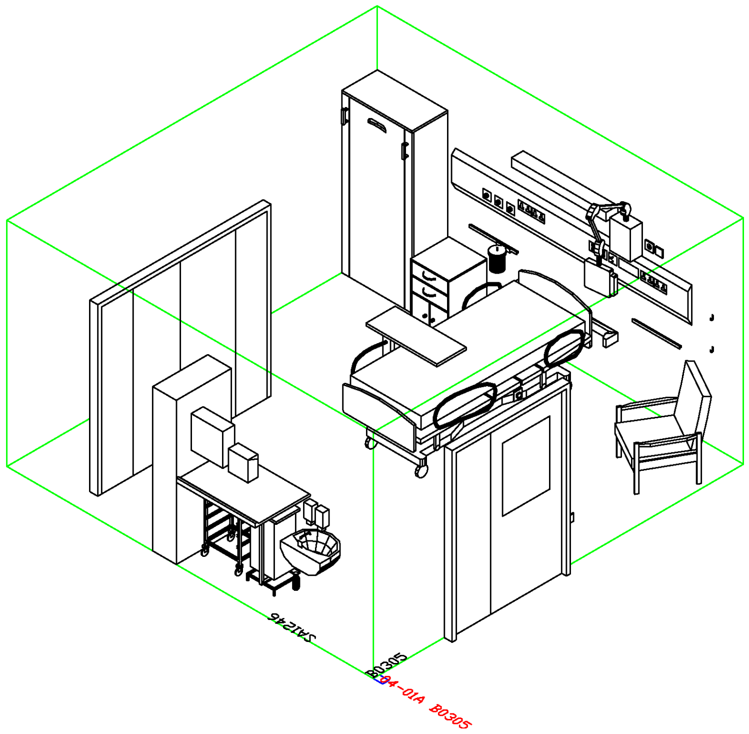


Figure 3.16: Single-bed in-patient unit (generated by ADB, 2009).

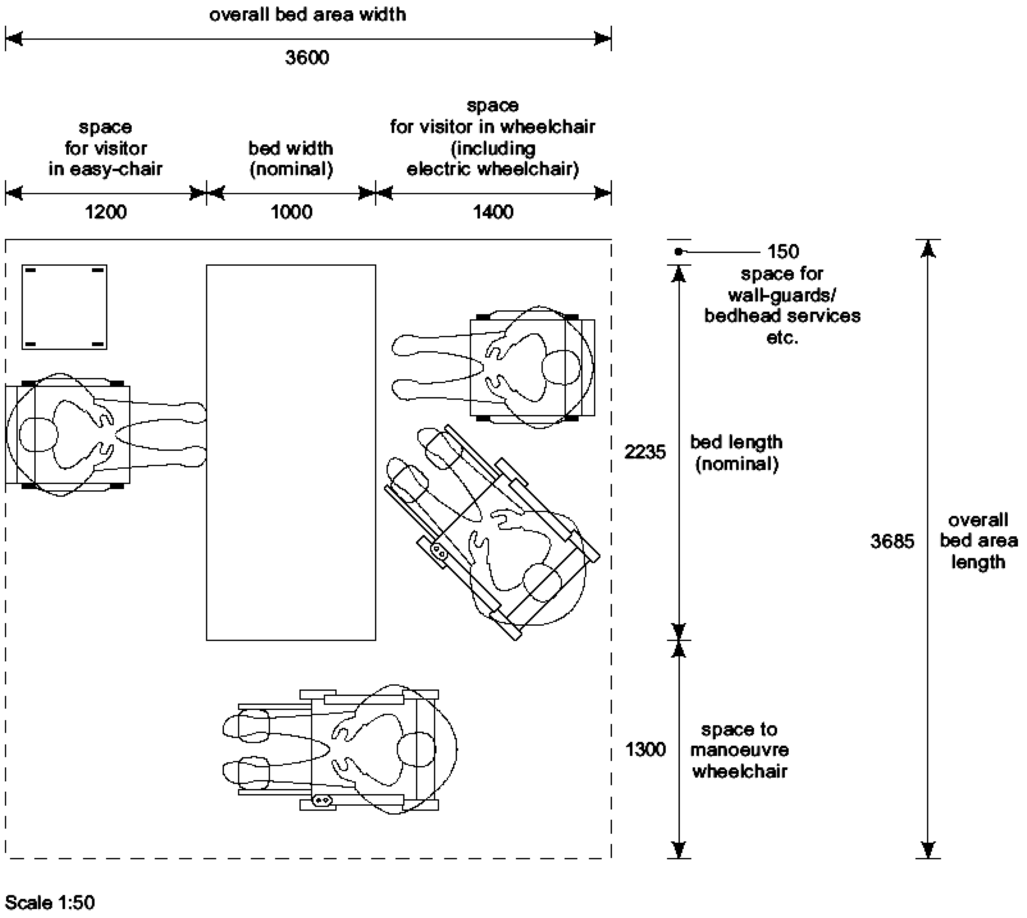


Figure 3.17: Bed area layout with space for visitors (source:DH, 2005b).

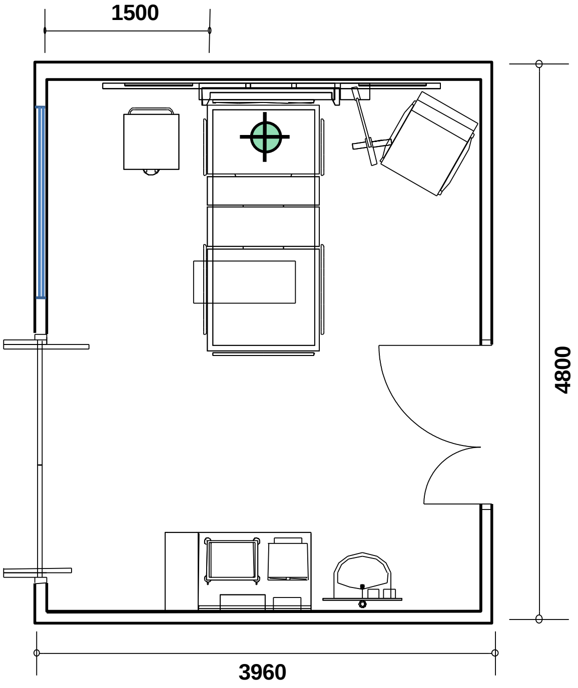


Figure 3.18: Dimension of single-bed in-patient room (4800 x 3900) and the location of test point for preliminary analysis.

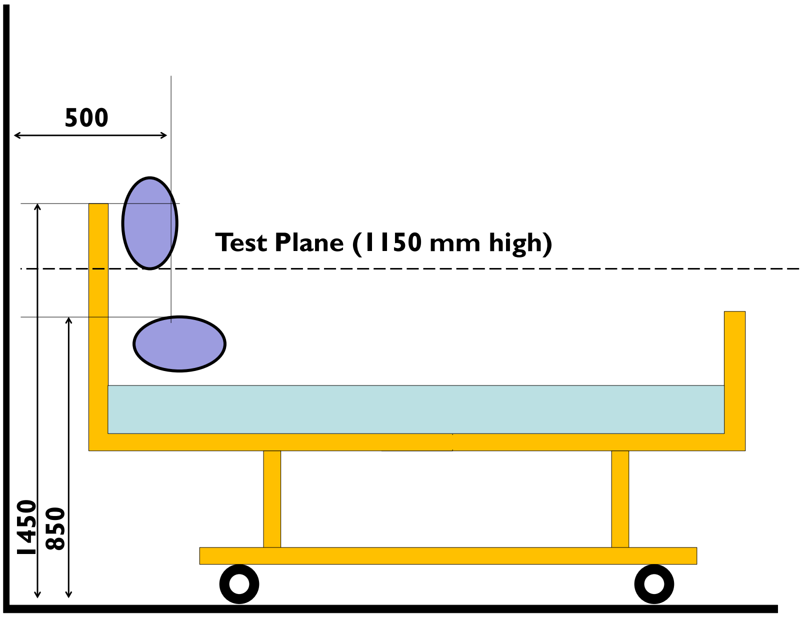


Figure 3.19: The height of the test point at 1150mm above floor level (after SLL, 2008).

d. Daylight design concept (sky window configurations)

Windows are the primary building element for ensuring daylight in a space. Windows are generally placed at the eye levels with an aim to maximise outdoor views through window apertures. For special purposes, windows often placed above or below the eye levels (e.g. clear storey windows, high windows, daylight windows, ventilation windows, sky lights and roof lights). A comprehensive guidance on design, installation and operation of window for healthcare buildings has been provided in Health Technical Memorandum 55: Windows (HTM 55, 1998). According to the outline of HTM 55 (1998) the design a standard window was developed for selected external en-suite layout (option 4 in Figure 3.15(d)) in this study. A window with a sill height of 450mm and ended at 1800mm is suitable for viewing outside from investigated ergonomics positions of hospital patients (e.g. laying on a bed, sitting on an easy chair or wheel chair and standing positions) (Figure 3.20). When the en-suite is located on the external side of the building, the maximum width of the window become restricted to 1800mm. The interpretations of MLR models from both the pilot and principal studies confirmed that both daylight and POV are very important to cause reduction in the patient LoS, therefore, the size of the viewing windows should be as large as possible. The size of the viewing window was fixed, 1350mm (height) x 1800mm (width) started from the sill height at 450mm for case external en-suite layout.

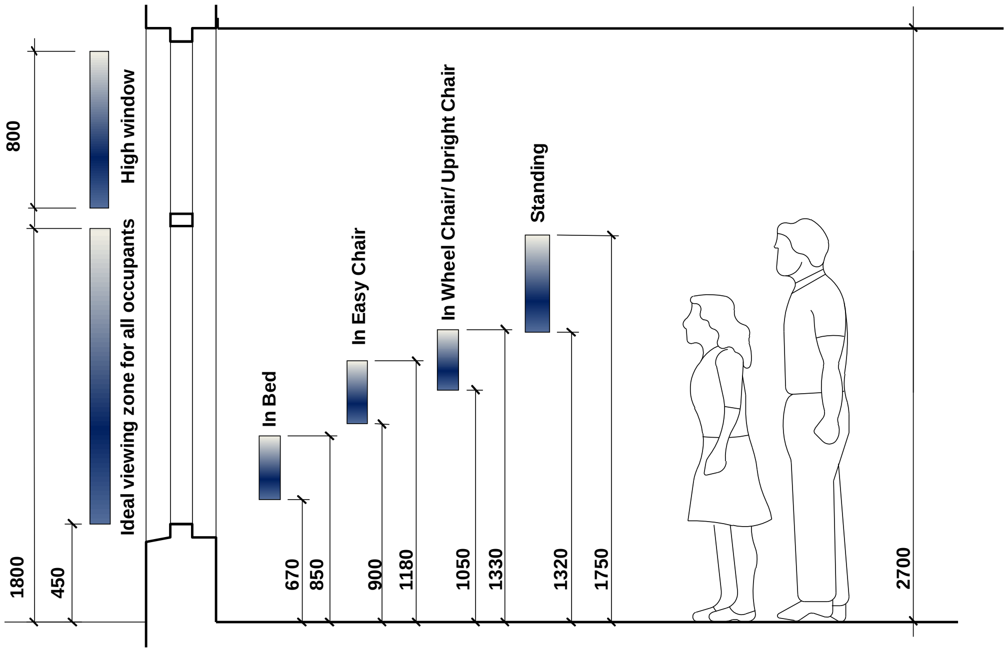


Figure 3.20: The ideal viewing zone and ranges of eye levels for different types of occupants (after HTM 55, 1998).

According to HBN 04-01(2008), the standard clear height (from finished floor to ceiling) for adult in-patient facilities should be 2700mm. If the viewing window ends at 1800mm, there is 900mm length of space left for high windows above the viewing windows. A high window with a dimension of 800mm (height) x 1800mm (width) can be placed above the viewing window starting at 1850mm height. For selected external en-suite option, it is difficult to further increase the size of the aperture for an intermediate floor of a multi-storey hospital building. Sky lighting/roof lightings are mostly applicable for single storey hospital buildings and top floors of multi-story hospital buildings. Decreasing the sill height will have no contribution in increasing the daylight in the test point (1150mm from finished floor) (Joarder, 2007). In a climatic condition similar to London, where overcast sky is predominant, increase of the area of the window aperture is one of the very effective options to increase daylight intensity inside rooms. A different type of inclined daylight window for hospital in-patient room was proposed in this PhD research in the place of the high window (Figure 3.21), which is also applicable to multi-storey buildings, and proposed a term to define the window as “Sky Window”.

The term “Sky Window” is not common in daylighting glossary. The term is generally used to define an element (a piece of mirror) of astronomical binocular to see the sky. In this research, the term was redefined for daylighting considering its similarities with Sky Light and High Window (*Sky Window* = *Sky* Light + High *Window*). With greater window-to-floor ratio and providing daylight from multiple directions (through facade and ceiling) sky window configurations might perform better than high window in increasing therapeutic effect of daylight for an imaginary patient lying on the bed far from the window. On the other hand, sky window with appropriate shading devices is better than skylights in reducing the possibilities of glare and direct daylight during noontimes (when the sun is near zenith and intensity of daylight is the highest).

To place the inclined sky window above viewing window, some modifications is needed at the edge of the service space located above the ceiling. A void space above the ceiling is required to place a sky window. In a hospital in-patient room, a void space above the ceiling is necessary to accommodate service lines such as ventilation ducts and electrical conduits. Experience shows that if the depth of the building is limited to 16,500mm with reasonable provision of vertical service ducts, the height of the void space can be kept to about 750mm above a 2700mm high hospital room (Smyth et al., 2007). In this research, the performance of sky window was compared with traditional standard hospital windows.

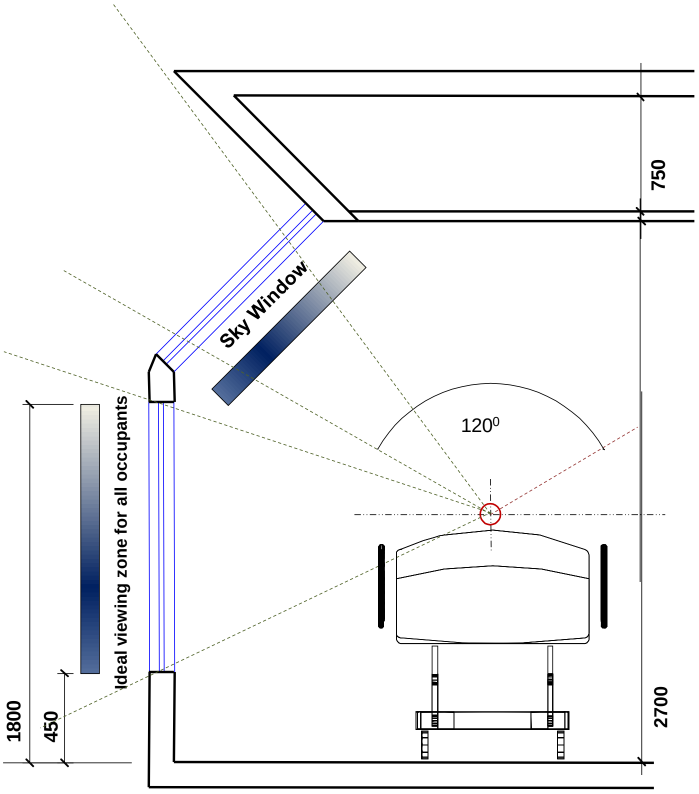
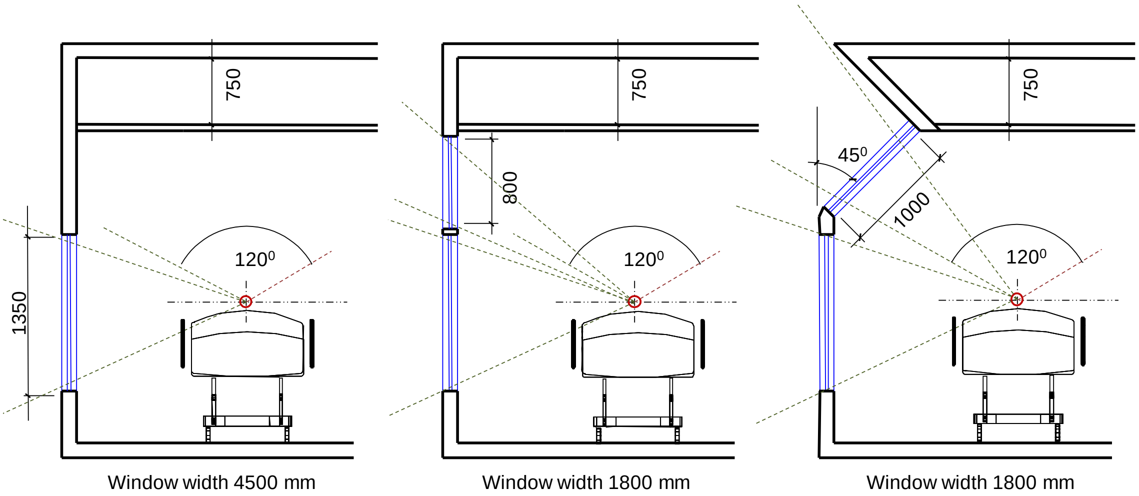


Figure 3.21: Section shows location and position of sky window above viewing window.

Comparison was made by prospective simulation analysis, between the performances of sky window with two options for traditional window configurations. In the absence of an external en-suite, the width of the viewing window can be increased horizontally to a maximum 4500mm (Figure 3.22(a)). When restricted by the external en-suite, the other option is to increase the height of the window vertically upward, by placing a high window above viewing window (Figure 3.22(b)). The third option is to increase the size of aperture diagonally above the viewing window in the place of the high window (Figure 3.22(c)) for a multi-storey building, defined above as sky window in this research. The possible three extensions (horizontal, vertical, and diagonal) of a viewing window was analysed in this research to identify the best option among these three at the beginning (Section 5.4), and appeared that sky window configurations performed better than traditional typical standard hospital window configurations in order to ensure therapeutic benefit of daylight inside in-patient rooms more effectively. Later shading devices were introduced to sky windows for different orientations to minimise glare and to satisfy the comfort levels recommended in Section 3.4.3(b).



a) Full width viewing window b) Viewing + High window c) Viewing + Sky window

Figure 3.22: Section shows three studied window configurations.

e. Performance measures

Primarily, the upper and the lower limit of therapeutic daylight intensity was fixed to 2000 lx and 180/190 lx (discussed in Section 3.4.3) and confirmed with principal study data (Section 4.9) before finalising as the goal for prospective simulation analysis. Hence, the goal of the simulation analysis was to provide a minimum 190 lx daylight for south, east and west orientations, and 180 lx for north orientations within a maximum limit of 2000 lx for four orientations, for a duration of 12 hours in a day from 06:00 AM to 06:00 PM, for an imaginary patient laying on the bed in a hospital room located in central London.

Intensity of light is the key factor for achieving circadian illumination goal with timing and duration of light exposure (Pechacek, 2008). Therefore, to evaluate therapeutic potentiality of a daylit in-patient room, it is necessary to consider the variability of daylight at patient head with time, season and weather, when the patient lay on the bed inside the room. As outdoor natural light is extremely dynamic, it is essential to calculate the daily and seasonal development of indoor illuminances in order to evaluate the therapeutic potentiality of a space. Dynamic Climate-Based Daylight Modelling (CBDM) methods (Mardaljevic, 2006) consider the time development of indoor illuminances under multiple sky conditions and the resulting annual illuminance profiles may serve as a basis to quantify the effectiveness of the therapeutic potential of a space due to the changed parameter.

To consider daylight's variability with time, season, and weather and evaluate how effectively daylight can reach an imaginary patient in a hospital bed, DA can be a useful dynamic performance measure (Pechacek et al., 2008). The DA depends on the illuminance requirements of the user and occupancy hours. The probabilistic rating of DA is expressed as a percent (%) of hours per year, when the required illumination (i.e. 180/190 lx for this research) at the point of interest can be maintained by daylight alone. In the simulation analysis, DA was used for the objective assessment of the therapeutic potential of the hospital rooms. As, therapeutic illumination goal is primarily depends on the intensity of light and duration of light exposure, any reduction of DA will reduce the therapeutic potentiality of the space.

Increasing the intensity of daylight to a higher level that may create discomfort will not be beneficial for hospital patients, and it is also important to consider the discomfort possibilities in conjunction with DA. Useful Daylight Illuminances (UDI) is a dynamic daylight performance measure scale aimed to determine when daylight levels are 'useful' for the user and when they are not. In this scale illumination higher than 2000 lx (UDI>2000) was considered as too bright with an excess of daylight that might lead to visual and/or thermal discomfort (Nabil et al., 2005), therefore, UDI>2000 can be a useful dynamic performance metrics to measure patients' discomfort.

Rogers (2006) proposed another set of metrics as the maximum Daylight Autonomy (DAmax) that considers the likely appearance of glare and expressed in percentage of the occupied hours when the daylight level is 10 times higher than design illumination. As the design illuminance is 180/190 lx on test point for the simulation study, DAmax corresponds to 1800/1900 lx which is close to UDI>2000. In most of the cases the results for UDI>2000 and DAmax will be similar. The number of points that have a DAmax above 5% of occupied time, among observed illuminance measuring points in the space, can provide an indication of the overall glare possibilities of the rooms when the points are distributed evenly throughout the room (500mm x 500mm grid, Figure 3.23). In most of the cases the discomfort possibilities at test point (UDI>2000) are positively correlated with the glare possibility for the sensors on the test plane (DAmax above 5%). Means, an increase of overall glare of the room (DAmax above 5%) will also increase the discomfort level at test point, results a higher UDI>2000 at test point. Most of the decisions of simulation exercises on discomfort are based on the UDI>2000 where it behaves similar with DAmax above 5%. The situations were discussed when UDI>2000 and DAmax above 5% do not behave similarly.

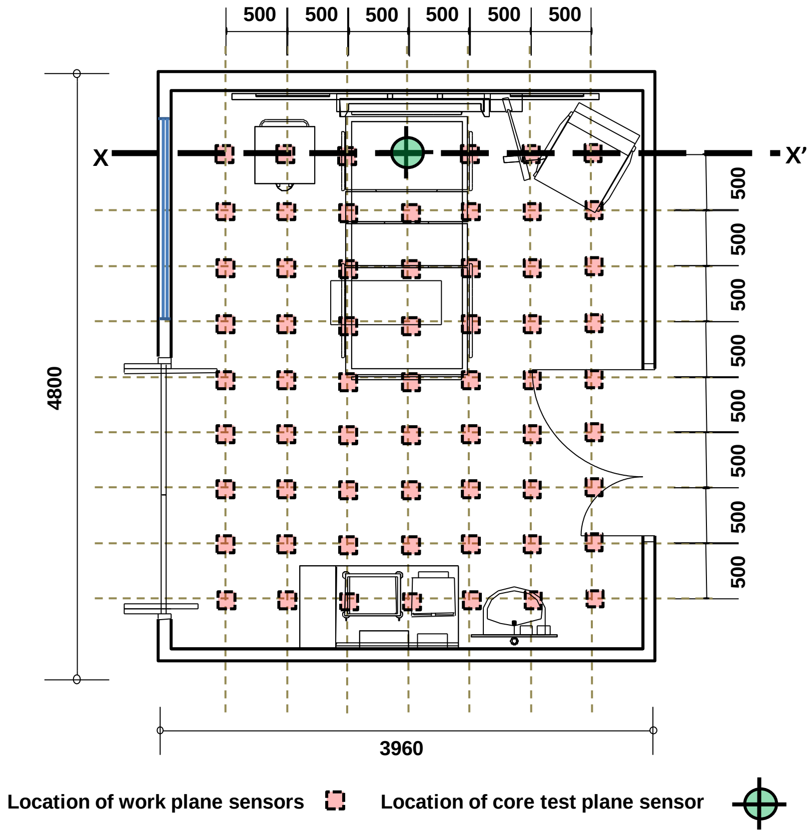


Figure 3.23: Distribution of sensors in case space and primary location of core test plane sensor.

To find out the uniformity of daylight level in the rooms, drop of illuminations on a line perpendicular to the window plane and go through the test point (XX' axis in Figure 3.23) was also considered for critical situations. For these critical situations, the sensors were placed at 500mm intervals and the highest illumination at the brightest sunny day (28 June at 10:30 AM) and the most overcast day (13 November at 11:30 PM), based on the TMY2 weather data of London (ECOTECT, 2010), was analysed.

f. Simulation tools

It is difficult to simulate light-dependent therapeutic potentiality of spaces, accurately, with available knowledge and simulation program. There are numbers of lighting simulation tools available in the market. The Tools Directory of Building Energy Software (US-DOE, updated in August 13, 2008) listed 41 tools under the 'Lighting Systems' category, among them 21 were advertising daylighting as a key feature

(Reinhart et al., 2007). The listed computer-based tools have different level of prediction accuracy and modelling capacities. For example LUMEN MICRO (Baty 1996) and SUPERLITE (Modest 1982) can compute daylight under strict boundary limitations, whereas, some other software can compute complex model geometry and arbitrary environments, such as LIGHTSCAPE (Khodulev et al., 1996) and RADIANCE (Ward 1998), with photorealistic rendering capacity to evaluate quality of lighting in 3D space. Some tools can integrate lighting (daylight and artificial light), heating and cooling loads and HVAC performance but have simple daylight calculation capacity for example ENERGY-10 (PSIC 1996) and DOE-2 (Birdsall et al. 1990; Winkelmann et al. 1985; Papamichael et al., 1998). The lighting software packages used algorithms based on either total radiosity (flux transfer) computations (e.g. IES-FlucsDL, DELIGHT) or physically accurate ray tracing (e.g. RADIANCE, IES-LightPro). For the evaluation of the daylighting concept to ensure therapeutic benefit, a suitable simulation tool was required, which

- has high prediction capability for indoor daylight distribution;
- can model simple to complex geometry with surrounding environments; and
- can provide climate based daylight metrics as output (e.g. DA and UDI).

RADIANCE, a backward ray tracing software package for lighting simulation, was validated for accurate prediction of the distribution of indoor daylight environments by many researchers for example Du et al., (2009), Ibarra, et al. (2009), Estes et al. (2004), Bryan et al. (2002) and Reinhart et al. (2001). Though RADIANCE can predict light levels for complex geometry accurately, RADIANCE does not have any built-in graphical interface to generate physical model, however, it is possible to use other software as modelling interface for RADIENCE, e.g. AUTOCAD and ECOTECT. Among the RADIENCE based ray tracer, a limited number of software are able to calculate climate based metrics as final output, such as 3D SOLAR, GENELUX, LIGHTSWITCH WIZARD, S.P.O.T, LIGHT SOLVE and DAYSIM. Among the climate based daylight simulation programs DAYSIM was first used by Pechacek et al. (2008) for reasonable assertions of the probabilistic potential of circadian daylight in hospital environment, and later by Gochenour et al., (2009) for residential environment. In this research, DAYSIM was selected for daylight simulation analysis which also satisfied the above mentioned three criteria. DA, UDI>2000, DAmax above 5% and illumination on a specific point can be calculated by using DAYSIM simulation program. DAYSIM use RADIANCE (backward) raytracer combined with a daylight coefficient approach (Tregenza, 1983) considering Perez all weather sky luminance models (Perez et al, 1990; 1993). DAYSIM have been validated comprehensively and successfully for daylighting analysis (Reinhart et al., 2009; 2001).

g. The goal for DA and UDI>2000 for London

DA and UDI>2000 are positively co-related, therefore, increase of DA (i.e. wanted daylight) will also increase UDI>2000 (i.e. unwanted daylight) and vice-versa. It is necessary to fix the DA level under a maximum discomfort limit, considering sky conditions and daylight hours of the geographical location of the hospital building site. The sky of London is mostly overcast with average 4 hours of sunshine a day and 8 - 16.5 daylight hours throughout the year (Section 2.5.1a). Hence, it is not possible to achieve 100% of target level of DA (180/ 190 lx) for 12 hours from 06:00 AM to 06:00 PM for each day of the year. Presently, there is no target level for DA/UDI>2000 to comply with a standard such as LEED (Leadership in Energy and Environmental Design). Under these circumstances, it is necessary to codify a reliable workflow and regulation on the application of CBDM to evaluate the daylight potentiality of a space by dynamic daylight metrics. The standard techniques to evaluate indoor built environment by dynamic daylight metrics are recognised in need for upgrading (Mardaljevic, 2008).

In absence of an appropriate standard for CBDM, in this research a workflow was proposed and followed by the researcher to set targets for indoor DA and UDI>2000 based on the maximum outdoor DA and UDI>2000. To find out the maximum outdoor DA and UDI>2000 for London that can be achieved between 06:00 AM to 06:00 PM, a 3D model was developed where 17 un-shaded sensors were placed outside the room at 500mm distance from the outer building surfaces (Figure 3.24). The sensors were placed at each corner of the room and at the middle point of four facades (north, south, east and west). Eight sensors were placed at the same level of test plane height (1150mm from finished floor) and nine sensors were placed at a height of 500mm above the top of the roof including one at the centre of the roof top (Figure 3.24). The model was placed on a vacant field without any natural or built surroundings that may cast shadow on sensors.

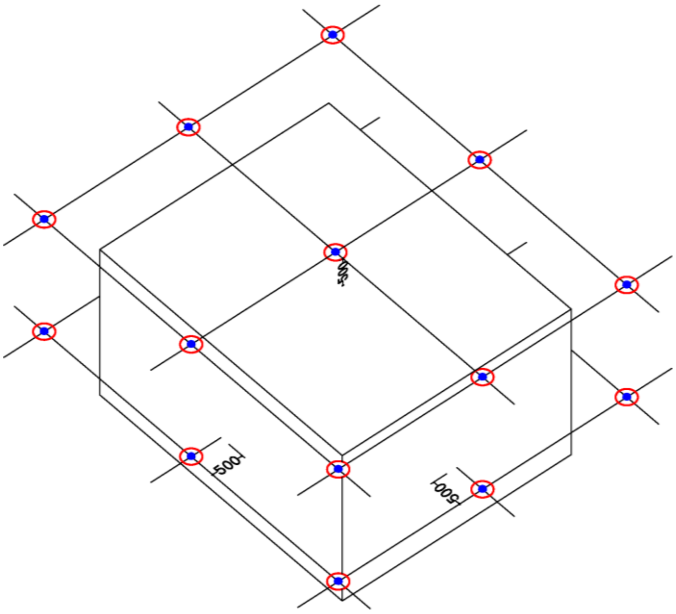


Figure 3.24: Location of 17 un-shaded sensors outside the room at 500mm distance from the outer building surface.

The DA achieved for 17 fixed outdoor sensors was 78% and UDI>2000 was 70%. Both the DA and UDI>2000 will be reduced when the sensors will be placed inside the rooms. The DA and UDI>2000 will be higher near the window and will decrease with distance from window towards back wall (Figure 5.14).

DA levels from 80% to 100% fall in the excellent daylight designs, but it is evident from above study that 80% DA is not possible to be achieved under London climate. DA levels from 60% to 80% represent some of the good daylighting designs (Rogers et al., 2006) and achievable for London climate. For the simulation exercise of this research, trial will be done to achieve a minimum of 80% of outdoor DA at the test point which will be 62.5% (78% x 0.8) approximately and falls into good daylighting design category (60%-80% DA) (Figure 3.25). The UDI>2000 should be kept as low as possible keeping the DA level above 62.5%. After analysing 123 number of simulations, done on London climate (Appendix D), it was found that it will be practical to set indoor UDI>2000 target at test point as 20% of outdoor UDI>2000 in conjunction with 80% of outdoor DA at the same point. Therefore, the benchmarks will be to allow a maximum 20% of outdoor UDI>2000 at the test point which will be 14% (70% x 0.2) approximately for four orientations. The strategy for trial and error exercise will be to increase the DA first and then reduce UDI>2000 (of course, it will reduce the DA then).

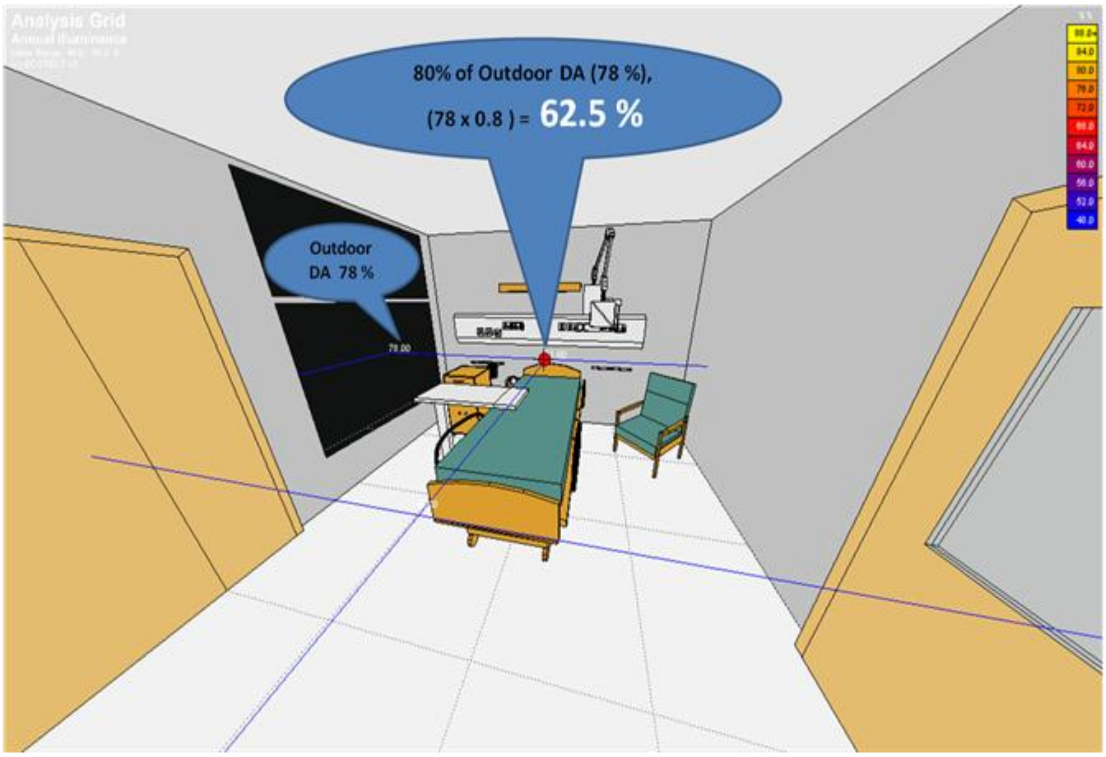


Figure 3.25: Location of test point, where a minimum 80% of outdoor DA will be achieved.

h. Parametric simulation study

Parametric simulation study was done to compare the therapeutic potentiality of the case in-patient room with standard traditional hospital window configurations, with a concept developed by the researcher (sky window configurations), based on past literature on daylighting and therapeutic environment, rules of thumb, standards, existing guidelines, published case studies and multiple linear regression models developed during retrospective field investigation (Section 3.5.1(d)).

The 3D CAD drawings generated in ADB (2009) software for single-bed in-patient unit with furniture layouts (Figure 3.16) was imported to ECOTECT. Based on the recommendations of HBN 04-01 (2008) and DH (2006), necessary modification of the model was done in ECOTECT to place an en-suite, and add void spaces above ceiling. Introduction and changes of windows with varying shading devices for 3D spaces were done in ECOTECT. DAYSIM was then run and necessary changes were assigned to material properties and simulation parameters (e.g. intensity, timing and duration) according to the evaluation criteria fixed by literature review in Section 3.5.1(e) and 3.5.1(g). The location of core test plane sensor (test point) was then fixed at patient head (Pechacek et al., 2008) when lying with his/her spine on the bed, and directed towards the ceiling. To analyse performance metrics, the same annual illuminance profiles were used based on DAYSIM calculations. The simulation time step was one hour. Table 3.5 shows the material properties of the investigated inpatient unit used for simulation.

Table 3.5: Material properties of the case space used for simulation analysis.

Building element	**Material description**	**Material properties**
Ceiling	Suspended plaster board ceiling	80% diffuse reflection
Walls	Brick with plaster either side	50% diffuse reflection
Floor	Concrete slab on ground plus ceramic tiles	30% diffuse reflection
Door	Solid core oak timber	30% diffuse reflection
Window	Double glazed low-e aluminium frame	90% visual transmittance
Furniture	Plywood	40% diffuse reflection
Fabric	Heavy cloth	10% diffuse reflection
Metal	Stainless steel	90% diffuse and specular reflection

DAYSIM uses the same raytracer used to generate RADIANCE rendering. As DAYSIM calculate illuminances at discrete sensors, the simulation parameters needed to be modified slightly. Higher parameter settings will result in longer process time. Therefore, the art is to use parameters that are ‘sufficiently high but not too high’. Table 3.6 summarizes the non-default RADIANCE simulation parameters for the simulation analysis recommended by Reinhart (2006) for complex geometry. Appendix A provides the definition of terms used in Table 3.6.

Table 3.6: Utilized simulation parameters in DAYSIM (Reinhart, 2006).

Ambient bounces	**Ambient division**	**Ambient sampling**	**Ambient accuracy**	**Ambient resolution**	**Specular threshold**	**Direct sampling**
7	1500	100	0.01	300	0.0	0.0

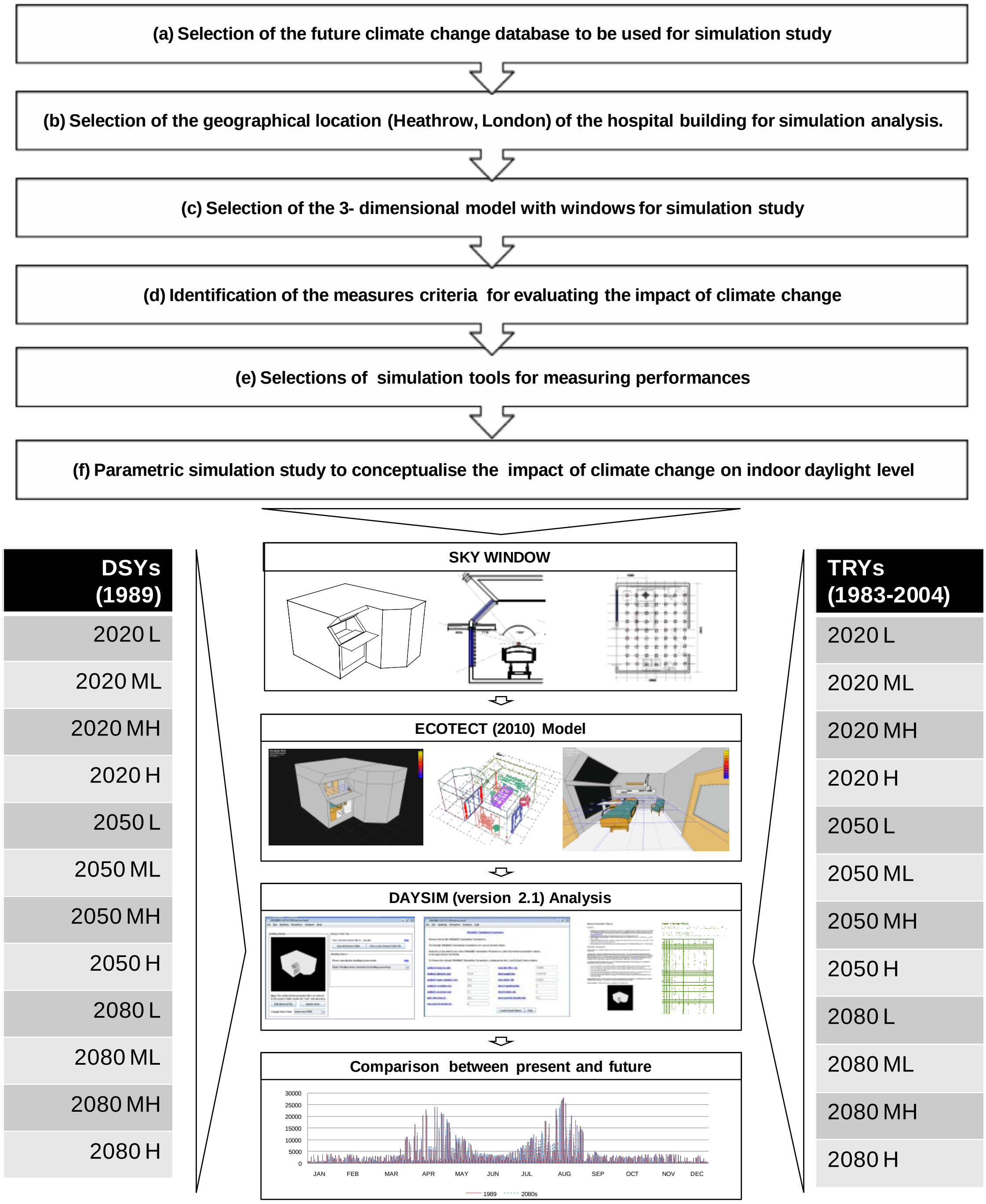
It was evident from simulation analysis that a window configurations with specially designed 45^0 inclined high windows (Sky Window) performed better than traditional standard hospital window configurations in order to ensure better therapeutic daylight inside patient rooms. The experience and results of simulation analysis helped to identify some parameters that can help to improve the daylight environment of hospital in-patient rooms for therapeutic purpose.

3.5.2. Impact of climate change on indoor daylight level

The majority of the climate scientists of the world agree that climate is changing rapidly (UKCIP, 2008) and is one of the largest threats to human life, health and well-being (NHS-SDU, 2009). Individual environmental variable will be affected due to the change of a global climate. For example, changes are expected in level of temperature, relative humidity, vapour pressure, atmospheric pressure, wind speed, wind direction, precipitation, cloud cover, sunshine hours and surface radiation (UKCIP02, UKCP09). The increase of surface radiation is a combined impact of the increase of infrared radiation (i.e. heat), visible radiation (i.e. light) and shortwave radiation (i.e. UVR). Most of the research on the impact of climate change and adaptation are focussed to the changes in the infrared radiation for example to identify the extent of overheating and thermal discomfort during summer time and describes measures to improve the conditions and related energy implications strategies (CIBSE TM36, 2005). Little research have been done to identify the impact of climate change on shortwave radiation and few (if any) research on visible radiation (i.e. daylight). This part of the PhD research focuses on the impact of climate change on indoor daylight and UVR levels, and its contribution to daylit in-patient rooms, designed for therapeutic purpose.

In this research impact of climate change on indoor UVR level with protection measures have been identified by reviewing previous literatures (Section 2.5 and Section 6.8) and impact of climate change on daylight level inside in-patient rooms have been analysed in the second phase of prospective simulation study.

The simulation method used in this phase was adapted from the simulation methodology developed and demonstrated in Section 3.5.1 (Figure 3.9), but TMY2 weather data provided with ECOTECT 2010 software was replaced by the future climate projection data (i.e. CIBSE, 2008), during daylight calculations. To understand the magnitude of the changes in indoor daylight levels, the performance of the proposed sky window was evaluated under the future climate change time slices, under the different future emissions scenarios for an overall perception of the change of daylight intensity in the future. The steps of the gradual development of the methodology for evaluation of the therapeutic daylighting concept under the future climate change scenarios have been illustrated in Figure 3.26 and are described below.



(a) Selection of the future climate change database to be used for simulation study

(b) Selection of the geographical location (Heathrow, London) of the hospital building for simulation analysis.

(c) Selection of the 3- dimensional model with windows for simulation study

(d) Identification of the measures criteria for evaluating the impact of climate change

(e) Selections of simulation tools for measuring performances

(f) Parametric simulation study to conceptualise the impact of climate change on indoor daylight level

**L: Low; ML: Medium-Low; MH: Medium-High; and H: High.*

Figure 3.26: Flow diagram of prospective simulation study under the future climate change scenarios.

a. Future climate change database

To conceptualise the future performance of a building, use of the future climate files in modelling process is widely recognised practice (CIBSE TM48, 2009). For building simulation analysis, time series/time-scales data are required in hourly or more precise levels. The information available in portable document format (PDF) describes the UKCIP02 (United Kingdom Climate Impacts Programme 2002) or the UKCP09 (United Kingdom Climate projection 2009) climate change scenarios are therefore not directly applicable to daylight simulation analyses (Murphy et al., 2009). High time resolution (daily or hourly) data needs to be derived from projections described under the UKCIP02 or the UKCP09. Presently, two sources of time series climate change projection data are available, that can be used for climate change simulation analysis. The first one is Chartered Institution of Building Services Engineering database (CIBSE, 2008), created on October 2008 and modelled by CIBSE in collaboration with UKCIP and ARUP, which support the projections of climate change, described by UKCIP02 and can be purchased from CIBSE. The second one is Weather Generator (WG) output created on June 2009, modelled by the Met Office Hadley Centre, UK and funded by the Department for Environment, Food and Rural Affairs (DEFRA), that support the projections of climate change described by UKCP09 and available to online free of cost (UKCIP, 2010). Both the data sets can provide hourly weather time series data. CIBSE database has two future hourly weather time series, based on the existing Design Summer Years (DSYs) and Test Reference Years (TRYs). On the other hand, WG output has two set of a 10,000 future hourly weather time series data for 30 years in length, based on the baseline period (control run) and a user-defined runs perturbed for a given future climate (the future climate runs). As a result, for a particular time (for example 1 April, 2050 at 11.00 am), under one climate change scenario, CIBSE database has two options/projections (DSYs/TRYs), whereas WG output has 600,000 options/projections (sampled data are different, but statistically equivalent) for consideration. As currently there is no suitable methodology to consider the large volume of output (raw hourly time series weather data generated by WG) in research, CIBSE database was used to conceptualise the impact of climate change on indoor daylight level in this research. Though, UKCP09 has superseded UKCIP02 and WG is the only source of hourly time series both for the baseline and the future time periods within UKCP09, UKCIP02 has been kept live for research purposes and to meet existing standards and guidance that needs to confirm UKCIP02 projection scenarios (UKCP, 2010). The major differences between CIBSE (2008) database and WG (2009) outputs have been briefed in Table 3.7.

Table 3.7: Comparisons between CIBSE (2008) database and WG (2009) outputs.

CIBSE (2008) database	WG (2009) output
Support the projections of climate change described by UKCIP02.	Support the projections of climate change described by UKCP09.
Regional climate model produced at a spatial resolution of 50km and available for 14 UK sites.	Gridded observed climate datasets and operates at a 5km spatial resolution, although the climate change factors are developed using the UKCP09 probabilistic projections at a 25km by 25km resolution.
Based on four different levels of anthropogenic CO_2 emissions scenarios (Low, Medium-Low, Medium- High and High).	Based on three different emissions scenarios (Low, Medium and High).
Presented for three future time-slices (2020s, 2050s and 2080s).	Presented for seven future time-slices (2020s, 2030s, 2040s, 2050s, 2060s, 2070s and 2080s).
Provided with two future hourly weather time series, based on the TRYs (1983-2004) and DSYs represent a year with a hot summer (1989).	Consists of two sets of a 10,000 future hourly weather time series from 30 years in length, based on the baseline period (1961 - 1990) and the future climate generated from UKCP09 climate change projections added to the baseline period.
CIBSE data provide a deterministic outlook (Smith et al, 2010).	Including uncertainty in climate projections, the data are probabilistic in nature and allow users to generate many different, but statistically equivalent time series that can be used to evaluate different eventualities and possible response strategies/measures using risk management approaches.
The climatic variables available include: dry bulb temperature (°C), wet bulb temperature (°C), atmospheric pressure (hPa), wind speed (knots), wind direction (degrees clockwise from north), cloud cover (oktas), diffuse irradiation (Wh/m^2) and global irradiation (Wh/m^2).	The climatic variables available include: mean hourly temperature (^oC), vapour pressure (hPa), relative humidity (%), total hourly precipitation (mm), sunshine (fraction of an hour), diffuse radiation (Wh/m^2) and direct radiation (Wh/m^2).

The UKCIP02 scenarios are based on one of the world's most comprehensively validated climate model: Hadley Centre models (Hulme et al., 2002). The DSYs consists of an actual one year sequence of hourly data, selected from the 20-year data sets (1983-2004) to represent a year with a hot summer (1989). The selection is based on third highest average dry bulb temperatures during the summer months period (April to September). The TRYs consists of hourly data for twelve typical months, selected from the same 20-year data sets (1983-2004), and smoothed to provide a composite, but continuous one year sequence of data. The most average months were selected using the Finkelstein -Schafer (FS) statistic selection (Levermore et al., 2006) method with equal weighting for cloud amount, dry bulb temperature and wind speed. Selected years for each month are, January from 1988; February from 2004; March from 2004; April from 1992; May from 2000; June from 2001; July from 1991; August from 1996; September from 1987; October from 1988; November from 1992 and finally December from 2003. CIBSE (2008) data are available for three future time-slices (2020s (2011-2040); 2040s (2041-2070) and 2080s (2071-2100)) under four different emissions scenarios (Low, Medium-Low, Medium- High and High) defined by the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES).

b. Geographical location (Heathrow, London)

CIBSE data were produced at a spatial resolution of 50 km and available for 14 UK sites: Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton and Swindon. To conceptualise the impact of climate change on indoor daylight level by simulation analysis, it will be sensible to compare the performance of the case space based on the current CIBSE TRYs/DSYs hourly weather data set for London with the future CIBSE TRYs/DSYs hourly weather data sets. The current and the future CIBSE TRYs/DSYs hourly weather data set for London are based on the geographical location of Heathrow (Latitude = 51.48N, Longitude = 0.45W, and Altitude = 25m). Heathrow is located at 12 nautical miles (22 km/14 mile) west of Central London.

c. 3-dimensional model with widow design

The single-bed in-patient room of 19m^2 (4800mm x 3960mm) with an external en-suite of 4.5m^2 (2285mm x 2100mm) developed for simulation analysis in Section 3.5.1(b) and 3.5.1(c) was used as case space for the simulation analysis in this phase. The clear height of the room was 2700mm and there was a 750mm high void space above ceiling. The room had two windows with a total 22.3 % Window-to-floor ratio. The 45^0 angled sky window (1.8m^2) was placed above a viewing window (2.43m^2) (Figure 3.27).

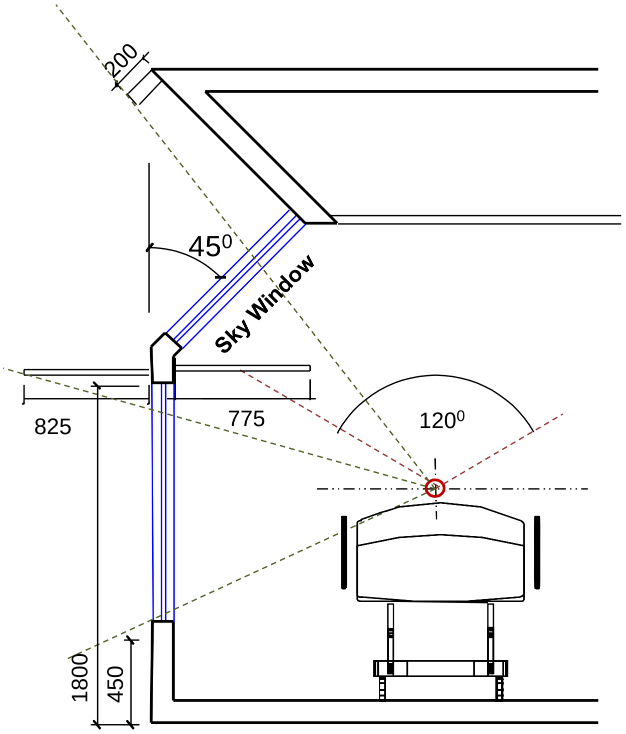


Figure 3.27: Shading devices for south sky windows.

The shading for the windows were as it was recommended for south orientations in Section 5.7.7 (Table 5.2) with 825mm external sunshade, 200mm external 45^0 angled overhang, and 775mm internal light shelf (Figure 3.27). At the beginning of the simulation analysis, the windows were considered without any blind to isolate the impact of the change of outdoor daylight level on indoor daylight level due to the climate change and, also, to avoid the effect of the operations of the internal venetian blinds in daylighting the space. Later to evaluate the therapeutic potentiality of the space an internal blind, controlled by an active user, was considered.

d. Measures criteria

The height of the test plane was fixed to 1150mm above floor level which represent the patient average eye level when lying on a bed (Figure 3.19). For the purpose of the simulation, the entire room space was divided into 500mm x 500mm grids (Figure 3.28). Among 63 intersecting grid points one point on test plane which is 1500mm distant from window and located at the head side of the bed (test point) was fixed as core test plane sensor (Figure 3.29). The initial daylight measurements were taken for the 63 intersecting grid points and were averaged for different scenarios to have an idea of the variation of the indoor daylight levels with climate change. Later, the changes in core test plane sensor (test point) were considered in terms of point illumination, DA and UDI>2000 to evaluate the change in therapeutic potentiality.

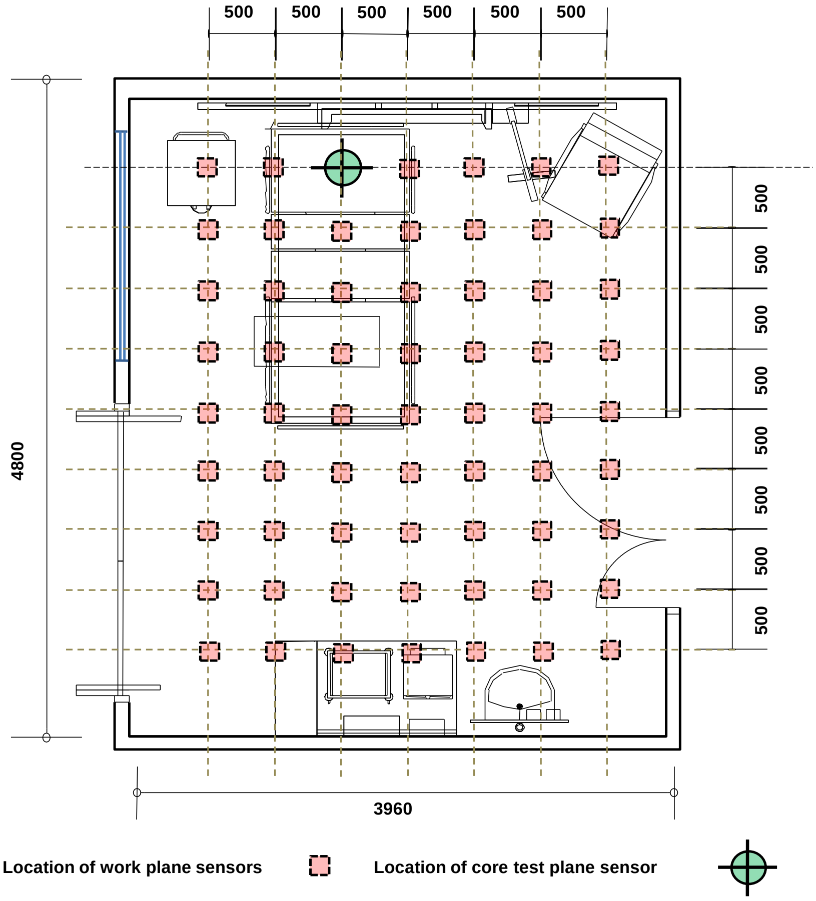


Figure 3.28: Location of sensors in case space.

e. Simulation tools

The DAYSIM dynamic climate based annual daylight simulation method that use RADIANCE (backward) raytracer combined with a daylight coefficient approach (Tregenza, 1983) considering Perez all weather sky luminance model (Perez et al, 1990; 1993), identified in Section 3.5.1(f) was also used in this phase to generate annual illumination profiles, DA and UDI>2000. The goals for dynamic simulation analysis for this phase was to provide a minimum 190 lx daylight within a maximum discomfort limit of 2000 lx for south orientation, for a duration of 12 hours in a day from 06:00 AM to 06:00 PM, for an imaginary patient laying on the bed in a hospital room located in Heathrow, West London.

f. Parametric simulation study

Calculation of hourly illumination at 63 intersecting grid points was done for the whole year. Each points has 8760 (365 x 24) illumination data considering 24 hours of the day and 4380 (365 x 12) data considering 12 hours of daylight from 06:00 AM to 06:00 PM. The hourly illumination for individual 63 points were averaged for the whole year at the beginning and then average of 63 points were taken as the average illumination of the room for one specific time slice under particular emission scenario. The evaluation of the daylighting performance of the proposed sky window under different future emissions scenarios revealed that there is a possibility to increase the average indoor room illumination by a maximum 5% and average indoor illumination at test point (patient head) can raise a maximum 8% in the future (2080-2100) compared to the present (1983-2004). It was also evident that the proposed design of sky window with integrated shading systems was capable to protect the increased level of indoor daylight illumination due to climate change.

The specific limitations of the climate change simulation study was that, UKCIP02 scenarios are not designed to formally or quantitatively reflect all of the uncertainties of the future climate (UKCIP02, 2002) and the future global and diffuse irradiance data of UKCIP02 have been generated from synoptic data (mainly sunshine duration and cloud cover) using computer models, due to the difficulty of obtaining consistent irradiation data (CIBSE, 2008). Therefore, the assumptions of the climate change simulation study will only satisfy the projections described by UKCIP02 and will not support other climate change models for example UKCP09. The detailed findings of climate change simulation study have been provided in Chapter 5 of this PhD thesis.

3.6. Summary

This chapter has described the methodology of the research in the order of the two main phases, namely retrospective field investigation and prospective simulation study.

Retrospective field investigation was done to establish strong evidence of the outcome of daylight for therapeutic purpose. In this stage, recently completed four key pieces of research, relating to the therapeutic environment of hospital room and lighting, were critically reviewed to outline guidelines for sample selection criteria and to identify primary variables to be used in statistical model to analysis the collected data from field. Development of MLR models was recommended to establish evidence based relationship between daylight availability and patient recovery rate in general hospital environment. A two month pilot study was done to identify and confirm the sources of the data required to generate MLR models and then the proper application of data in statistical model to pursue the expected outcomes. Incorporating the experiences of pilot study, a more precise and extensive study was done as a principal study for 12 months (one year), to establish a stronger evidence of the statistical relationship between daylight intensity and patient LoS in hospital rooms. The data collected during principal study was also used to test the range of daylight intensities within which positive health outcomes are expected referred from literature review.

Once the analyses of field data confirm the benchmarks to ensure therapeutic effect of daylight, recommended from literature, it was finalised as a goal for prospective simulation analysis for this research. The DAYSIM dynamic annual CBDM method was used to evaluate and compare the therapeutic potentiality of standard traditional hospital window configurations with a daylight design concept developed by the researcher during this research period. The similar type of simulation analysis procedure was also followed to conceptualise the impact of climate change on daylight intensity inside in-patient rooms and its contribution to therapeutic lighting environment, where the TMY2 weather data provided with ECOTECT 2010 software was replaced by climate change data defined by UKCIP02 under different future emissions scenarios for London climate, during daylight calculations.

It was expected that, based on the developed methodology of this chapter, the outcomes of retrospective field investigation in Chapter 4 and prospective simulation study in Chapter 5 will enable the researcher to recommend architectural design strategies in Chapter 6 for therapeutic daylit hospital in-patient room design.

CHAPTER 4
Retrospective Field Investigation

4.1. Introduction

The previous chapter reviewed the methodology of this research in the order of the two main phases, namely retrospective field investigation for this chapter and prospective simulation study for Chapter 5. This chapter reports the activities and findings of two field studies: pilot study and principal study. This chapter consists of three major parts. The first part describes the outcomes of pilot study to explore the relationship between average daylight intensity of the room, and heart surgery patient LoS in hospital. The second part presents the results of principal study to establish stronger evidence, than pilot study, to explore the relationship between daylight intensity at a particular point above patient head (on the wall) and Coronary Artery Bypass Graft (CABG) patient LoS in hospitals. The third part describes the findings of the experiment which was done to verify the intensity of daylight within which positive health outcomes are expected, recommended from past literature identified in Chapter 3 (Section 3.4.3(a)). The intensities of daylight, verified as beneficial for reducing patient LoS, have been used as simulation goal for prospective simulation studies in Chapter 5. The strategies based on the activities of this chapter have been discussed in Chapter 6 and key findings have been presented in concluding Chapter 7.

4.2. Background

A significant number of research have been conducted to construct and maintain sustainable and green buildings for healthcare institutions, but in practice only a handful projects have been executed (Sandric, 2003). For example, among 450 buildings registered for certification from the LEED initiative in the US, only seven were health care institutions (Balaras et al., 2007). This figures also emphasis that there is a lack of confidence among the decision makers to implement the output of the environmental research in the projects.

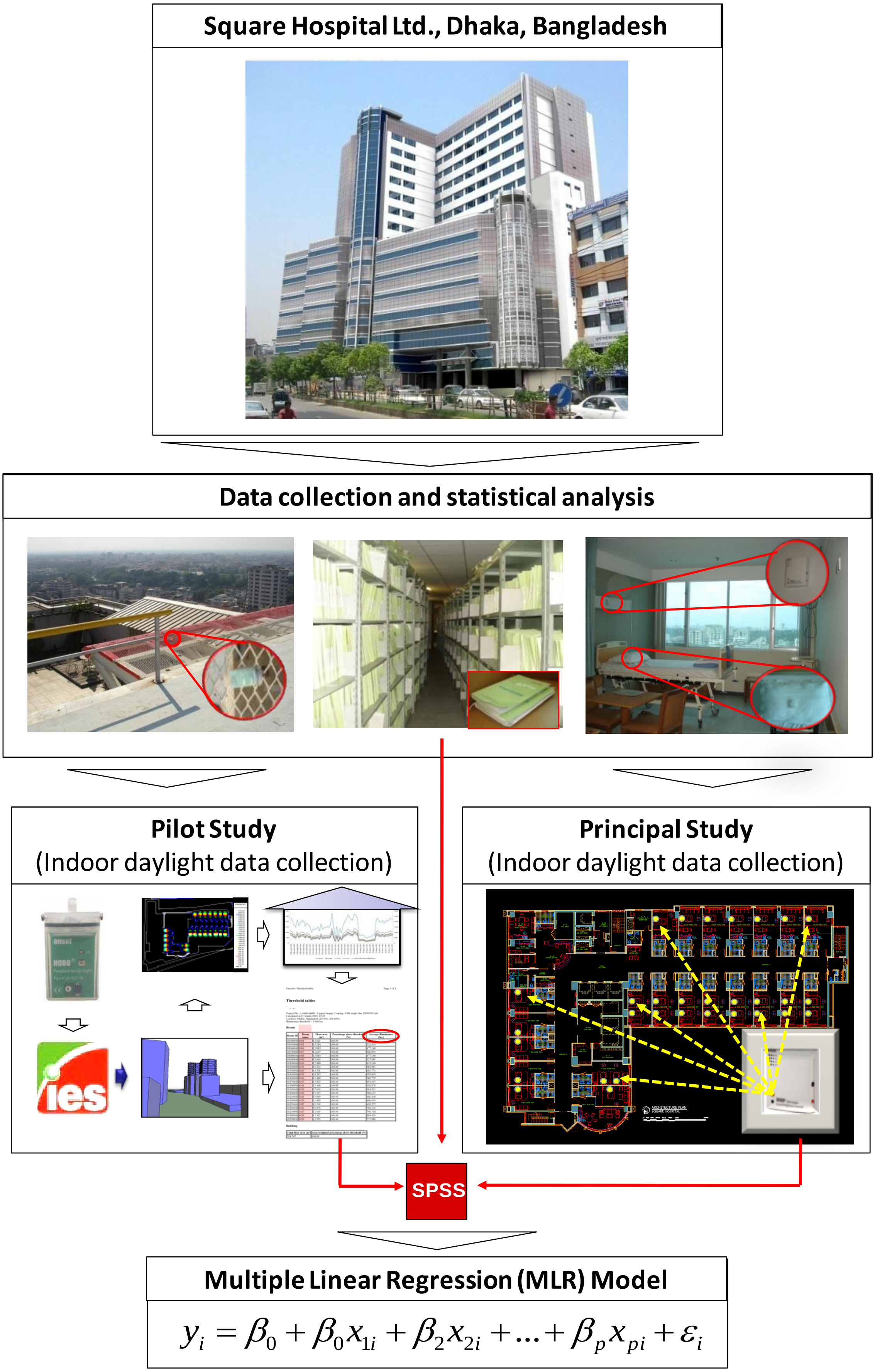


Figure 4.1: Graphical representation of field investigation process.

It was identified in previous Chapter 2 that, to implement daylight strategies within the therapeutic design of hospital in-patient rooms, the physiological impact of daylight on general patients need to be established based on sound evidence. Evidence of patients' physiological and clinical improvement is necessary to be linked with daylight availability inside in-patient rooms. Therefore, the primary goal of field investigation was to establish strong evidence of quantitative relationship between daylight intensities and patient LoS. From the literature review of Chapter 2 and Chapter 3, it is also evident that excess daylight can be harmful. Therefore, the other purpose of field investigation was to identify the range of daylight intensity within which positive health outcomes are expected.

The output of this chapter generated strong evidence which will build confidence to architects, owners and policy makers to use daylight for therapeutic purpose in hospital projects. Figure 4.1 presents a graphical representation of field investigation process for pilot and principal study and following sections describes the activities and results of the surveys.

4.3. Microclimate of Dhaka city

The case hospital building (Square Hospital Ltd.) selected for field investigation of this research is located in Dhaka. Dhaka is the capital of Bangladesh. The city lies between longitude 90°20′E and 90°30′E and between latitudes 23°40′N and 23°55′N at the southern extremity of the Pleistocene Terrace of the Madhupur Tract (Mridha, 2002). Dhaka uses GMT +6.

The climate of Dhaka is tropical and greatly influenced by the presence of the Bay of Bengal in the south and Himalayan mountain range and Tibet plateau in the north (Mridha, 2002). Dhaka City has mainly three distinct seasons: the hot dry (March-May); the warm humid (June-November) and the cool dry season (December-February) (Ahmed, 1995). The summer (hot dry and warm humid) is long and wet with the hottest month April when the average maximum temperature varies from 30.3ºC to 34.8ºC. The winter (cool dry season) is short with average temperature ranging from 9ºC to 15.2ºC during January: the coldest month. Overheating is the major problem of Dhaka, because some other factors are always associated with air temperature during summer.

For example, it is observed that from June to October there is high air temperature associated with high humidity, while from March to May, conditions of high solar radiation is associated with high air temperature (Rahman, 2004). Table 4.1 shows the summary of seasonal variations of Dhaka climate.

Dhaka has more than 8 hours of sunshine per day during the cool periods. During warm-humid seasons, sunshine per day comes down to 4 hours due to cloud cover. After July the sunshine hours increases steadily and a wide variation in sunshine hours is observed during July to November (Rahman, 2004). The diffused component of the daylight is considerably high during July to November due to cloudy atmospheric condition.

Table 4.1: Monthly statistics for climatic data of Dhaka (source: U.S. Department of Energy, 2008).

Climatic factors		**Sunlight* (Hours)**			**Dry bulb temperatures (°C)**			**Relative humidity (%)**			**Precipitation /Moisture (kPa)**
Climatic period		**Max**	**Min**	**Avr**	**Max**	**Min**	**Avr**	**Max**	**Min**	**Avr**	
Hot-Dry	**Mar**	10.1	7.5	8.8	35.4	15.8	26.1	94	18	59	1.8
	Apr	10.2	7.8	8.9	37.9	20.1	28.1	96	27	72	2.7
	May	9.7	5.7	8.2	39.1	21	28.2	96	45	78	3
Warm-Humid	**Jun**	7.3	3.8	4.9	37	24.3	29.3	99	49	80	3.3
	Jul	6.7	2.6	5.1	35	24.9	28.4	100	56	86	3.4
	Aug	7.1	4.1	5.8	36.5	25.6	29	97	58	84	3.4
	Sep	8.5	4.8	6.0	39.4	16.5	28.6	100	44	81	3.1
	Oct	9.2	6.5	7.6	34.9	20.4	27.4	98	39	77	2.8
	Nov	9.9	7.0	8.6	32	15.8	23.8	100	34	76	2.2
Cool-Dry	**Dec**	10.2	7.4	8.9	31.2	12	19.9	100	32	72	1.6
	Jan	9.9	7.5	8.7	29.2	8.2	18.5	100	28	71	1.4
	Feb	10.7	7.7	9.1	31.9	12.4	21.9	100	17	62	1.4

*(*Source:Rafique, S., Department of Applied Physics, Dhaka University, recorded from 1988 to 1998, cited from REEIN, 2010)*

The sky of Dhaka remains overcast, intermediate and clear in different parts of various seasons. During hot dry seasons the sky remains both overcast and clear (sunny with the sun), and the sky remains considerably overcast during the warm-humid periods.

During cool-dry periods, the sky remains mostly clear. Figure 4.2 shows the cloud cover for TRYs for Dhaka city.

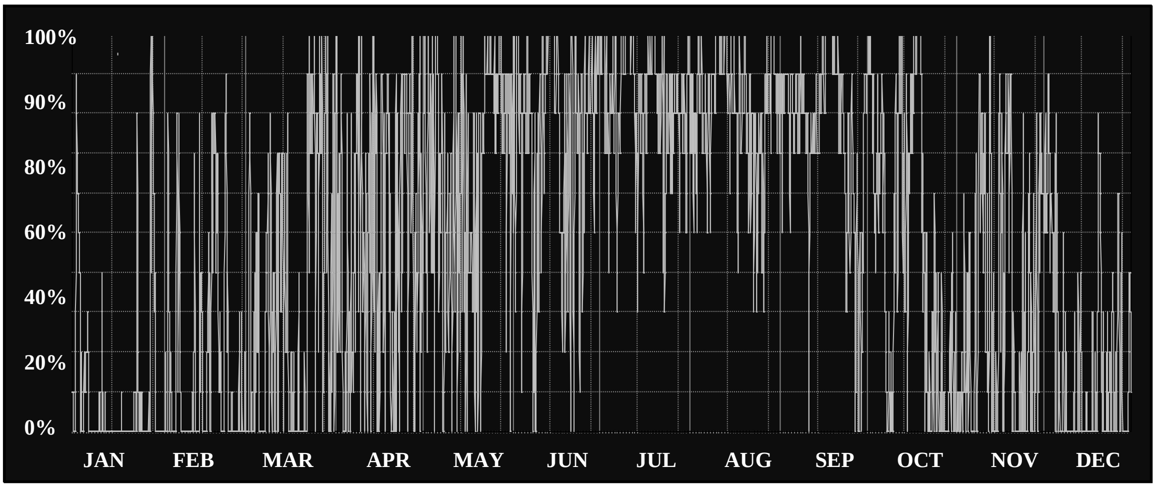


Figure 4.2: Cloud cover for TRYs, Dhaka (source: U.S. Department of Energy, 2008).

In a study conducted by Renewable Energy Research Centre (RERC) in Dhaka, it was found that the daily average solar radiation of Dhaka varies between 4.0 - 6.5 kWh/m^2. The maximum amount of radiation is available on the month of March-April and the minimum on December-January (REEIN, 2010). Figure 4.3 shows the Hourly solar radiation (direct and diffuse) averaged by month.

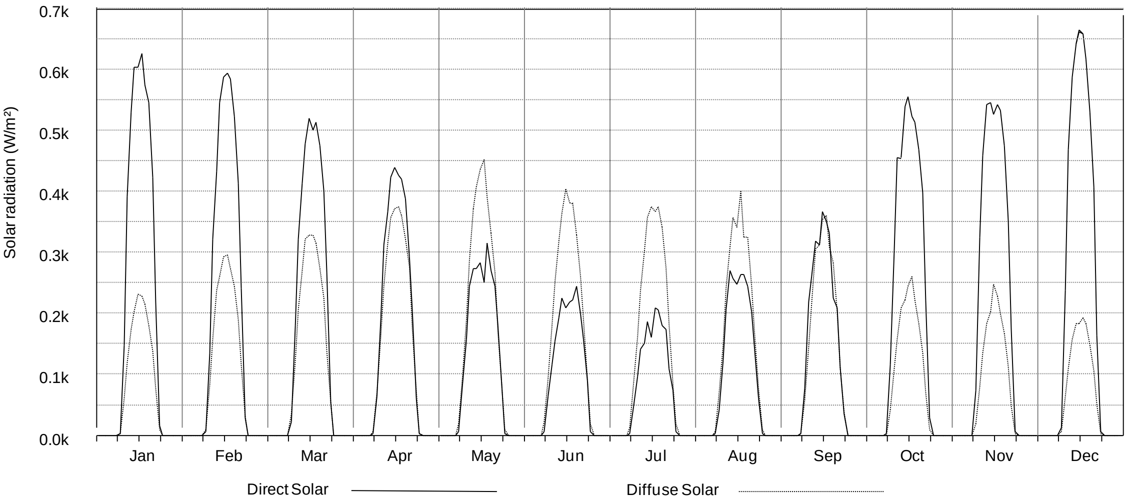


Figure 4.3: Hourly solar radiation averaged by month for TRYs, Dhaka (source: U.S. Department of Energy, 2008).

Figure 4.4 shows the sun path diagram of Dhaka, Bangladesh. The daylight hour for Dhaka varies from 10.5 hours (during December) to 13.5 hours (during June) throughout the year. Analysing the sunrise - sunset data of Dhaka, it was found that the earliest sunrise time was at 05:12 AM and late sunset time at 06:48 PM on June 21 with a daylight hour of 13 hour 36 minute. The late sunrise time at 06:36 AM and early sunsets at 05:17 PM recorded on December 21 with a daylight hour of 10 hour 41 minutes (WCI, 2010a). Though the data is for 2010, the sunrise and sunset times can be applied for any year (LW, 2009). Figure 4.5 presents the hourly HEI of the 21st of each month for the year 2009-10 for Dhaka, Bangladesh, recorded by an outdoor data logger from the site by the researcher. From the recorded data it was evident that the highest HEI was 165, 334 lx on 21 March 2010 at 12:00 PM and lowest HEI at 12:00 PM was 14,466 lx on 21 January 2010. Considering the daylight situations, it can be concluded that an average 12-hour daylight hour from 06:00 AM to 06:00 PM can be considered for Dhaka for the whole year.

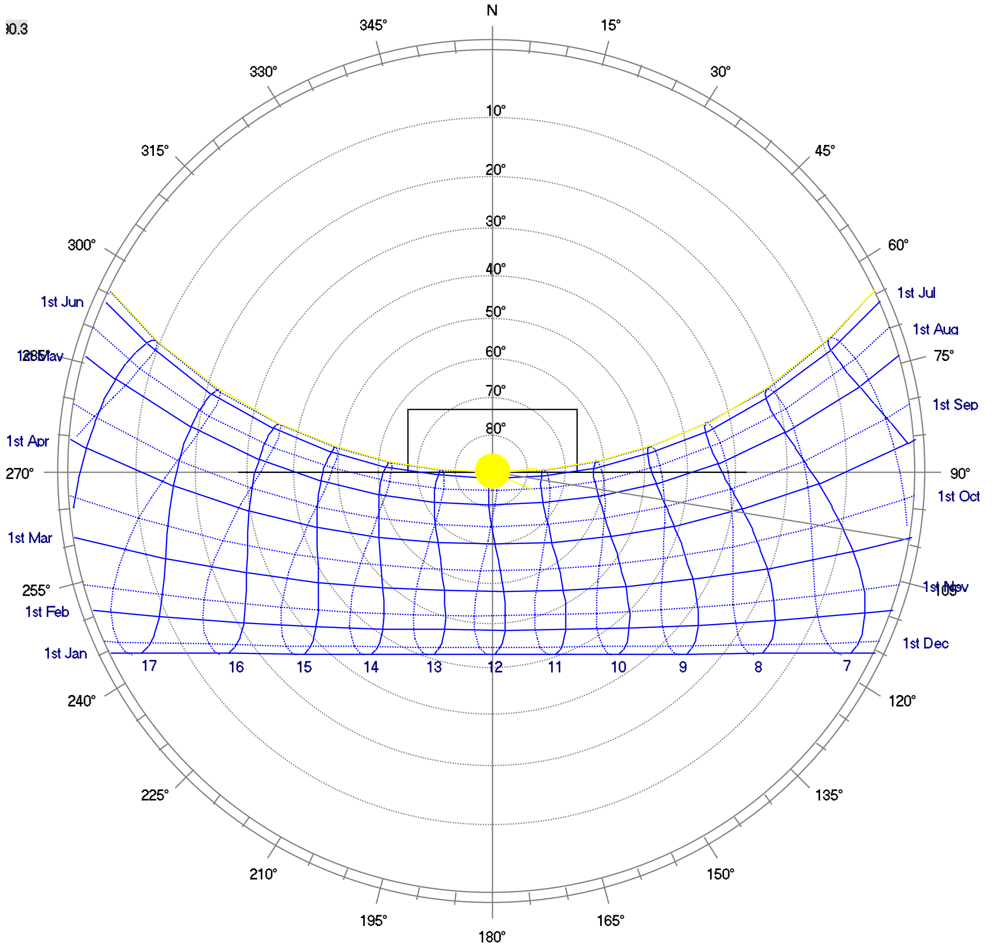


Figure 4.4: The sun path diagram of Dhaka, Bangladesh (source: SUNTOOL - Solar Position Calculator, 1998).

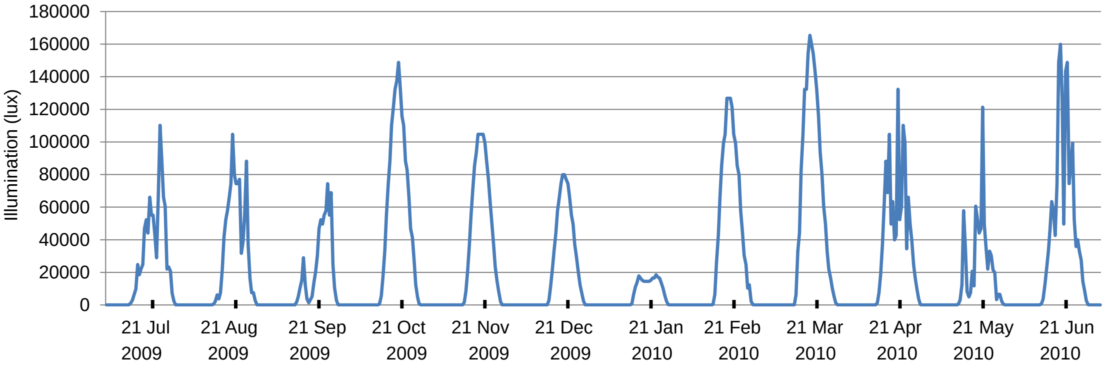


Figure 4.5: Hourly horizontal exterior illuminances of the 21st of each month for the year 2009-10 for Dhaka, Bangladesh (recorded from site).

4.4. Hospital building - Square Hospital

Square Hospital (a concern of Square Group) is a 320 bed tertiary care hospital. The construction of the hospital started in 2004 and finished in 2006. The hospital was opened on 16 December 2006. The architectural consultant of the building is Sold Unity Co, Ltd. Bangkok, Thailand. The hospital is an affiliate partner of Methodist Healthcare, Memphis, Tennessee, USA; SingHealth, Singapore; Bangkok Hospital Medical Centre, Thailand; and Christian Medical College, Vellore, India. The vision of Square Hospital is be ‘the location of choice for Bangladeshis and people of South and Southeast Asia for quality healthcare and an integrated centre for clinical services, medical and nursing education and research’ (SHL, 2010).

Square Hospital is located in the heart of Dhaka and aims to serve greater portion of the capital city. The outpatient department of the hospital can serve up to 1200 patients daily through 60 examination rooms. The hospital building is 18 stories occupying approximately 41,800 m^2 floor area in total. The hospital is constructed in accordance with US Fire and Building safety standards. The hospital building consists of a tower (eight story high “L” shaped plan) resting on a podium (seven story high). In-patient rooms mostly located from tenth to fifteenth floor of this building. Tables 4.2 summarises the organization of the main building and facilities of each floor.

Table 4.2: Basic organization of the main building of Square Hospital Ltd.

Level	**Facilities**
Basement three and two	Car park (can accommodate 80 cars).
Basement one	Emergency room (ER) registration and ER pharmacy; ER with six beds for non-critical cases; two procedure rooms; two trauma rooms; linear accelerator for radiation therapy; and morgue.
Ground floor	Lobby; ER with four beds for critical cases; ER triage; cafeteria; and flower and gift shop.
First and second floor	Physiotherapy center and OPD clinics with 60 consultation rooms
Third floor	Outpatient fine needle aspiration cytology (FNAC) clinic; outpatient bone marrow procedure room; chemotherapy center; radiology and imaging; and dialysis unit.
Fourth floor	Coronary care unit (CCU) with 11 beds; intensive care unit (ICU) with 21 beds of which two are isolation units; endoscopy and bronchoscopy suite with complete facilities for ERCP (equipped with C arm) as well as lithotripsy.
Fifth floor	OR complex with eight ORs, including two dedicated for Cardiac surgery; Cardiac surgical intensive care unit (CSICU) with seven beds; Surgical intensive care unit (SICU) with 13 beds; two cath labs and post-cath recovery room with seven beds.
Sixth floor	Hospital pharmacy; Pathology; central sterile services department (CSSD); and twenty four foundation beds.
Seventh floor	Obstetrics and gynaecology (OBGYN) OPD clinic; Labour and delivery (L&D) with four L&D rooms; two dedicated ORs for Caeserian section; invitro fertilization (IVF) center; paediatric intensive care unit (PICU) and neonatal intensive care unit (NICU) with 21 beds of which two are isolation units.
Eighth floor	Mother and child floor: 19 rooms with 28 beds.
Ninth floor	Pediatrics floor: 19 rooms with 26 beds.
Tenth to fourteenth floor	Each floor has 22 rooms with 31 beds. The Tenth floor is equipped with Telemetry service.
Fifteenth floor	Library and training rooms.
Roof top	Helipad.

4.5. Hospital site and surroundings

Square Hospital is located at West Panthapath, a growing mix-used developing area with high demand for commercial spaces. The main entrance is connected to a 30 meter wide road (Bir Uttam Qazi Nuruzzaman Sarak) in front of the building to the south. There is a four meter wide road at the north. Six storey residential buildings are located on the opposite side of the north road (Sukrabad Residential Area). There were some single-storey semi-pucca structures (demolished to construct a high-rise mixed use commercial-cum-residential building while the survey and data collection were carried on) on the west; a nine-storey building (Salim Centre) is at the south-east corner of the hospital plot and another nine storey building at east was under construction. Opposite the 30 meter front road, there is a 16 storey building connected by bridge at third floor with the Square Hospital (proposed Square Medical College under construction), 18 storey commercial building (Envoy Tower under construction), three storey school building (Lake Circus Girls' High School), and 20 storey apartment building (Concord Regency) in front of the hospital building (Figure 4.6). Most of the surrounding buildings have commercial facilities (e.g. shops, restaurant and offices) at the lower floors (e.g. 1st, 2nd and 3rd floors) due to the high commercial nature of the locality.

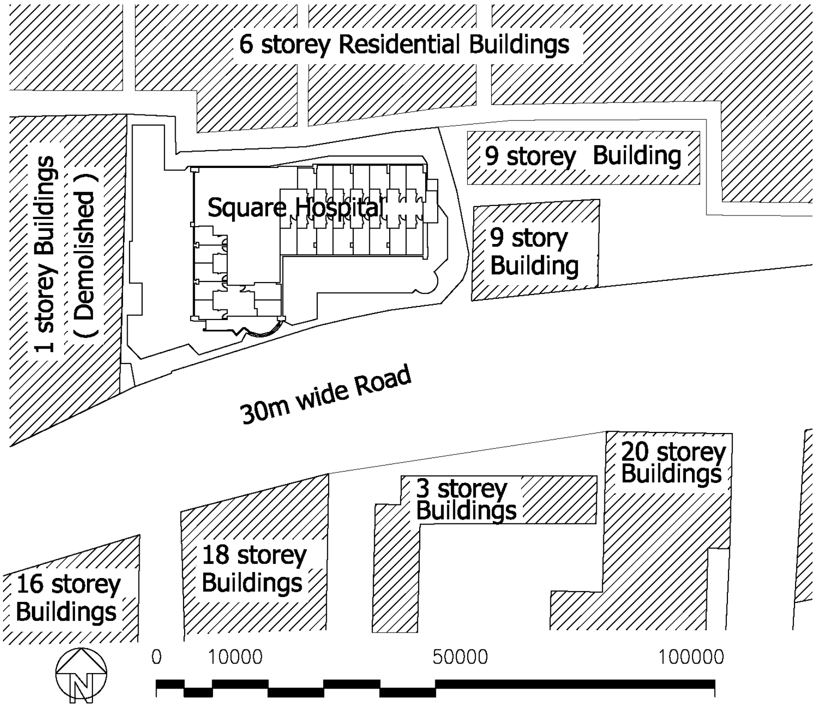


Figure 4.6: Site and surrounding of Square Hospital building, Dhaka.

4.6. Study space- Cardiac Inpatient Unit

According to the sample selection criteria (Section 3.4(a)) a number of open-heart surgery patients who were treated in cardiac inpatient unit, were taken for observational study. The cardiac inpatient unit is located at tenth floor at the "L" shaped tower (Figure 4.6) comprise of 22 rooms with 31 beds (Figure 4.7). The tenth floor is spatially equipped with telemetry service and dedicated for cardiac patients. The floor has four categories of rooms: one suite; seven single deluxe rooms; five single standard rooms and nine semi private double bed rooms. The rooms were full furnished with specialized hospital beds with state-of-the-art medical outfits and central gas system (piped oxygen in all units). The rooms were also equipped with cable TV and telephone services with 24-hour nurse call and monitoring system. Hospital services were carried out with the support of the hospital information system. In the layout of the floor plan, the toilets were located on the corridor side of the patient rooms rather than on the facade side, thus provide scopes for ample daylight inclusion from outsides (Figure 4.7). As the location of the unit is in tenth floor and majority of the surrounding buildings, were six stories or below (Figure 4.6) close to the hospital building, there were fewer obstructions to daylight from surroundings. Rooms were painted with the same colour scheme and were equipped with similar furniture and facilities. The floor consists of 13 single bedrooms and 9 double bedrooms. In double bedrooms, 1.8 meter high movable screens were used for privacy (Figure 4.8). As a result, POV was restricted for the patients who stayed in the inner side beds. As one of the interests of the study was to compare patients, who had experienced varying daylight intensities during their stay time in hospital rooms and with/without POV, the architectural layout and arrangement of the floor was suitable for the study.

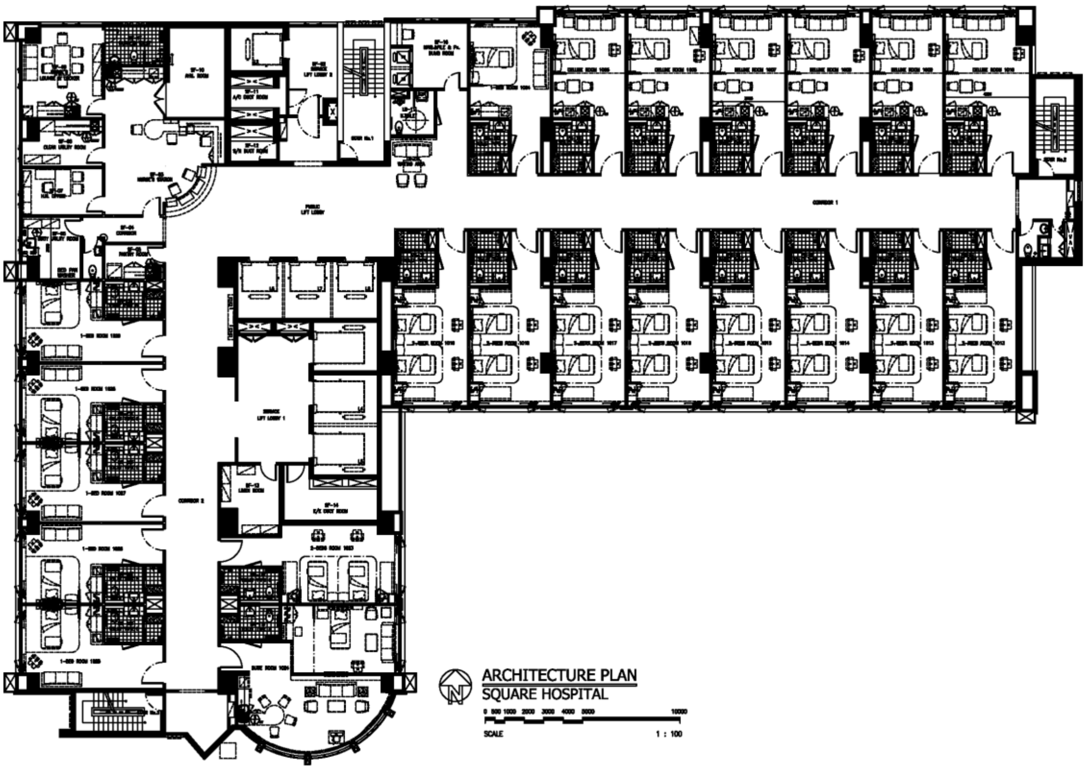


Figure 4.7: Architectural plan of 10th floor of Square Hospital (courtesy: SHL).

Figure 4.8: Location of 1.8 meter high movable screen in a double bedroom.

4.7. Pilot study

The pilot study started on 18 November 2008 and ended on 22 January 2009. A total number of 278 patients were treated in case unit during pilot study period. Admitted patients can be grouped in three major categories: open heart surgery patients, patients treated with only medicine; and other patients who had undergone a minor surgery such as Coronary Angiography and Coronary Angioplasty. According to the recommendation of Section 3.4(a), 41 open heart surgery patients were primarily selected as sample for the pilot study.

Among the 41 patients, 33 were CABG surgery patients and the rest of eight were other types of surgery, for example coarctation repair, valve replacement, atrial septal defect (ASD) or patch closure. Operations were successful for primary selected 41 patients. One patient was excluded from study, because he stayed less than 48 hours in the Cardiac Unit after being transferred from CTICU. Finally, 40 patients were taken as sample for statistical analysis. After surgery, the patients are moved to a bed in the CTICU. With gradual improvement to satisfactory levels, the patients were transferred from the CT ICU to the Cardiac Surgery In-patient Unit (CSIU). When the patients are assigned to hospital rooms in CSIU they were ready for the observational study. Patients usually stay in CSIU for two days to a week or longer after transferred from CTICU. The interest of the pilot study was whether the condition of daylight had any influence on patient LoS and recovery process.

4.7.1. Development of MLR model

For each observation, a total of 32 possible explanatory variables were considered at the beginning (Table 4.3). Greater variations were observed in lighting intensities from the readings of three indoor data loggers (Figure 3.5) installed in three representative rooms oriented in north, south and east (Table 4.3). The variations in temperature and RH were not significant, as the building was centrally air-conditioned. Average illumination values of each patient room, with respect to the patient stay time in cardiac surgery unit after surgery, were obtained by daylight simulation (Figure 4.9), as described in Section 3.4.1.

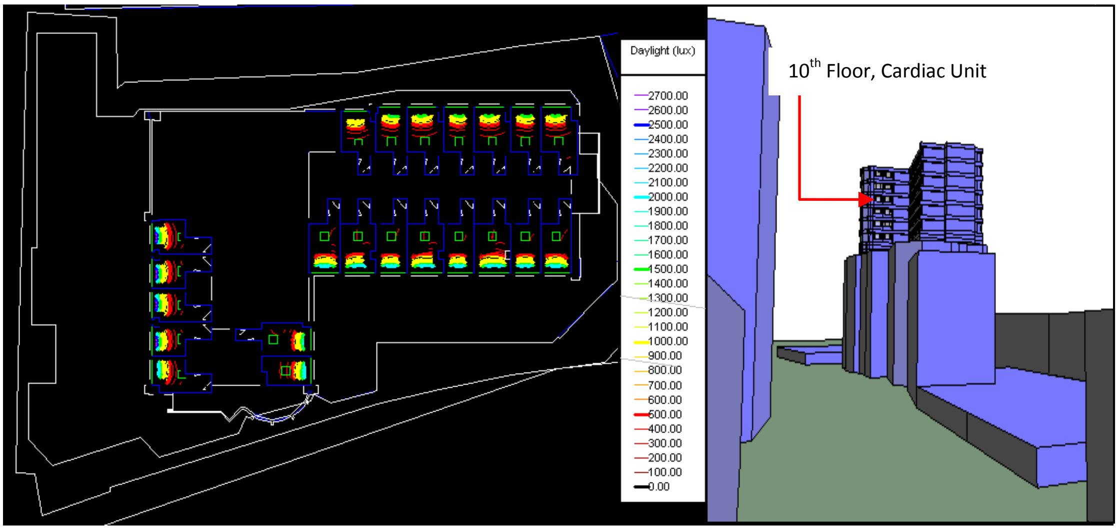


Figure 4.9: *Daylight simulation with a full progressive radiosity inter-reflection method.*

Table 4.3 presents a sample summary statistics of the variables considered primarily. Column one of Table 4.3 shows the list of provisional variables for the model. In the sample group there was no case of CRF and TIA, and there was only one case of stroke and bronchial asthma and two cases of CVD. The maximum body temperature of the patient was recorded as 99.0 degree F and a minimum 98.0 degree F with a mean of 98.05 degree F and 0.22 std. deviation. Due to the lack of significant differences in CRF, TIA, stroke, bronchial asthma, CVD and body temperature in sample group, these variables were excluded from the model at the beginning of analysis.

Pearson Correlation among the rest of the variables showed mean arterial pressure (MAP) was significantly correlated with weight, height, BMI, age, gender, systolic blood pressure, diastolic blood pressure, respiratory rate, fluid balance, smoking habits and hypertension, and the correlated variables were dropped from the model. In the next stage, insignificant variables identified by stepwise regression analysis such as MI, EF, dyslipidaemia and room type were eliminated from the model. Finally, two environmental variables and five clinical variables were selected for MLR model. The final set of variables, their coefficients (B), standardized coefficients (Beta), t-statistics together with the *p-value*s are shown in Table 4.4.

Table 4.3: A sample summary statistics of variables primarily considered for the pilot study model.

Variables (unit/total no.)	**Min/No.**	**Max/No.**	**Mean**	**Std. Deviation**
Patient LoS (hour)- dependent variable	48.00	178.00	88.43	29.88
Systolic blood pressure (mm Hg)	83.00	153.00	117.43	14.26
Diastolic blood pressure (mm Hg)	49.00	90.00	74.48	7.71
Mean arterial pressure (mm Hg)	60.00	106.00	88.83	9.45
Heart rate (beats/ min)	78.00	102.00	87.95	6.90
Respiratory rate (resp/min)	16.00	30.00	19.95	2.73
Body temperature (^oF)	98.00	99.00	98.05	0.22
Saturation of peripheral oxygen (%)	93.00	99.00	96.33	1.87
Fasting blood sugar (mmol/l)	5.00	11.40	7.49	1.85
Fluid balance (ml)	-1800.00	195.00	-642.50	419.72
Ejection fraction value (%)	35.00	65.00	52.69	7.87
Smoker (40)	Y (17)	N (23)	-	-
Hypertension (40)	Y (30)	N (10)	-	-
Dyslipidaemia (40)	Y (21)	N (19)	-	-
Diabetes mellitus (40)	Y (15)	N (25)	-	-
Myocardial infarction (40)	Y (13)	N (27)	-	-
Transient ischaemic attack (40)	Y (0)	N (40)	-	-
Bronchial asthma (40)	Y (01)	N (39)	-	-
Stroke (40)	Y (01)	N (39)	-	-
Cerebral vascular diseases (40)	Y (02)	N (38)	-	-
Chronic renal failure (40)	Y (0)	N (40)	-	-
Gender (40)	M (33)	F (07)	-	-
Age (year)	5.00	70.00	50.70	16.60
Weight (Kg)	22.00	92.00	60.05	14.95
Height (cm)	99.00	180.00	155.10	15.92
Body mass index	15.40	34.70	24.80	3.91
Room type (40)	S (15)	D (25)	-	-
Rent (Tk/day)	3500.00	17500.00	3976.55	1705.18
Provision of outdoor view (40)	Y (30)	N (10)	-	-
Room temperature (^oC)	19.28	27.28	24.12	1.14
Relative humidity (%)	72.74	82.60	75.83	5.44
Point illumination (lx)	3.90	668.80	61.67	94.15
Room average daylight intensity (lx)	200	1080	598.43	185.32

* Y – Yes; N – No; M – Male; F – Female; S – Single; D – Double.

4.7.2. Model interpretation

Analysis of pilot study data (Table 4.4) shows that six variables decrease patient LoS inside in-patient unit and one variable is responsible for increasing the stay time (DM). Four variables were highly significant (MAP, DM, SPO2 and FBS), two variables were significant (daylight and HR) and one variable can be considered as marginally significant (POV) in the MLR model. The column of un-standardised coefficients (B) provides the values for explanatory variables for final MLR equation.

Table 4.4: MLR Model for patient LoS in cardiac unit based on pilot study data.

Explanatory variable	**Un-standardized coefficients (B)**	**Standardized coefficients (Beta)**	**t-statistics**	***p*-values**
Constant	1086.209	-	5.029	<0.001
Average daylight intensity of the room	-0.040	-0.245	-1.995	0.055
Provision of outdoor view	-13.495	-0.198	-1.636	0.112
Mean arterial pressure	-2.365	-0.748	-5.218	<0.001
Heart rate	-1.444	-0.333	-2.626	0.013
Diabetes mellitus	38.049	0.624	4.441	<0.001
Saturation of peripheral oxygen	-5.839	-0.366	-3.052	0.005
Fasting blood sugar	-10.517	-0.651	-4.989	<0.001

**Dependent Variable: Patient LoS in hour; R square =0.591; Adjusted R square =0.502, F =6.617(Sig. < 0.001).*

Therapeutic and intuitive judgement confirmed the validity and practicality of the mathematical signs in the model (Table 4.4). A view to the outdoor may help to reduce the LoS of patients (t=-1.636, p value=0.112), and reduction of patient LoS with the increase of daylight (t=-1.995, p value=0.055) agreed with the finding of past researchers Ulrich (1984) and Choi et al., (2012). It was evident from model that daylight is more significant between two room variables daylight and POV. The coefficient estimates showed that while holding the other explanatory variables constant, the provision of outdoor views reduced patient stay time by, on average, 13.5 hours and stay time by 4 hours per 100 lx increase of daylight (multiplying B with 100 lx).

According to Equation 3.2, the elasticity (η_y) of patient stay time with respect to average daylight intensity of the room is -0.27 (Equation 4.1), therefore, if average daylight intensity of the room were increased by 1%, patient LoS is expected to be decreased by 0.27%.

$$\eta_y = (-0.04) * \frac{598.43}{88.43} = -0.27 \tag{4.1}$$

Medical judgements also confirmed the validity and practicality of the mathematical signs of clinical variables. During and after open heart surgery, due to the influences of anaesthesia, the blood pressure and heart rate are usually reduced compared to patients' normal state (Neto et al., 2004). Therefore, patient recovery process accelerates with the increase of blood pressure (t=-5.218, p value<0.001) and heart rate (t=-2.626, p value=0.013) to normal stage, as a result, patient LOS is expected to be reduced. It is logical that patients with diabetes will take more time (Morricone et al., 1999) compared to non-diabetes patients to recover (t=4.441, p value<0.001) and an increase of patients FBS (t=-4.989, p value <0.001) and SPO2 (t=-1.636, p value=0.005) will accelerate recovery after surgery (Kurki et al., 1989; Parish et al., 2007).

4.7.3. Limitations of the pilot study and strategies for principal study

Specific limitations of the pilot study were that the duration of the study was around two months; as a result, a smaller sample size (40 patients) was possible to include in the model. To include a large number of samples, the duration of principal study was designed for one year to generate statistically more significant model with greater confidence level on the impact of daylight on patient LoS.

Another, limitation of pilot survey was that, the study population was restricted to the patients who had undergone heart surgery of different types (eight types) comprises of CABG, coarctation repair, valve replacement, ASD or patch closure. To build a stronger model for principal study, only CABG patients, who were the highest in number among heart surgery cases, were separated (as a more uniform sample group) for analysis at the beginning.

Under the limitation of actual prediction capacity of daylight intensity by available simulation software (Pechacek et al. 2008), FlucsDL of IES software package was used to calculate average daylight intensity of the in-patient rooms. Actual HEI measured by an outdoor data logger from site, was used to include the unpredictable nature of outdoor daylight intensity. As a result, the patients, who may have adjusted their blinds, were not accounted in pilot study and the simulated data for average daylight inside the room represents a part of outdoor daylight due to the room location and geometry that a patient might experience without any internal obstruction to windows (e.g. blinds). Due to the lack of sufficient number of indoor data loggers and pyranometers to measure outdoor radiation data to do a raytracing simulation, the validation of the simulated daylight data generated during pilot survey was not possible. To overcome this limitation and to consider the outcome of internal blind operations, 31 indoor data loggers were installed above each bed of the cardiac unit of the hospital to measure the daylight that the patient actually experienced during their stay in inpatient rooms, during principal study periods.

4.8. Principal study

The principal study started on 21 July 2009 at 00:00 and ended on 31 July 2010 at 23.00. Illumination values above patient beds with respect to the patient LoS in cardiac surgery unit were obtained by the readings of indoor data loggers (Figure 3.5) as described in Section 3.4.2.

A total number of 1889 patients were admitted during principal study period in cardiac inpatient unit. Among them 339 were open heart surgery cases including 278 CABG patients. Operations were successful for the primary selected 278 CABG patients. Five patients were excluded from study, who stayed less than 48 hours in the Cardiac Unit after being transferred from CTICU. Three data loggers were stopped for some times during the principal study period on bed No. 1014A (from 17 April 2010 at 13:00 to 26 May 2010 at 10:00); bed No. 1017A (from 11 November 2009 at 11:00 to 26 May 2010 at 10:00) and bed No. 1007 (from 27 October 2009 at 16:00 to 26 May 2010 at 10:00). Once the malfunction of the data loggers were identified, necessary steps were taken (e.g. restarting and/or replacement of the batteries) to reinstall the data loggers. As a result, three CABG patients lighting data were missed and the patients were excluded from the study. Necessary clinical data was missing (e.g. heart rate and blood pressure) in patient record file for seven patients and they were not included in the sample. Finally, 263 patients were taken as sample for principal study who stayed at least 48 hours in the in-patient rooms and have the necessary data (clinical and environmental) for statistical analysis.

4.8.1. Development of MLR model

For each observation, a total of 31 possible explanatory variables were considered at the beginning. Table 4.5 presents a sample summary statistics of the variables. Column one of Table 4.5 shows the list of provisional variables for the model. After Pearson Correlation and stepwise regression analysis, finally three environmental variables and three clinical variables were selected for MLR model. The final set of variables, their coefficients (B), standardized coefficients (Beta) t-statistics together with the *p-value*s are shown in Table 4.6.

Table 4.5: A sample summary statistics of primary variables for principal study model.

Variables (unit/total no.)	**Min/No.**	**Max/No.**	**Mean**	**Std. Deviation**
Patient LoS (hour)- dependent variable	48.00	666.00	109.63	61.67
Systolic blood pressure (mm Hg)	87.00	158.28	113.16	10.00
Diastolic blood pressure (mm Hg)	52.00	86.72	72.55	4.84
Mean arterial pressure (mm Hg)	60.00	110.57	85.85	6.34
Heart rate (beats/ min)	72.00	120.00	91.03	7.79
Respiratory rate (resp/min)	14.00	32.00	19.92	4.54
Body temperature (^{o}F)	97.80	100.00	97.86	0.16
Saturation of peripheral oxygen (%)	91.00	98.13	96.06	1.25
Fasting blood sugar (mmol/l)	4.20	16.58	7.82	2.39
Fluid balance (ml)	-2963.33	920.00	-575.47	396.71
Ejection fraction value (%)	23.00	73.00	54.96	8.13
Smoker (263)	Y (90)	N (173)	-	-
Hypertension (263)	Y (189)	N (74)	-	-
Dyslipidaemia (263)	Y (115)	N (148)	-	-
Diabetes mellitus (263)	Y (107)	N (156)	-	-
Myocardial infarction (263)	Y (95)	N (168)	-	-
Transient ischaemic attack (263)	Y (1)	N (262)	-	-
Bronchial asthma (263)	Y (19)	N (244)	-	-
Stroke (263)	Y (0)	N (263)	-	-
Cerebral vascular diseases (263)	Y (1)	N (262)	-	-
Chronic renal failure (263)	Y (5)	N (258)	-	-
Gender (263)	M (235)	F (28)	-	-
Age (year)	23.00	87.00	54.21	9.71
Weight (Kg)	39.00	93.00	63.44	9.22
Height (cm)	144.00	183.00	162.03	7.15
Body mass index	17.00	34.00	24.15	3.09
Room type (263)	S (109)	D (154)	-	-
Provision of outdoor view (263)	Y (210)	N (53)	-	-
Rent (Tk/day)	3500	17500	4655.89	1658.44
Room temperature (^{o}C)	18.56	28.36	25.46	1.18
Relative humidity (%)	68.64	84.75	77.38	6.16
Daylight intensity at head point (lx)	5	549	185.41	106.59

* Y – Yes; N – No; M – Male; F – Female; S – Single; D – Double.

4.8.2. Model interpretation

One of the interests of principal study was to check the results of pilot study (as the pilot study was done under several limitations) and build a stronger model. The analysis of principal study data (Table 4.6) showed that four variables decreased patient LoS inside in-patient unit and two variables were responsible for increasing the stay time (rent of the rooms and DM). Four variables were highly significant (rent, MAP, HR and DM), daylight was significant at a level of two percent and POV at a level of four percent in the MLR model. The column of un-standardised coefficients (B) provides the values for explanatory variables for final MLR equation.

Table 4.6: MLR Model for patient LoS in cardiac unit based on principal study data .

Explanatory variable	**Un-standardized coefficients (B)**	**Standardized coefficients (Beta)**	**t-statistics**	***p-values***
Constant	289.891	-	5.953	<0.001
Daylight intensity at head point	-0.073	-0.127	-2.425	0.016
Provision of outdoor view	-17.437	-0.114	-2.100	0.037
Rent of the rooms	0.015	0.397	8.398	<0.001
Mean arterial pressure	-1.703	-0.175	-3.960	<0.001
Heart rate	-1.162	-0.147	-3.363	0.001
Diabetes mellitus	73.313	0.587	13.402	<0.001

** Dependent Variable: Patient LoS in hour; R square =0.516; Adjusted R square =0.505; F =45.473 (Sig. < 0.001).*

Therapeutic and intuitive judgement confirmed the validity and practicality of mathematical signs in the model (Table 4.6). In a developing country, i.e. Bangladesh with per capita income around $418 a year (BBS, 2010), the government does not have the sufficient funds to address the adequate healthcare needs of the people. The government provides free health services to rural areas and the health system has not been designed to serve densely populated cities such as Dhaka, where the patient need is greatest. Due to the government's inadequacy in the health sector, only 30% of population use the free health services (Chaudhuri, 2003) and rest of the people need to pay for health services. According to the World Bank's estimation, more than 60% of Bangladeshis, about 80m people, have no access to modern health services (Mehovic and Blum, 2004) which are too expensive for average income group of people. Mainly the private hospitals meet the healthcare needs of the capital city with costly services.

The rent of the hospital in-patient rooms with modern facilities are usually high in private hospitals, and contribute to the major expenses of the treatment of the patients during hospital stay periods. Luxury rooms are only affordable to very rich people to whom cost of treatment matter little and they tend to stay longer in hospital till their complete satisfaction to recovery. On the other hand, patients who preferred a shared room to reduce the treatment cost tend to leave the hospital earlier with a reasonable recovery status of their health with doctors' consent. The impact of the rent of the room which reflects patients' economic capabilities, therefore, have a strong influence on LoS in hospital rooms. It is logical that in a modern and expensive hospital, such as Square Hospital, patients with better economic conditions are more intend to stay longer in luxury rooms with higher rents than the patients with less affording capabilities who choose a room with cheaper rent to reduce treatment cost (t=8.398, p value<0.001).

A view to the outdoor may help to reduce the stay time of patients (t=-2.1, p value=0.037), and reduction of patient stay time with the increase of daylight (t=-2.425, p value=0.016) agreed with the findings of pilot survey at a higher significance level. It is evident from principal study model that daylight is more significant between two environmental variables daylight and POV. The coefficient estimates show that while holding the other explanatory variables constant, the POV reduces patient LoS by, on average, 17.4 hours and stay time by 7.3 hours per 100 lx increase of daylight intensity (multiplying B with 100 lx) near a point above patient heads.

According to Equation 3.2, the elasticity (η_y) of patient stay time with respect to daylight intensity, near a point above patient head, is - 0.12 (Equation 4.2), implying that, if daylight intensity were increased by 1% at a point above patients' head, patient stay time would decrease by 0.12%.

$$\eta_y = (-0.073) * \frac{185.41}{109.63} = -0.12 \tag{4.2}$$

Medical judgements also confirmed the validity and practicality of the mathematical signs of clinical variables such as blood pressure (t=-3.96, p value<0.001), heart rate (t=-3.363, p value=0.001) and diabetes (t=13.402, p value < 0.001). Mathematical signs of the common explanatory variables also agreed with the findings of pilot survey.

4.8.3. Comparison between the results of pilot and principal studies

In case of the analysis of the pilot and principal surveys, dependent variable of both the MLR models was patient LoS in hours. Comparing the sample summary statistics of variables primarily considered in the model of pilot and principal study, it is evident that the Std. Deviations for demographic variables (e.g. age, weight and height) are smaller for the sample of principal study because of the inclusion of a more specific disease (i.e. CABG patients) in the model. Therefore, more uniform patient sample was included in principal study compared to pilot study.

Table 4.7: Major differences between pilot and principal study.

		Pilot survey	**Principal survey**
Daylight data (lx)		Average daylight intensity inside the room	Daylight intensity at a point near patient head
Duration		75 Days	375 Days
No. of samples		40	263
F		6.617 (Sig.<0.001)	45.437 (Sig.<0.001)
Adjusted R square		0.502	0.505
R square		0.591	0.516
Dependent variable		Patient LoS in hours	
Explanatory variables		7 (Daylight, POV, DM, MAP, HR, SPO2 and FBS)	6 (Daylight, POV, Rent, DM, MAP and HR)
Common explanatory variables		5(Daylight, POV, DM, MAP and HR)	
Constant	*Un-standardized coefficients(B)*	1086.209	289.891
	t-statistics (p-values)	5.029 (<0.001)	5.953 (<0.001)
Daylight	*Un-standardized coefficients(B)*	-0.040	-0.073
	Standardized coefficients (Beta)	-0.245	-0.127
	t-statistics (p-values)	-1.995 (0.055)	-2.425 (0.016)
POV	*Un-standardized coefficients(B)*	-13.495	-17.437
	Standardized coefficients (Beta)	-0.198	-0.114
	t-statistics (p-values)	-1.636 (0.112)	-2.1 (0.037)
MAP	*Un-standardized coefficients(B)*	-2.365	-1.703
	Standardized coefficients (Beta)	-0.748	-0.175
	t-statistics (p-values)	-5.218 (<0.001)	-3.960 (<0.001)
HR	*Un-standardized coefficients(B)*	-1.444	-1.162
	Standardized coefficients (Beta)	-0.333	-0.147
	t-statistics (p-values)	-2.626 (0.013)	-3.363 (0.001)
DM	*Un-standardized coefficients(B)*	38.049	73.313
	Standardized coefficients (Beta)	0.624	0.587
	*t-statistics (*p-values*)*	4.441 (<0.001)	13.402 (<0.001)

In the set of explanatory variables, five variables (daylight intensity, POV, MAP, HR and DM) were common in both pilot and principal survey data analysis. In addition to five common explanatory variables, the analysis of pilot survey data showed FBS (t=-4.989, p value <0.001) and SPO2 (t=-1.636, p value=0.005) as highly significant and during principal survey rent of the rooms (t=-8.398, p value < 0.001) were found highly significant. Both the F and adjusted R square values were higher for principal survey model (adjusted R square =0.505, F =45.437) than pilot survey model (adjusted R square =0.502, F =6.617). Explanatory variables, that were common in both pilot and principal study, have a higher t-statistics value in the MLR model except one (MAP), and have an equal or lower *p-values* for the MLR model of principal study. Table 4.7 shows the major differences between pilot and principal study with the statistical out comes.

4.9. Daylight intensities for positive health outcomes

The results of principal and pilot study confirmed that the increase of daylight intensities inside hospital rooms reduced patient LoS gradually. From literature, it was found that excess and higher intensive daylight might cause discomfort (Section 3.4.3(a)) and, therefore, might liable to reduce the rate of recovery of hospital patients. In this section, the collected principal study data was used to determine the effects of upper (2000 lx) and lower (190 lx) limits of therapeutic daylight, identified from literature review in Section 3.4.3(a), on patient LoS. The hypothesis of this particular study was that, patient LoS will be higher if they spent most of their hospital stay time under lower and higher levels of daylight environment compared to moderate level of daylighting (190-2000 lx).

After completing the principal study on 31 July 2010 another experiment was conducted from 9 September 2010 to 18 September 2010. The amount of daylight that a particular patient might experience on head, during his/her stay in the bed, was calculated following the method described in Section 3.4.3(b). Based on this estimated amount, average daylight intensity that a patient experienced in the maximum time in hospital rooms was identified and the sample patients were grouped under three categories: lower (below 190 lx), moderate (190-2000 lx) and higher (above 2000 lx) daylight group. The moderate group was taken as reference and their stay time was compared with other two groups.

4.9.1. Model interpretation

The dependent variable and most of the explanatory variables were the same as the MLR model for principal study (Table 4.6). Only the explanatory variable “Daylight intensity at head point”, was replaced by two-categorical variables represented by lower (lx<190 lx) and higher (lx>2000 lx) daylight group of patients mentioned above. Finally four environmental variables and three clinical variables were selected for this third MLR model. The final set of variables, their coefficients (B), standardized coefficients (Beta), t-statistics together with the *p-value*s are shown in Table 4.8.

The analysis of the third MLR model (Table 4.8) showed that four variables increased patient LoS inside in-patient room, and three variables were responsible for decreasing the stay time (POV, MAP and HR). Six variables were highly significant (lx<190, POV, Rent, MAP, HR and DM) and one variable (lx<2000) was significant at a level of four percent in the MLR model. The column of un-standardised coefficients (B) provides the values for explanatory variable for final MLR equation.

Therapeutic and intuitive judgement confirmed the validity and practicality of mathematical signs in the model (Table 4.8). A view to the outdoor may help to reduce the stay time of patients (t=-3.340, p value=0.001), and patients with better economic conditions are more intend to stay in luxury hospital rooms than the patients with lower affording capabilities (t=7.363, p value < 0.001), agree with the finding of principal survey. It is evident that the stay time of the patients for two daylight categories used as explanatory variables for the model, were significantly higher compared to the reference group who experienced moderate levels of daylight in the maximum time of their stay inside in-patient unit, therefore, confirmed the recommendations of previous research (e.g., Pechacek et al., 2008; Rogers, 2006; Nabil et al., 2006; 2005). The coefficient estimates show that while holding the other explanatory variables constant, being in lower daylight group adds 42 hours (t=3.096, p value=0.002) and being in higher daylight group (lx>2000) adds 29 hours (t=2.094, p value=0.037) in patient LoS compared to the group experienced moderate levels of daylight. Medical judgements also confirmed the validity and practicality of the mathematical signs of clinical variables such as MAP (t=-3.238, p value=0.001), HR (t=-2.795, p value=0.006) and DM (t=13.120, p value <0.001). Mathematical signs of the common explanatory variables also agreed with the findings of principal study.

Table 4.8: MLR Model to confirm the range of daylight for therapeutic purpose.

Explanatory variable	**Un-standardized coefficients (B)**	**Standardized coefficients (Beta)**	**t-statistics**	***p-values***
Constant	242.596		4.959	<0.001
lx <190 lx	42.337	0.138	3.096	0.002
lx >2000 lx	28.592	0.093	2.094	0.037
Provision of outdoor view	-24.079	-0.157	-3.340	0.001
Rent of the rooms	0.013	0.353	7.363	<0.001
Mean arterial pressure	-1.392	-0.143	-3.238	0.001
Heart rate	-0.965	-0.122	-2.795	0.006
Diabetes mellitus	71.310	0.571	13.120	<0.001

** Dependent Variable: Patient LoS in hour; R square =0.529; Adjusted R square =0.516; F =40.931 (Sig. < 0.001).*

A fourth MLR model was developed to identify the recovery rate of patients under moderate levels of daylight above their heads during their stay in hospital rooms. Table 4.9 shows the results of the fourth MLR analysis where the patients experienced only moderate levels of daylight were taken as sample (241 patients). It was evident from the model that daylight became most significant (t= -4.091, p value<0.001) variable with DM (t = 17.815, p value<0.001) among five explanatory variables considered in the model. Rent of the rooms was also highly significant, however, MAP and HR were marginally significant and POV were not significant at a level of ten percent and not included in the model. Comparing this model (Table 4.9) with previous two models derived from principal study data (Table 4.6 and Table 4.8), it is evident that, to reduce patient LoS, the changes in MAP and HR are more likely to be occurred in case of the patients who experienced lower and higher level of daylight in the maximum time of their stay in hospital rooms, at the same time the effect of POV is also more likely to affect the LoS of these two groups.

Table 4.9: MLR Model for patient LoS in cardiac unit based under moderate levels of daylight.

Explanatory variable	**Un-standardized coefficients (B)**	**Standardized coefficients (Beta)**	**t-statistics**	***p-values***
Constant	159.140		4.791	<0.001
Moderate levels of daylight (180 -2000 lx)	-0.082	-0.180	-4.091	<0.001
Rent of the rooms	0.004	0.125	2.801	0.006
Mean arterial pressure	-0.498	-0.072	-1.665	0.097
Heart rate	-0.428	-0.080	-1.903	0.058
Diabetes mellitus	63.428	0.751	17.815	<0.001

** Dependent Variable: Patient LoS in hour; R square =0.587; Adjusted R square =0.578; F =66.723 (Sig. < 0.001).*

Therapeutic, intuitive and medical judgement confirmed the validity and practicality of mathematical signs in the model (Table 4.9) and agreed with the findings of previous two models derived from principal study. The coefficient estimates showed that while holding the other explanatory variables constant, patient LoS reduces by, on average, 8 hours per 100 lx increase of daylight intensity (multiplying B with 100 lx) near a point above patients' heads for the patients, under recommended range of daylight level (190-2000 lx), to ensure the therapeutic benefit.

According to Equation 3.2, the elasticity (η_y) of patient stay time with respect to daylight intensity, near a point above patient head, is - 0.14 (Equation 4.3), therefore, if daylight intensity were increased by 1% at a point above patient head, patient stay time would expected to be decreased by 0.14%.

$$\eta_y = (-0.082) * \frac{181.47}{104.05} = -0.14 \qquad (4.3)$$

4.10. Summary

This chapter has achieved the second and third objectives of the research.

The second objective has been achieved by establishing statistical relationship between daylight intensities and patient LoS. The hypothesis of statistical analysis was that increase of daylight intensity inside in-patient rooms might reduce patient LoS in hospitals. MLR models from the analysis of principal and pilot study data confirmed that the increase of daylight intensities inside in-patient rooms to a moderate level helped to reduce patient LoS significantly. The field study started with a pilot study to develop and test the suitability of the methodology. With certain limitations (Section 4.7.3) but with successful completion of pilot study with expected results leads to conduct an intensive principal study for one year. Principal study incorporated the experience of pilot study to overcome the limitations of pilot study and to build a stronger model. It was evident that inclusion of more uniform and higher number of sample group, and precise daylight data collection method in principal study result a stronger evidence based MLR model with greater confidence. The output of principal study, not only agreed with the analysis of pilot study, but also agreed more significantly that higher daylight intensities inside in-patient rooms reduce patient LoS in a general hospital environment.

The third objective has been achieved by checking the impact of upper and lower limits of daylight intensities, identified from the recommendation of previous researchers, to confirm the range of daylight intensities within which reduction of patient LoS is expected. It was found from the additional experiment with the principal study data, that the patients who experienced lower (less than 190 lx) and higher (more than 2000 lx) levels of daylight in the maximum time of their stay inside in-patient rooms, needed significantly more time to recover compared to the patients who experienced moderate levels of daylight (between 190 lx to 2000 lx) throughout their stay in hospital rooms. The benchmarks, to ensure the therapeutic benefit of daylight, verified from field data were fixed as simulation goals to evaluate the therapeutic potentiality of hospital in-patient rooms in this research, during prospective simulation analysis presented in next Chapter 5.

CHAPTER 5
Prospective Simulation Study

5.1. Introduction

This chapter contains the descriptions and outputs of simulation exercise done during this PhD research. Based on previous literature review done in Chapter 3 (Section 3.5.1(f)) the DAYSIM dynamic annual CBDM method was used for simulation analysis. Daylight intensities, within which positive health outcomes are expected recommended from past literature identified in Chapter 3 (Section 3.4.3(a)) and verified as useful for reducing patient LoS in hospitals in Chapter 4 (Section 4.9), have been used as simulation goal for prospective simulation study in this chapter. This chapter consists of major two parts. The first part shows how therapeutic effect of daylight can be incorporated in hospital in-patient room design, more effectively, by evaluating a concept of new window configurations developed by the researcher, and compared with the standard typical window configurations for hospital in-patient rooms. This part also elaborates the output of simulation analysis to find out the appropriate direction of aperture extensions, shading designs and materials of the proposed window Configurations. The second part showed the performance of the concept with different future emissions scenarios under UKCIP02 to conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose. The strategies based on the simulation exercise of this chapter have been discussed in Chapter 6 and key findings have been presented in concluding Chapter 7.

5.2. Background

Daylight is one of the free gifts of nature. Due to its vast availability, daylight is often overlooked and has become underutilized within building service design, although, strategies for 100% utilization of daylight in buildings is still an evolving topic of research. In a sense, daylight in buildings is not always free because conventional windows tend to cost more than solid walls and linear buildings (to keep the depth of building within reach of daylight) are more expensive to construct compared to compact buildings, let alone the sophisticated and high performance facades (for example intelligent skins, active facade systems and double-skin facades) to accommodate appropriate daylight into buildings (ERG, 1994). However, inclusion of daylight into building design was found beneficial by many researchers, if designed carefully (Rogers et al., 2006; Loftness et al., 2006; Clanton et al., 2004; Muneer et al., 2000; Ternoey, 1999). Along with energy conservation, the increasing realisation of the healing powers of natural elements on health and wellbeing is contributing to consider daylight as an important element for therapeutic environmental design of hospital in-patient rooms. Increase of daylight inside hospital rooms decrease patient LoS was supported by the field survey data analysis of this research in Chapter 4. Therefore, the primary goal of simulation analysis was to develop and implement a design concept to enhance the therapeutic effect of daylight inside hospital in-patient rooms to reduce patient LoS. Due to the rapid climate change, it is important to evaluate any concept under the future climate scenarios, where possible. The other purpose of simulation analysis was to conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose. Figure 5.1 shows the flow diagram of simulation analysis and following sections describes the activities and results of the study.

5.3. Simulation parameters for performance evaluation

In this first part of prospective simulation study, parametric simulation was used to conceptualise the performance of sky window configurations to enhance the therapeutic effect of daylight inside in-patient rooms, more effectively, compared to traditional standard hospital window configurations. The development of the design of sky window configurations by incorporation of shading devices was also done by parametric simulation analysis. The quantitative and qualitative assessments for the design strategies were based on the following parameters identified in Section 3.5.1.

Location: London, United Kingdom.
Longitude: 00°07′29″W
Latitude: 51°30′29″N
Ground reflectance: 0.2
Time: 6:00 AM – 6:00 PM (12 hour)

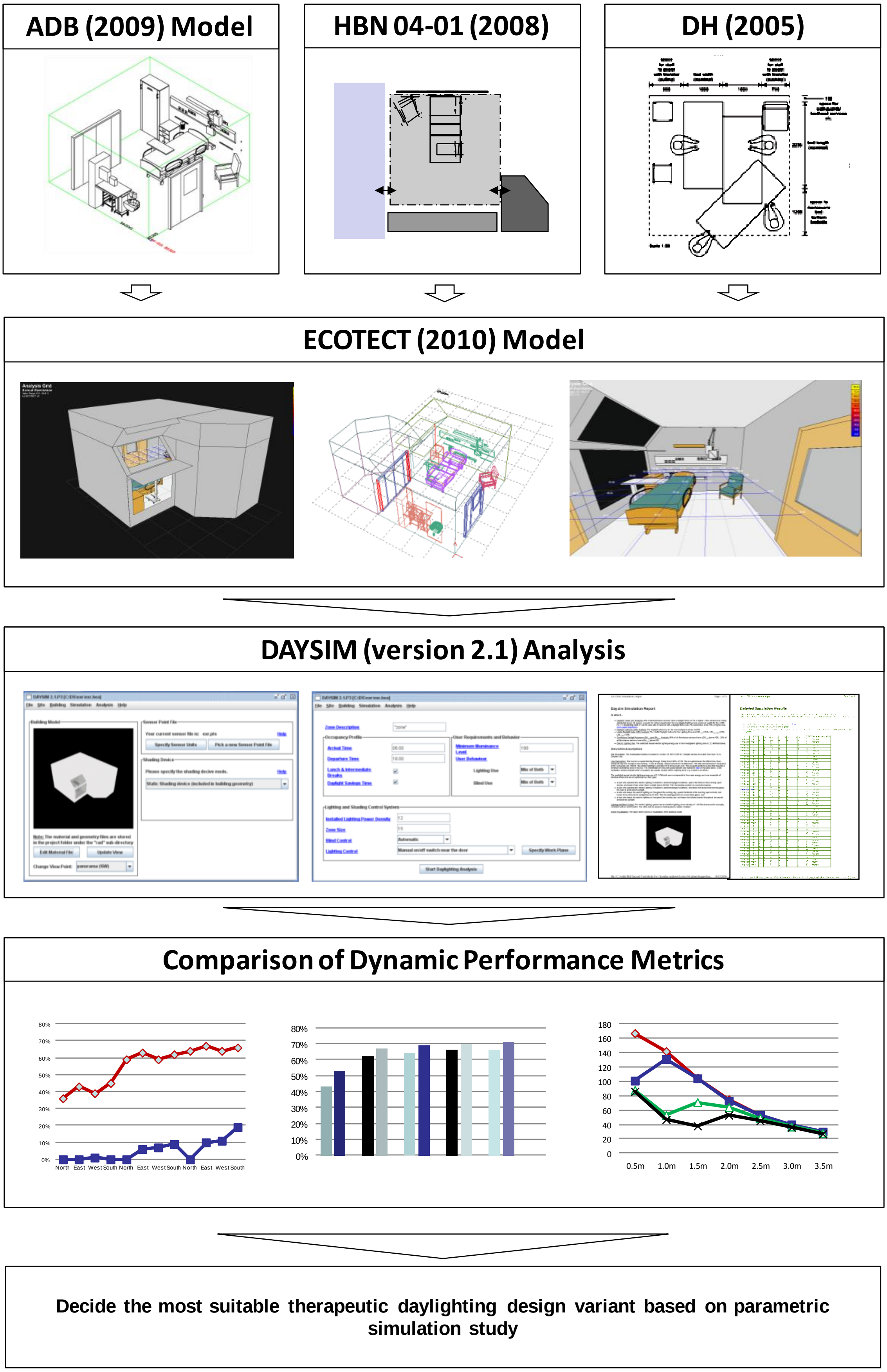


Figure 5.1: Graphical representation of parametric simulation study.

Duration: Whole Year

Sky model: Perez sky model (Perez, 1990; 1993)

Design illumination: Minimum 190 lx daylight for south, east and west orientations and 180 lx for north orientation (Pechacek et al., 2008)

Discomfort level: Above 2000 lx (Rogers, 2006; Nabil et al., 2006; 2005)

DA: 62.5% at core test plane sensor (minimum 80% of outdoor DA)

UDI>2000: 14 % at core test plane sensor (maximum 20% of outdoor UDI>2000)

Single-bed in-patient room area: 19 m^2 (4800mm x 3960mm)

External en-suite area: 4.5m^2 (2285mm x 2100mm)

Clear height of the room: 2700mm

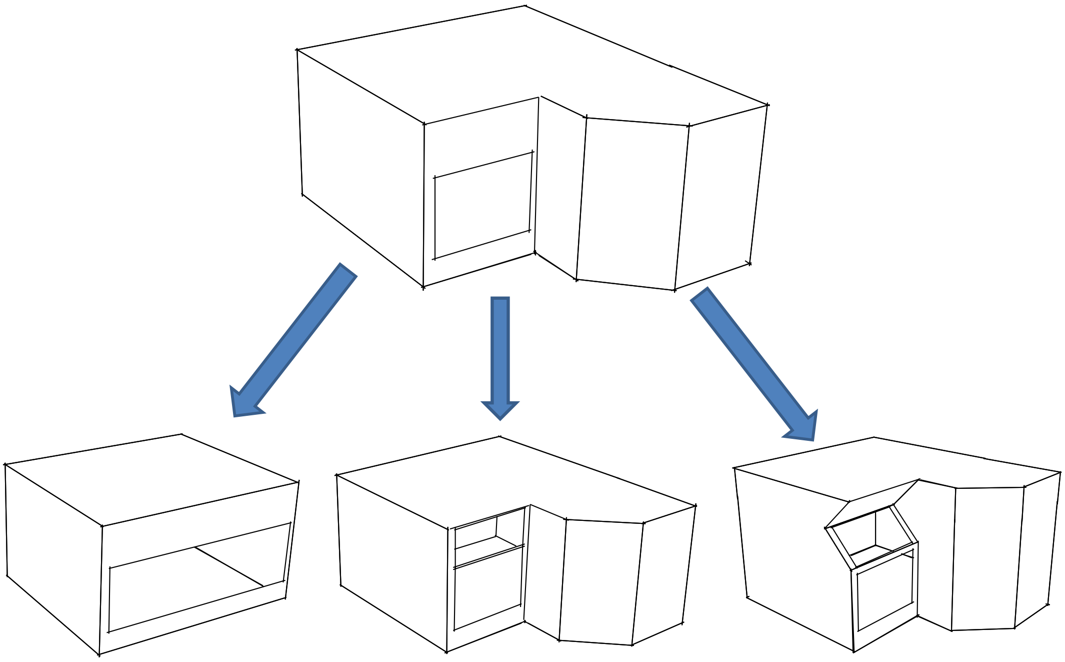
Height of the void space above ceiling: 750mm

Test plane height: 1150mm above floor level

Location of core test plane sensor (Test Point): Patient head (Pechacek et al., 2008)

5.4. Comparison between different window configurations

This section compares the performance of two options for traditional window configurations described in Section 3.5.1(d) (Figure 3.22) with sky window configurations (proposed by the researcher) with respect to increase the DA levels at test point for four orientations. The possible three extensions (horizontal, vertical, and diagonal) of a viewing window (Figure 5.2) have three different window-to-floor ratios. Window-to-floor ratio is the percentage of total unobstructed glass area of window to total area of floor served by the windows (GBE, 2009). The total glass area was the maximum for full facade viewing window (Figure 5.2(a)), and the minimum for high window option (Figure 5.2(b)). Usually with the increase of window-to-floor ratio, the possibilities of entering higher amount of daylight into the space are achieved. Figure 5.2 shows the 3D views of four studied models. Table 5.1 summarises the details of four studied window configurations.



a) Full width viewing window b) Viewing + High window c) Viewing + Sky window

Figure 5.2: 3D views of four studied window configurations with different window-to-floor ratios.

Table 5.1: Particulars of studied four configurations of window-to-floor ratio with alternative combination of viewing, high, and sky window configurations.

Window type	**window-to-floor ratio (%)**	**Total window glass area (m^2)**	**Served floor area (m^2)**	**Description**
Viewing window (smaller)	12.9	2.43	19	One window (2.43m^2): 1350mm (height) x 1800mm (width) with sill height at 450mm. (Figure 5.2)
Viewing window + High window	20.4	3.87	19	Two windows: One high window (1.44 m^2), 800mm (height) x 1800mm (width) started at a height of 1850mm above a viewing window (2.43m^2). (Figure 5.2(b))
Viewing window + Sky window	22.3	4.23	19	Two windows: One 45^0 angled sky window (1.8m^2), 1000mm (height) x 1800mm (width) started at a height of 1850mm above a viewing window (2.43m^2). (Figure 5.2(c))
Full width viewing window	32.0	6.10	19	One window (6.1m^2): 1350mm (height) x 4500mm (width) with sill height at 450mm. (Figure 5.2(a))

Analysis shows that increasing the width of viewing window (Figure 5.2(a)) more than twice (from 1800mm to 4500mm) results 148.1% increase in window-to-floor ratio, but only 10% increase in DA for south orientations at test point (Figure 5.3). On the other hand, addition of high window above viewing window result 58% increase in window-to-floor ratio and 17% increase in DA for south orientation. Addition of 45^0 angled sky window above viewing window result 72.9% increase in window-to-floor ratio and 21% increases in DA for south orientation. The trends of graphs for other three orientations are similar. It is evident from the result of simulation analysis that increase of window to floor ratio is the maximum when the width of the viewing window increased to the maximum, but resulted the minimum increase in DA levels at test point for four orientations (Figure 5.3). The DA of both high window and sky window configurations were higher with a smaller viewing window (with smaller window-to-floor ratios), compared to a large viewing window extend horizontally.

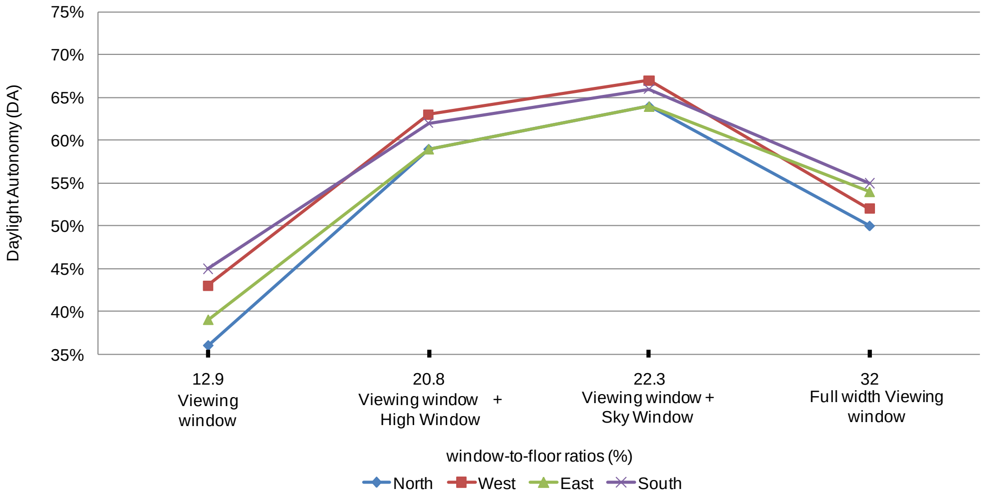


Figure 5.3: DA levels at test point with upright sensor position for four studied window-to-floor ratios.

Between high and sky window configurations, the DA of sky window configurations are higher (5% higher for north and east orientations, and 4% higher for south and west orientations compared to high window options) at test point. It can be concluded that sky window configurations is the best option among three studied configurations to increase the DA level at test point when the sensor points are upward towards the ceilings. Patients will gain more daylight to ensure therapeutic need under sky window configurations, if lying with their spine on bed; however, there are possibilities that the patients might prefer to stay upright (resting on their back) looking towards the partition walls.

Figure 5.4 compares the DA level between sky and high window configurations at a point 1250mm above floor level, when the sensors were pointing toward the partition walls. It is evident from Figure 5.4 that the performance to increase DA levels are better for sky window configurations compared to high window configurations for four orientations; implying that the patient will receive more daylight for therapeutic purpose under sky window configurations, even prefer to stay upright on their back for some times.

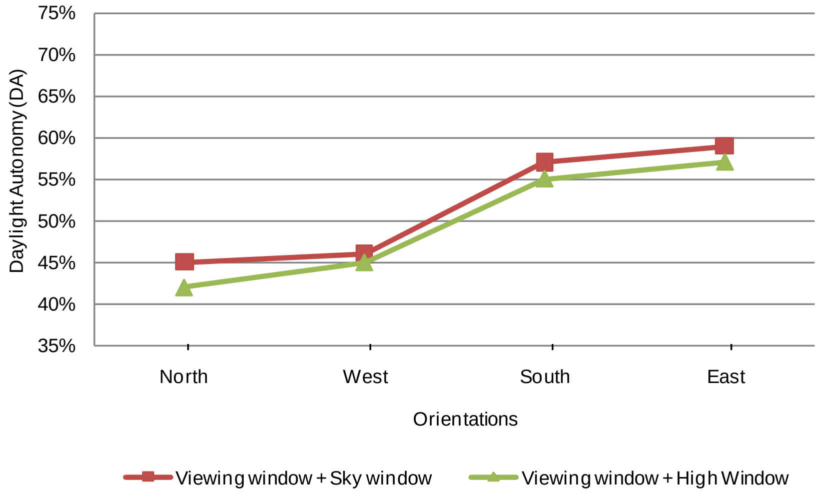


Figure 5.4: DA levels between sky and high window configurations, when the sensors were pointing toward the partition walls.

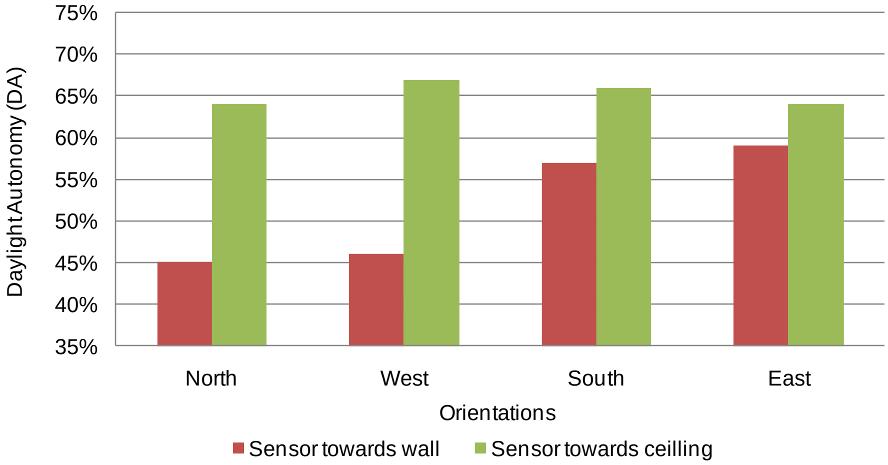


Figure 5.5: Comparison of two sensor directions (vertical and horizontal) for sky window configurations.

Figure 5.5 compares the results of two sensor directions (vertical and horizontal) presented in Figure 5.3 and Figure 5.4 for sky window configuration. It is evident that, the possibilities of getting higher illumination on retinas are higher, if patients lay with their spine on beds compared to upright for studied four orientations. The possibility of getting higher levels of DA is the minimum for east orientations (5% higher) and the maximum for west orientations (21% higher) when patients lay with their spine compared to upright positions.

It is evident from the above discussions that between high and sky window configurations, the DA of sky window configurations are 4% - 5% higher at test points for different orientations, with upright sensor positions. To provide a more detailed observation on the impact of these 4% - 5% higher DA on daylight intensity at test points, and patient LoS inside in-patient rooms, monthly average illumination at test point for four orientations were compared for the whole year. Figures 5.6 – 5.9 show comparisons between sky and high window configurations for average monthly illumination at test point with upright sensor positions for north, west, south and east orientations. It is evident from the figures that about 4% - 5% difference in DA level between high and sky window configurations result yearly 114 lx (for north orientations) to 521 lx (for south orientations) difference in average illumination levels for different orientations. According to the findings of this research, these increases in daylight intensity will cause around 9 hours to 43 hours (8 hours per 100 lux increase) reduction in average LoS of patients, depending on orientations and periods of the year. The difference in illumination will be higher in a geographical location, where the average ambient outdoor daylight level is higher (for example tropical cities e.g. Dhaka has nearly three times greater outdoor daylight level compared to London) and will get more benefit to patient LoS reduction by adopting sky window configurations.

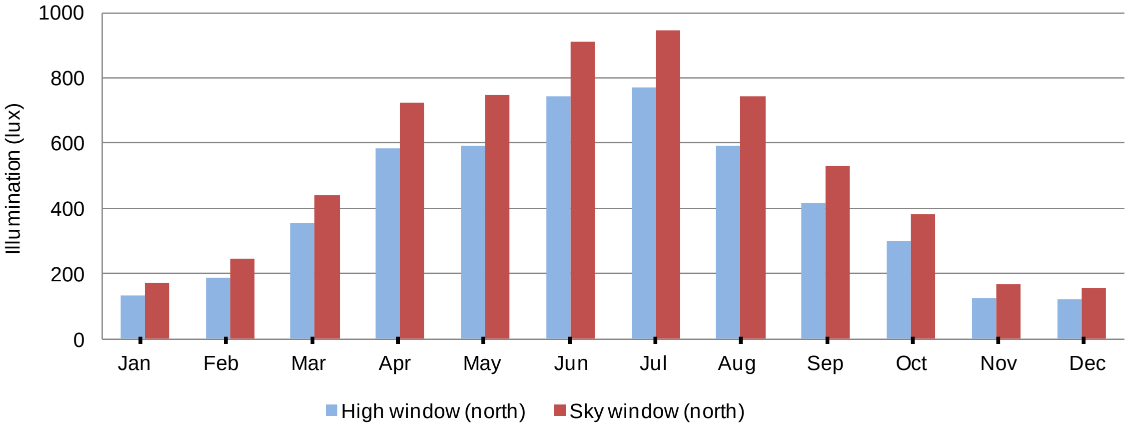


Figure 5.6: Comparison between sky and high window configurations for average monthly illumination at test point with upright sensor positions for north orinentation.

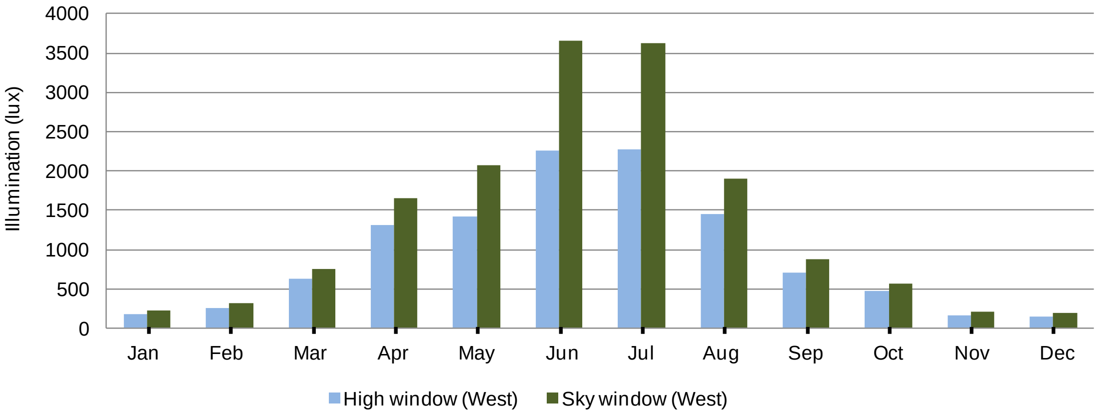


Figure 5.7: Comparison between sky and high window configurations for average monthly illumination at test point with upright sensor positions for west orinentation.

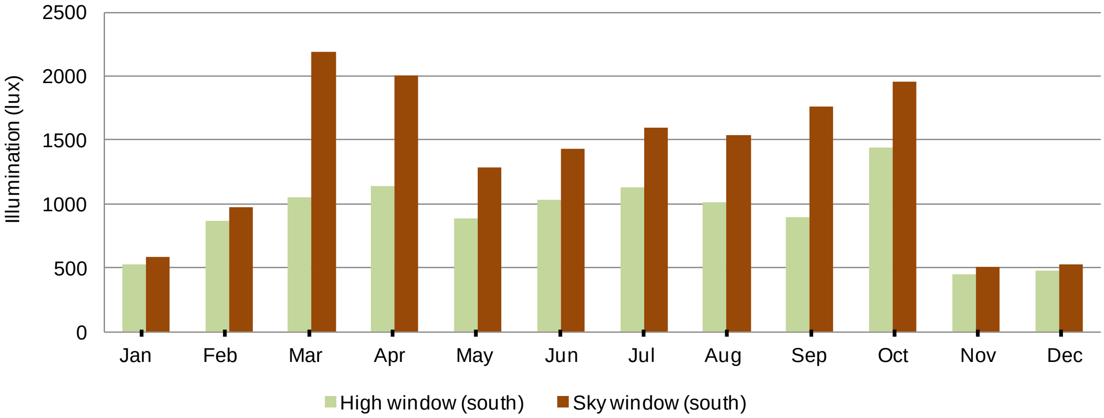


Figure 5.8: Comparison between sky and high window configurations for average monthly illumination at test point with upright sensor positions for south orinentation.

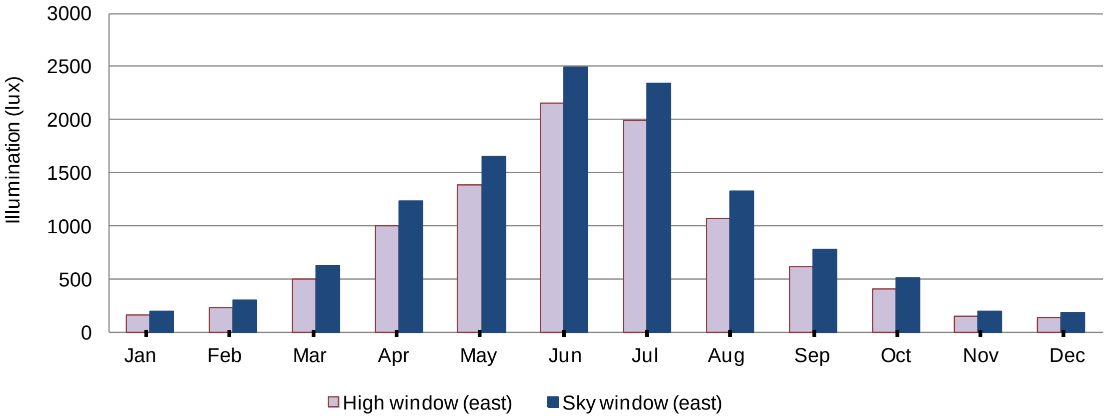
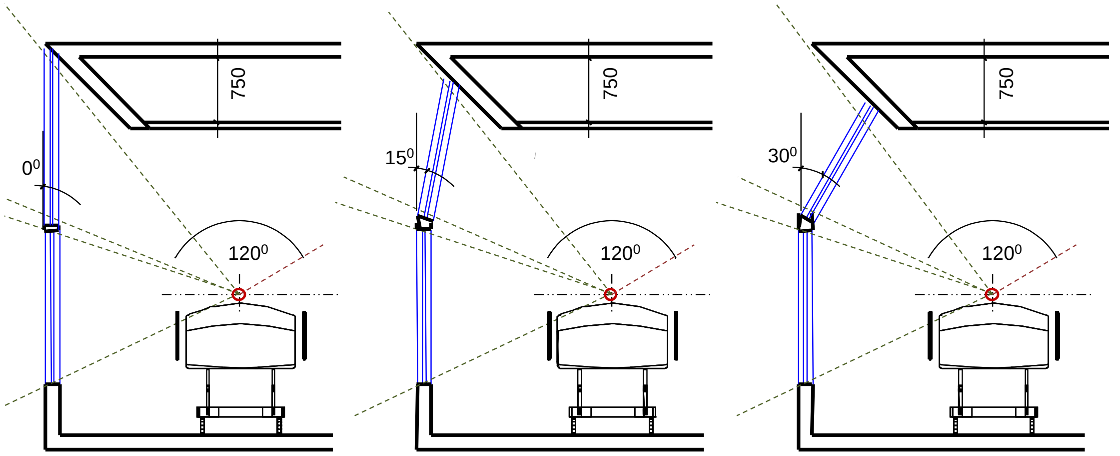


Figure 5.9: Comparison between sky and high window configurations for average monthly illumination at test point with upright sensor positions for east orinentation.

It needs to be mentioned that, the total configurations of sky window system with rebating false ceiling is the key factor to increase DA levels at test points. Keeping the rebating angle of false ceiling constant (i.e. 45^0), change of the angle of sky window with the line of viewing window surface, for e.g. 0^0, 15^0 and 30^0 (Figure 5.10), will create no difference to DA and UDI>2000 levels at test points. However, with the change of the angle of sky window the total glass area, as well as the window-to-floor ratio of the room, will be changed. The glass area will be the minimum when the rebating angle of false ceiling will be the same as the angle of sky window (e.g. 45^0). The glass area will be the maximum when the angle of sky window will be 0^0 (i.e. both viewing and sky windows are in same vertical surface). It is preferable to keep the window-to-floor ratio of the room a minimum, as higher window-to-floor ratio is associated with high heat gain/loss and extra UVR gain inside the rooms. In absence of false ceiling, it will be sensible to keep the angle of sky window 0^0 (i.e. high window) to avoid additional construction costs. It needs to clarify that, replacing 45^0 angled sky window configurations with any of the configurations shown in Figure 5.10 or similar, will not result any change to performance metrics (e.g. DA and UDI>2000) of the Figures shown earlier (e.g. Figures 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 and 5.9) and later (e.g. Figures 5.11, 5.19 and 5.20) parts of this chapter.



a) 0^0 angled sky window *b) 15^0 angled sky window* *c) 30^0 angled sky window*

Figure 5.10: Section shows three different angles of sky window configurations.

In terms of achieving the simulation goal fixed in Section 3.5.1(g), replacing the high window with sky window, the targeted DA (above 63%) was achieved for four orientations. Except south sky window configurations, the discomfort level (UDI>2000) is within the limit (less than 14%) for other three orientations. For the climate of

London, UDI>2000 increased in an order from north, east, west, and south progressively for studied cases (Figure 5.11). It seems that with the increase of DA the possibility of glare is also increasing. Considering the DA and UDI>2000 in test points, it appears that, south is the most critical orientation for achieving therapeutic effect of daylight without discomfort for sky window configurations and deserves special attentions while designing.

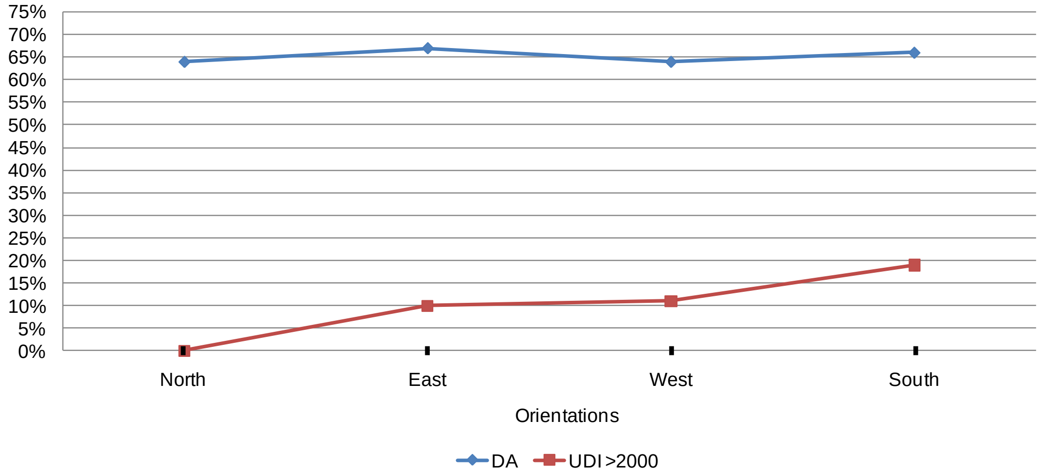
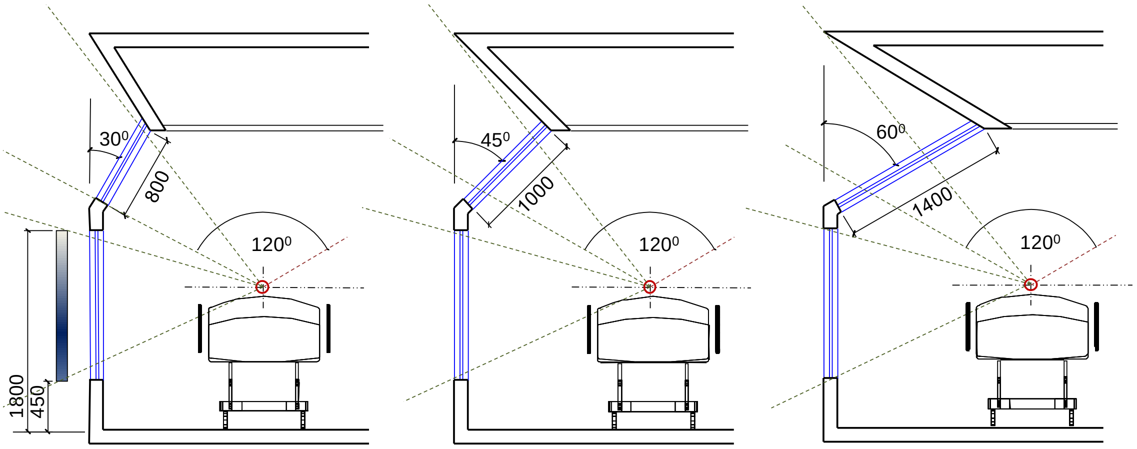


Figure 5.11 : The discomfort level (UDI>2000) is within the limit (less than 14%) for three orientations and exceeded for south sky windows (45^0 angled).

5.5. Angle of sky window and rebating false ceiling

When the angle of sky window and rebating false ceiling is the same, the glass areas of sky windows increase with the increase of the angle of sky window with the line of viewing window and thus increase window-to-floor ratios (Figure 5.12). However, for a wider angled (e.g., 60^0 angle) sky window, the acute service areas above ceiling also provide a greater shade on sky window, and minimise the benefit of increasing window-to-floor ratios. The angle of sky window should be minimised to ensure a higher DA effectively. In this exercise, angle of sky windows (and rebating false ceiling) were changed to observe the impact of changed angle of sky windows (and rebating false ceilings) on the daylight levels on test points. The popular three geometrical angles (30^0, 45^0 and 60^0) were examined for the proposed sky window configurations. The widths of sky windows were same (1800mm) for the three angles. The inclined height of sky window for 30^0 angle was 800mm, 45^0 angle was 1000mm and 60^0 angle was 1400mm. Figure 5.12 shows three different angles of sky windows with different window-to-floor ratios.



a) 30^0 angled sky window *b) 45^0 angled sky window* *c) 60^0 angled sky window*

Figure 5.12: Sections show three different angles of sky windows with different window-to-floor ratios.

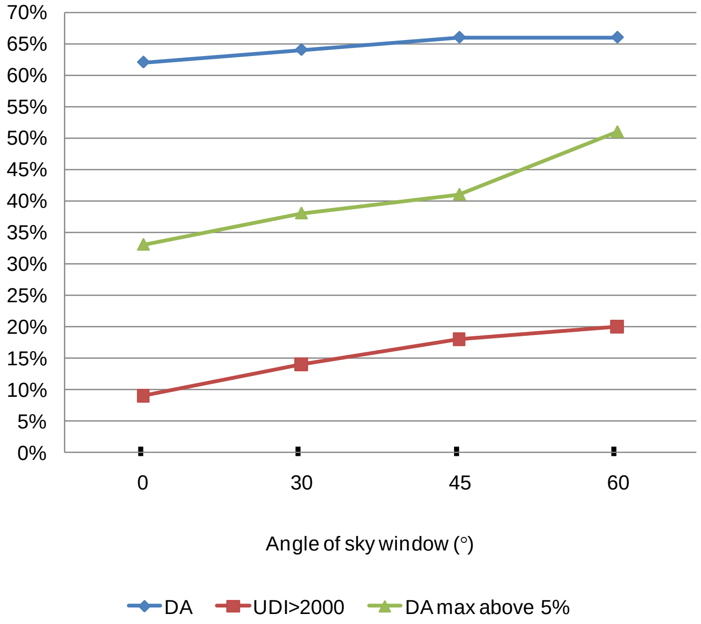


Figure 5.13: An increase of sky window angle from 45^0 to 60^0 cause much increase in DAmax above 5% among equally distributed illumination sensors with no increase in DA.

Figure 5.13 shows the DA, UDI>2000 and DAmax above 5% for south orientations (south is most critical in terms of daylight intensity and glare). Among three studied angles for sky windows DA is the minimum for 30^0 angled sky windows (64%) and the maximum for both 45^0 and 60^0 angled sky windows (66%) on the test points. Considering the UDI>2000 at test points, the maximum glare occurs for 60^0 angled sky windows (20%) and the minimum for 30^0 angled sky windows (15%). When glare possibilities were considered for equally distributed sensors on the test plane (DAmax above 5%) at a height of 1150mm above finished floor, it seems that the maximum glare occurs for 60^0 angled sky windows (52%) and the minimum for 30^0 angled sky windows (40%). A 15^0 increase of sky window angle from 30^0 to 45^0 causes 3% increase in DAmax above 5% among illumination sensors on the test plane with a 2% increase in DA. However, for next 15^0 increases of sky window angle from 45^0 to 60^0 causes 9% increases in DAmax above 5%, with no increase in DA level (Figure 5.13). Therefore, considering both the DA and overall glare potentiality, 45^0 angled sky windows performed better among three alternative studied options and recommended in this research for the angle of sky windows.

5.6. Distance from the window

Generally, daylight intensities are higher near the windows and decrease gradually with distance from the windows towards opposite/back walls. Figure 5.14 shows DA and UDI>2000 from outdoor to the back of the room for a 45^0 angled sky window configurations for south orientations. The sensors were placed at 500mm interval on a line perpendicular to the window plane and go through the test point. In previous exercises, a higher DA was achieved inside the in-patients' rooms at a point located at a distance of 2000mm from window (Figure 5.3). It is evident from Figure 5.14 that, a higher DA can be achieved in the same room by placing the bed nearer to the windows.

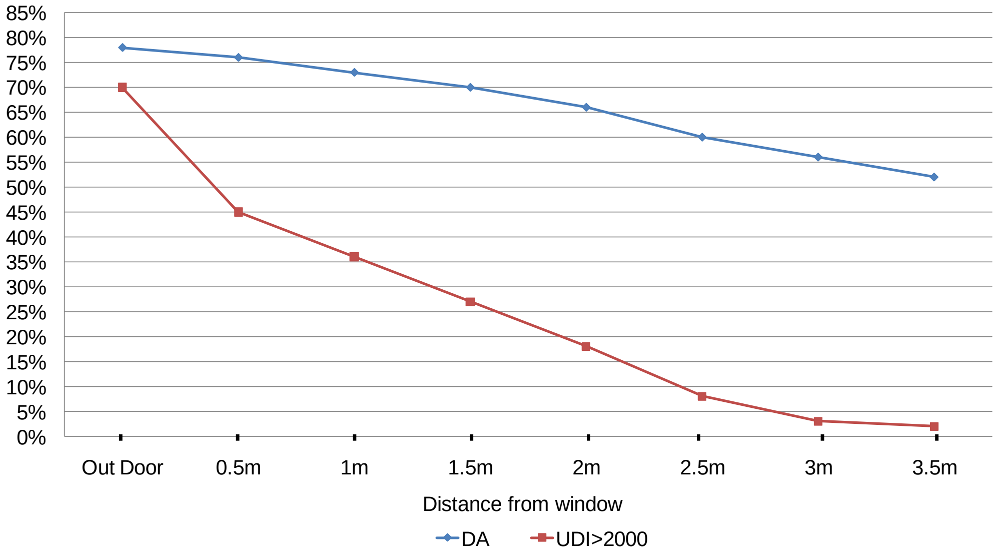


Figure 5.14: The DA and UDI>2000 are higher near the window and decrease with distance from window towards the back wall (45^0 angled sky window configurations for south orientation).

The common practice to place the beds inside in-patient rooms, from illustration of HBN 04-01 (2008) and ADB’s (2009) 3D diagrams, is at the middle of the room with equal distance from window and the back/corridor wall. In HBN 04 (1997), a detailed diagram for the location of a standard kings fund bed including extensions in a 3700mm x 3400mm space was provided (Figure 5.15). For clinical and support activities, a minimum clearance of 1200mm is recommended on both sides of the bed. The recommendation is for general core bed space applicable for both single and multi-bed wards. AIA (2006) suggests a more practical patient bed clearance, considering patient ergonomics in a 3964mm x 3658mm core bed space (Figure 5.16). A clearance of 1524mm (5 feet) diameter was recommended in one side of the bed for moving wheel chairs and 914mm (3 feet) clearance in other side for clinical and support activities. From daylighting potentiality, the recommendation of AIA (2006) is more suitable. AIA (2006) guidelines also satisfy the recommendation of DH (2005b) space requirement for single bed space with space for manoeuvring bed and transferring a patient to and from a second bed (Figure 5.17).

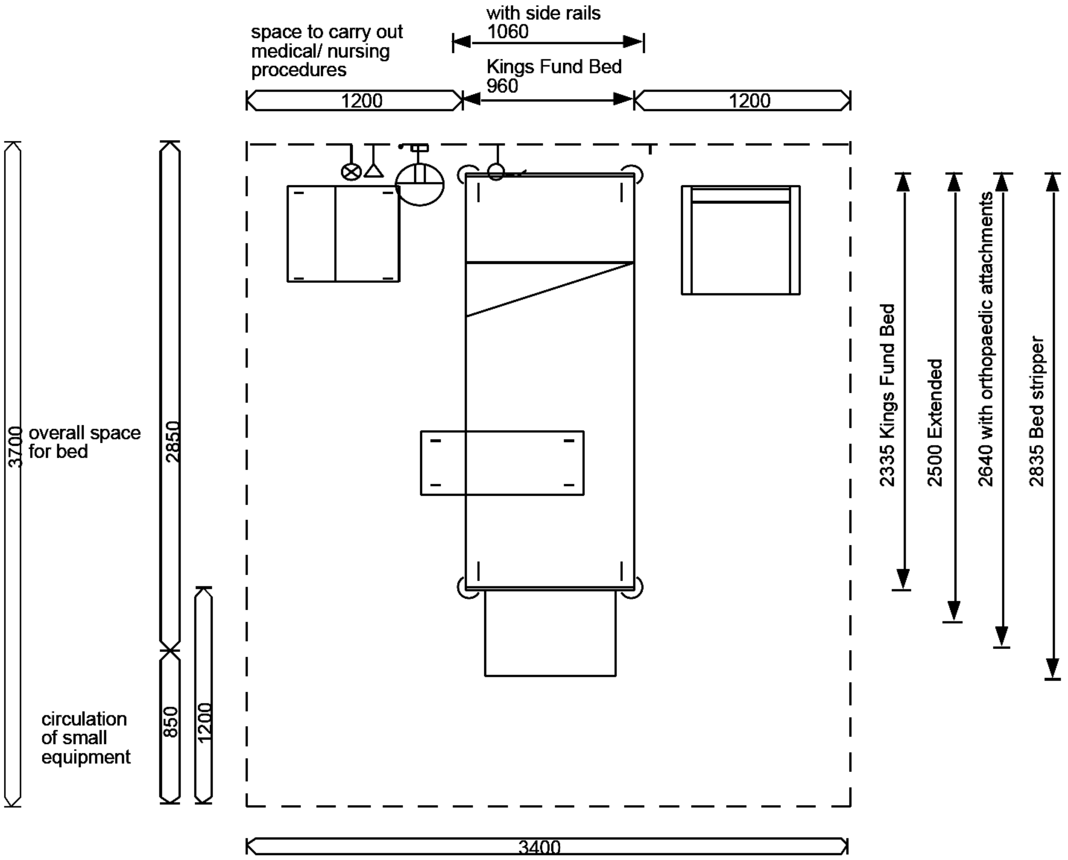


Figure 5.15: Core bed space (source: HBN 04, 1997).

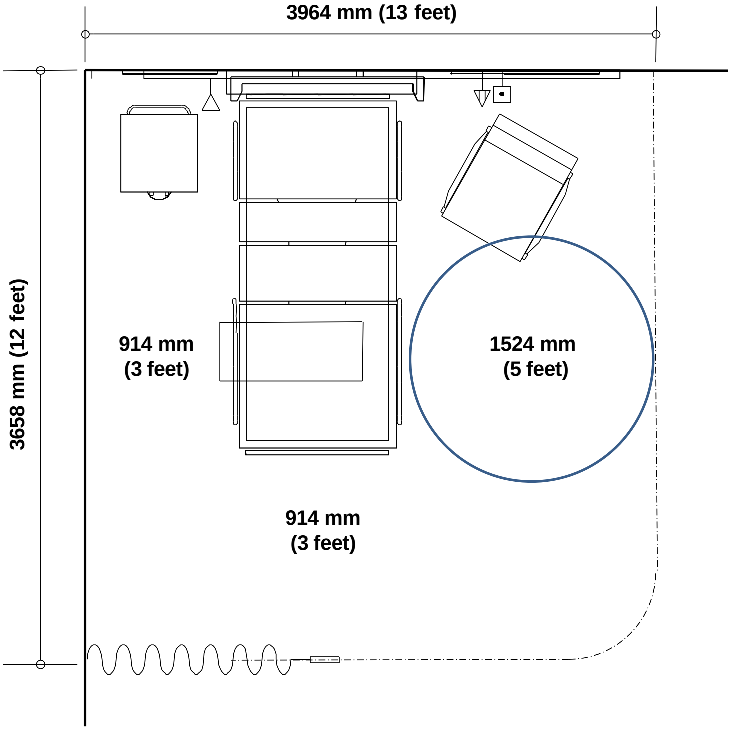


Figure 5.16: Patient bed clearance (after: AIA, 2006).

Satisfying the requirements of AIA (2006) guideline and DH (2005b), the bed in the case in-patient room can be shifted 500mm towards the window to achieve a higher DA (Figure 5.18(b)). This will also enable patients to have a better outside view. Figure 5.19 shows the comparison of DA between the previous location of the bed (1500mm from window) and new location (1000mm from window) for five configurations of windows studied earlier. In five studied cases, a higher DA was achieved for new location (Figure 5.18(b)).

Figure 5.20 shows dynamic daylight metrics (DA, UDI>2000 and DAmax aove 5%) for 45^0 angled sky window configurations, when the bed is placed at 1000mm distance from window and the test point is at a distance of 1500mm from window. For four orientations a higher DA was achieved for new location which satisfy the DA goal (minimum 63%) but at the same time additional glare was developed for east, west and south orientations that exceeds the target level of UDI>2000 (maximum 14%). As a result, shading devices were required to reduce UDI>2000 to 14% for east, west and south orientations. In the next section, shading devices have been developed for sky window configurations to keep the UDI>2000 level below to 14%.

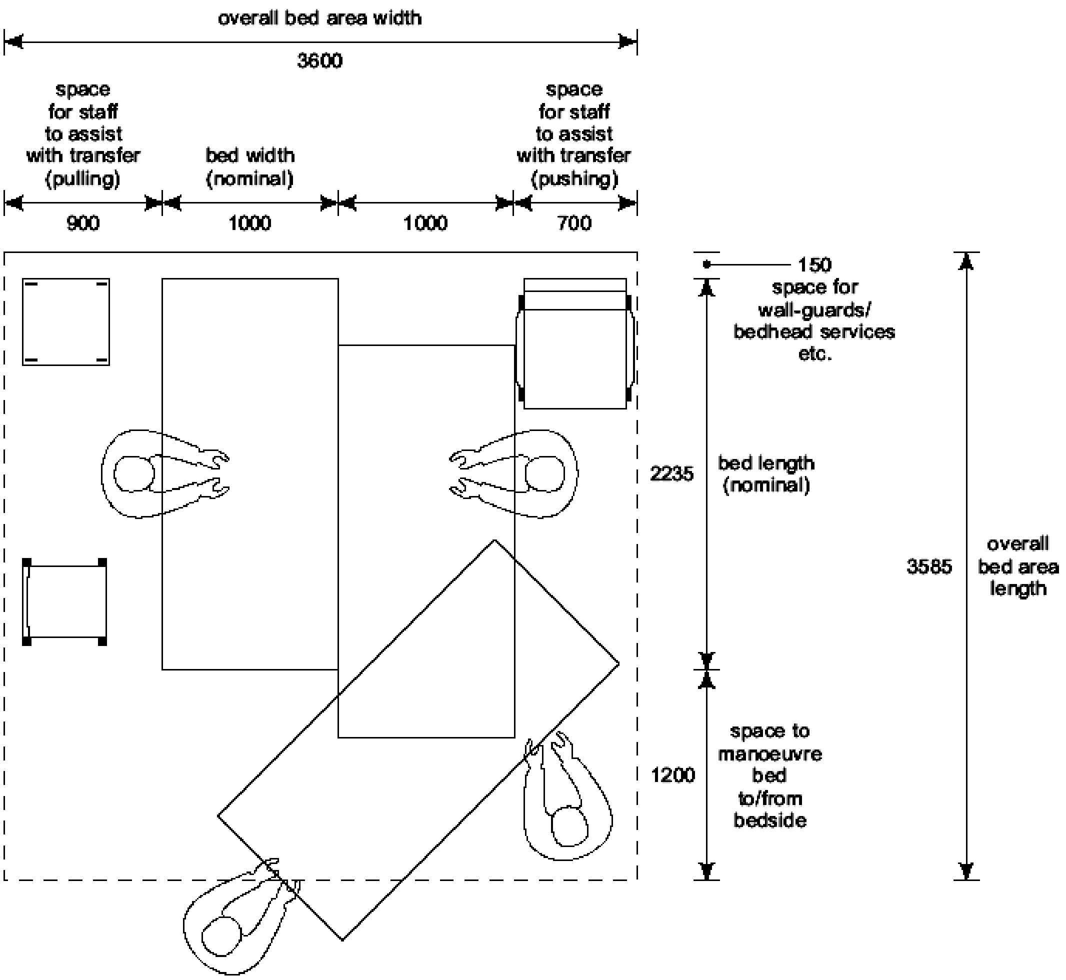
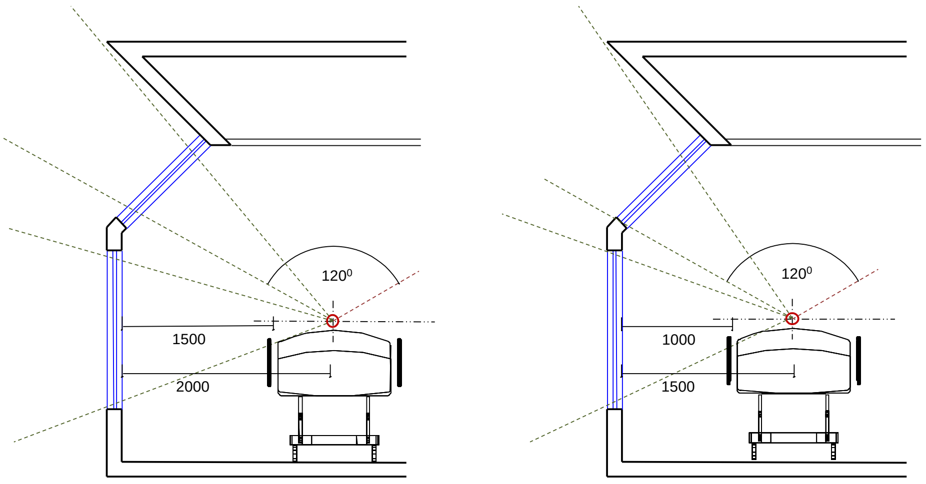


Figure 5.17: Core bed area with space for manoeuvring a bed and transfering a patient to and from a second bed(source: DH,2005b).



a)2000mm from window *b) 1500mm from window*

Figure 5.18: Sections show two alternative distance of patient bed from window.

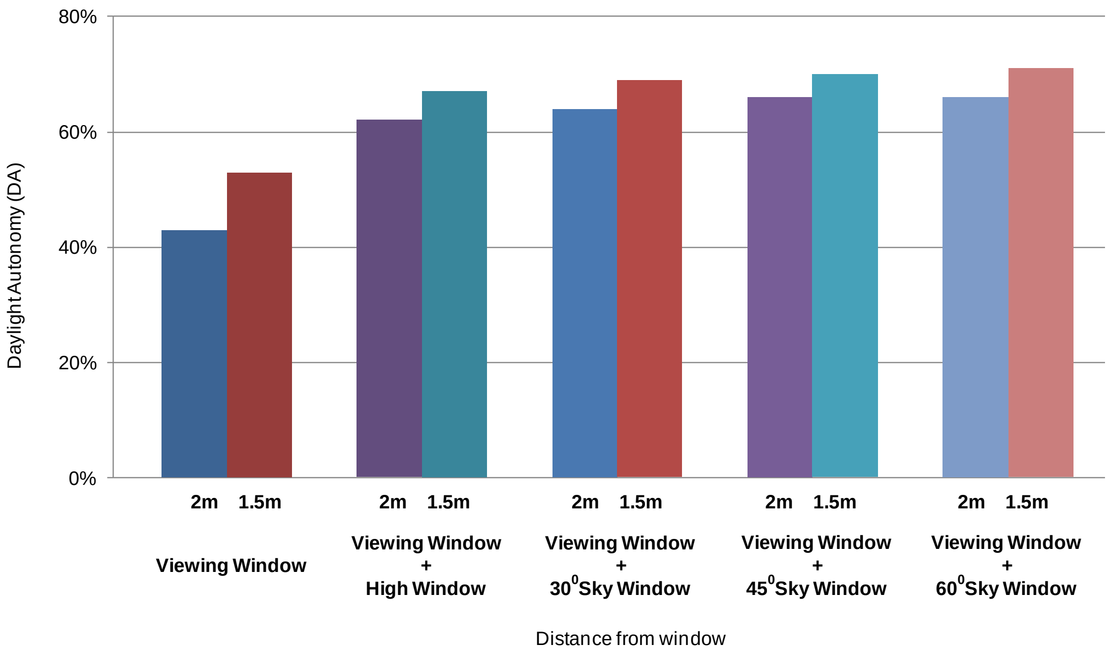


Figure 5.19: A higher DA is achieved at test point at 1.5m from window compared to a distance at 2.0m for studied window configurations.

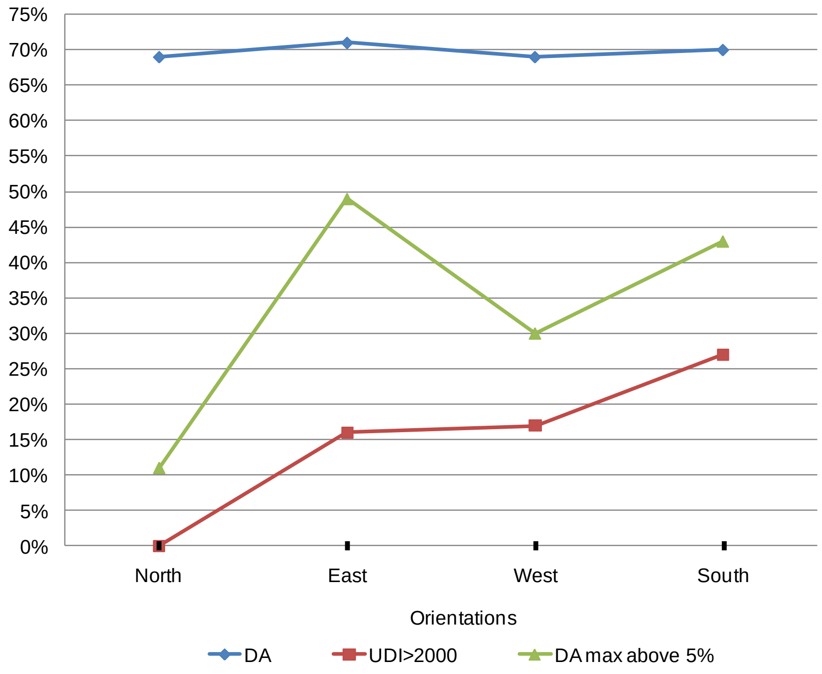


Figure 5.20: UDI>2000 is nearer to the target level (14%) for east (16%) and west (17%) orientations, however, much higher (27%) for south orientation (45^0 angled sky window configurations).

5.7. Shading devices for sky window configurations

Shading devices reduce glare, and control unwanted solar heat gain from direct sunlight. For the climate of London, UDI>2000 increases in an order of north, east, west, and south progressively for 45^0 angled sky window configurations (Figure 5.11). For north orientations, a higher DA was achieved (DA increased to 69% from 49%) without increasing the UDI>2000 level (both 0%) when the sky window was placed above the viewing window, therefore, no extra shade is required for north windows. UDI>2000 is nearer to the target level (14%) for east (16%) and west (17%) orientations. For south orientations the UDI>2000 is much higher (27%). To reduce the glare to the target level, the maximum shading is required for south windows and the minimum for east windows.

The shading requirements of a building mostly varied for different orientations, and it is difficult to satisfy the comfort levels with sufficient daylight for different orientations with a particular design of fixed shading device (e.g. sunshade with constant depth) for the entire building. Shadings should vary with orientations, and different configurations of shading devices should be tested during daylighting simulation analysis before finalising an architectural shading system. Nevertheless, the difficulties of incorporation of simulation analysis in architectural design process are experienced at the starting point and each step of design development process when thousands (even millions) of options are available which might alternatively be considered to lead to the next stage/phase of the design. For instance, if four (or more) types of shades (e.g. sunshade, overhang, light shelf and internal blind) are tested for four orientations (north, east, west, and south) and have four (or more) states (e.g. differ in angle, shape, size and material), the total number of simulation run will be $>(4^4)^4$, or >4,294,967,296 experiments. It is not possible to test each option simultaneously against all combinations of every other option due to the limitations of time and parametric simulation technologies. Therefore, it is difficult to advance and finalise architectural design decisions entirely based on simulation study. Moreover, decisions entirely based on simulation analysis might recommend totally different design of the window shades for different orientations. To maintain uniformity and develop an architectural grammar, in this PhD research, some principle of design was fixed at the beginning and, while progressing, simulation guided decisions were combined with some other practical factors such as solar control criteria, line of vision and aesthetics to meet the design goals. In the next exercises, trials will be made to increase the level of shading gradually from east to west and finally for south windows. The following principle of design was followed to develop shading by parametric simulation study in this research.

- To facilitate modular construction and maintain architectural uniformity, the design of a particular type of shading device (such as sunshade) will be kept constant for different orientations for the entire building and separate shades (such as overhangs/light shelves) will be added in different levels of windows where more shades will be required, than to change the design and depth of the same shading devices in different orientations.

- For standardised recommendations, a multiple of 25mm (approximately 1 inch) will be followed for examined depths of shading devices for easy perception and implementation in both feet and meter scales.

- The designs of the shading devices will be developed to keep the DA at the minimum 62.5% (80% of outdoor DA) with a maximum UDI>2000 of 14% (20% of outdoor UDI>2000), with the help of simple passive shading devices (external sunshades, overhangs, internal light shelves, and venetian blinds) for different orientations.

5.7.1. Sunshade

External sunshades generally block direct sunlight to enter into the interior space, and reduce glare and overheating due to direct sun light. As the sun changes its path at different times of the year, it is complicated to optimise the design of sunshade for the whole year. The requirement for shading varies with the change of seasons for same orientation. During summer when the days are hot, sunshades are very useful, but during winter when the days are too cold, the presences of sunshades are disadvantageous in terms of daylight and solar heat gain. In this exercise, an optimised depth of sunshade will be tried to install to shade the viewing windows during summer time and impact on DA and UDI>2000 will be observed on test point for different orientations.

In this section, a rectangular sunshade was generated for the rectangular viewing window (1350mm x 1800mm) optimised for the summer time in London by using ECOTECT. The rectangular device will completely shade the viewing window from the 1 June to the 31 August, from 6:00 AM to 6:00 PM. ECOTECT uses a series of solar profiles described by the path of the sun through the sky to generate the exact shape of the sunshade required to shade the rectangular window for a given range of cut-off dates and times (Figure 5.21). A sunshade with a minimum 820.3mm depth was recommended by the analysis of ECOTECT for south orientation, 4504mm for east orientation and 4731mm for west orientation.

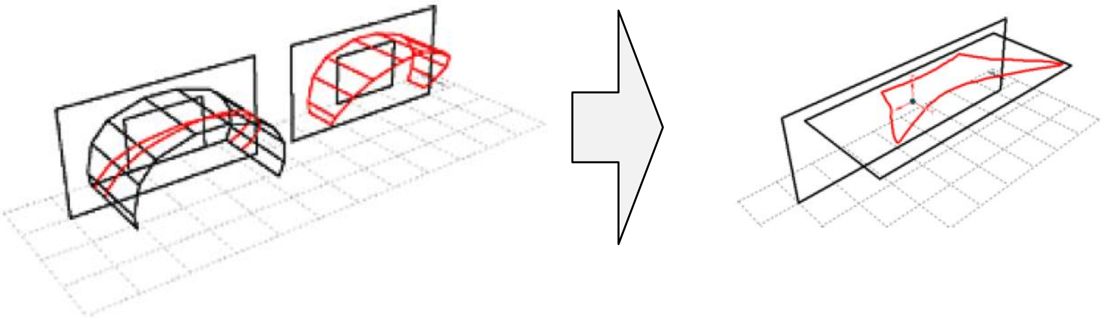
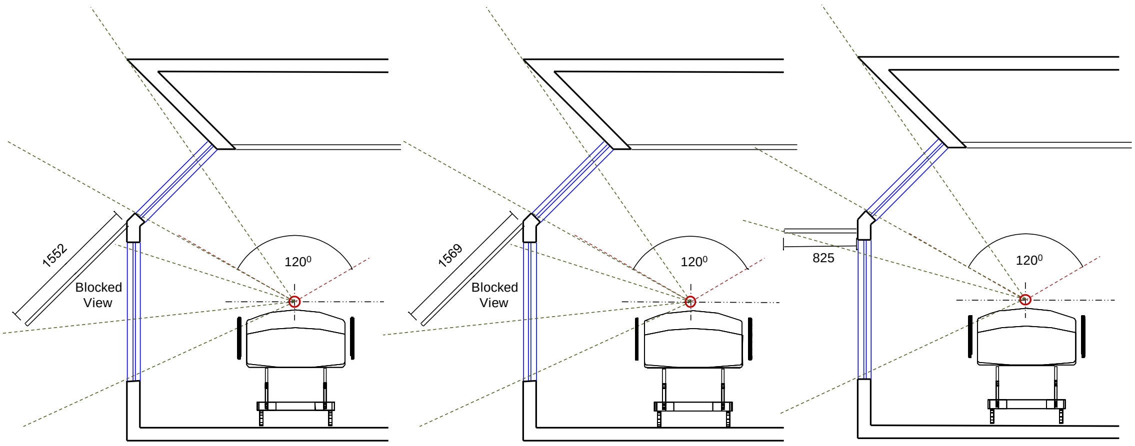


Figure 5.21: Concept of generating optimised rectangular sunshade by using cutting solar profiles (source:ECOTECT, 2010).

In fact, horizontal shading devices are not effective in east and west orientations. Search for a 45^0 angled sunshade for east and west orientations reduced the depth of sunshade to 1552mm for east and 1569mm for west orientations. A 1552/1569mm deep 45^0 angled sunshade will almost block the outside views (Figure 5.22(a) and Figure 5.22(b)). Vertical sunshade is most effective for east and west orientations to block direct sun, but permanent vertical shades will completely block the outside views of patients. It is unrealistic to provide a 45^0 angled sunshade of 1552/1569mm which will block the outer views and daylight; and a 4504/4731mm horizontal shade, which is deeper than the width of the room. Due to the changing position of the sun during daytimes, shades are required only in east during the mornings and west in the evenings. A movable internal blind is a better solution, which can be dropped in early mornings in east orientations and late afternoons in west orientations (the impact of blind control have been analysed in section 5.7.6).

As the glare problem is not so high for east and west orientations compared to south, this simulation exercise started with 825mm deep sunshades for three orientations (east, west, and south) that will completely shade the south viewing windows and partially shade east and west windows during summer. As the north facade of the building does not receive direct sunlight, no fixed shading is required for north windows. Figure 5.22c shows the studied depth of window shades (825mm) for south orientations. The material of sunshade was same as the material of the wall.



a) East *b) West* *c) South*

Figure 5.22: Sections show the depth of rectangular sunshade for different orientations optimised for viewing window for the summer time in London.

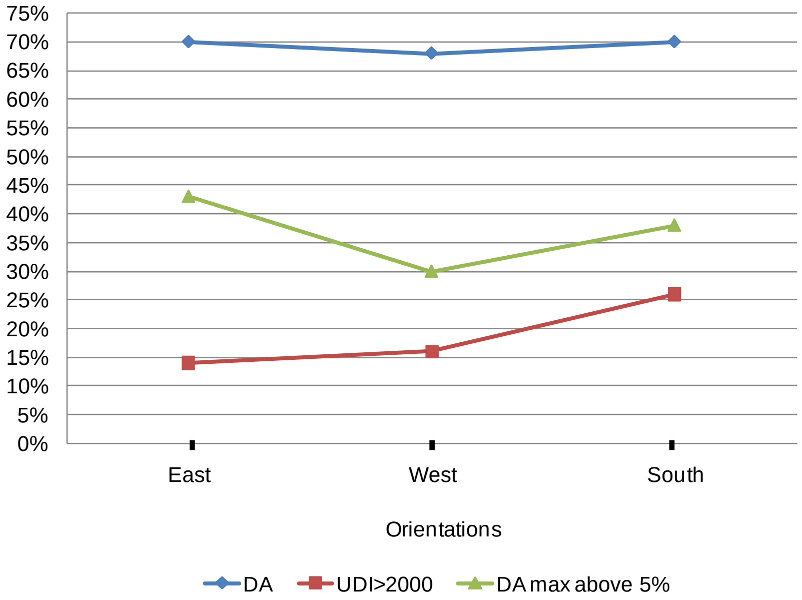
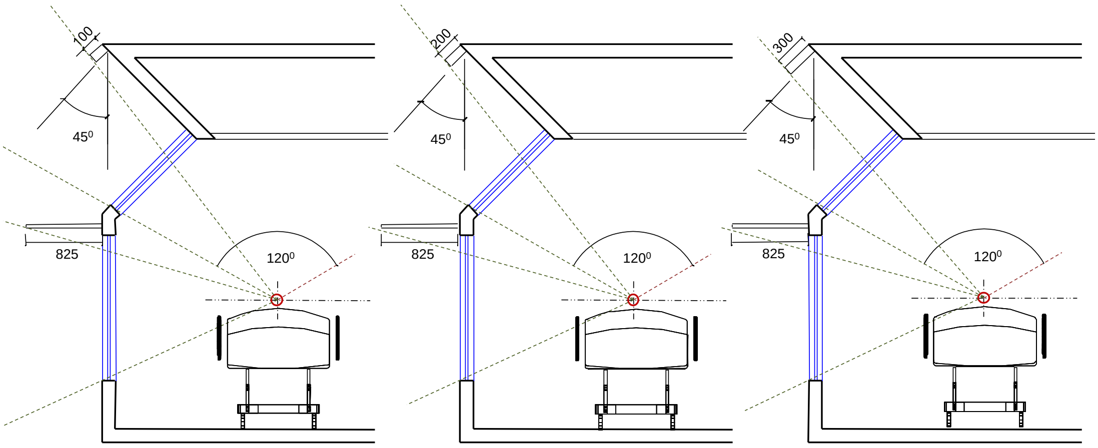


Figure 5.23: Impact of 825mm external sunshade in reducing the DA and UDI>2000 levels for different orientations.

Figure 5.23 compares the results of the analysis of the 825mm deep external sunshades for east, west and south orientations. The impact of external sunshades in reducing DA and UDI>2000 were the maximum for east orientation and the minimum for west orientation, among three alternative orientations studied. 825mm external sunshades were capable to reduce the UDI>2000 to the target level (14%) for east orientation, however, for west and south orientations additional shading were required. In the next exercise extra shades were added to west and south orientations to reduce the UDI>2000 level to 14%.

5.7.2. Overhang

An overhang is a secondary shading usually attached to the edge of the roof slab that is projected from exterior walls of the buildings. In commercial buildings, overhangs are generally used to provide shades, break steep winds, and protect rains or snows. In this exercise, a small angled overhang was developed at the edge of the roof slab above the void space for partial shading of sky window to reduce UDI>2000 at test point for west orientations at the beginning, and the performance of the shading on south orientations was observed. The shading device was placed parallel to the sky window surface (45^0 with building facade). Three alternative depths of overhangs (100mm, 200mm, and 300mm) were fixed for the west orientations in combination of 825mm external sunshades based on a primary analysis on the depth of overhangs (Appendix D). Figure 5.24 shows the locations of three alternative depths of overhangs. The material of overhang was same as the material of the wall (brick with plaster on either side with 50% diffuse reflection).



a) 100mm overhang *b) 200mm overhang* *c) 300mm overhang*

Figure 5.24: Sections show three alternative depths of overhang for west orientations.

Figure 5.25 shows that with the increase of the projection of the overhang, both the DA and UDI>2000 reduces for west orientations. For the first 300mm depth both DA and UDI>2000 reduces 1% per 100mm increase of the depth of overhangs. Overhangs with 200mm depth satisfy the requirement of UDI>2000 (14%) for west orientations. A 200mm deep overhang reduces 2% DA (from 70 to 68) and 3% UDI>2000 (from 26% to 23%) for south orientation. To reduce the glare level to the target level (14%), it was necessary to reduce the UDI>2000 level another 9% for south orientations, and further shades were required for south orientations. In the next exercise additional shades were added to south orientations only, to reduce the UDI>2000 levels to 14%.

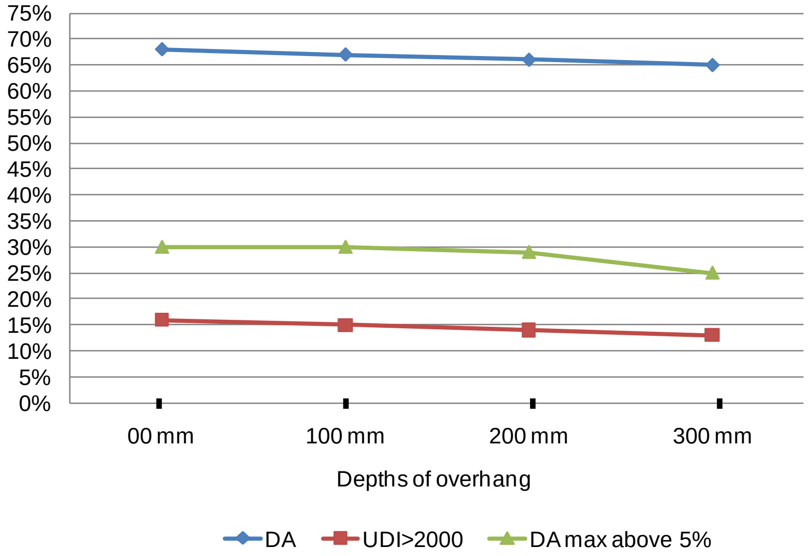


Figure 5.25: Increase of the projection of the overhang decreases both the DA and UDI>2000 for west orientations.

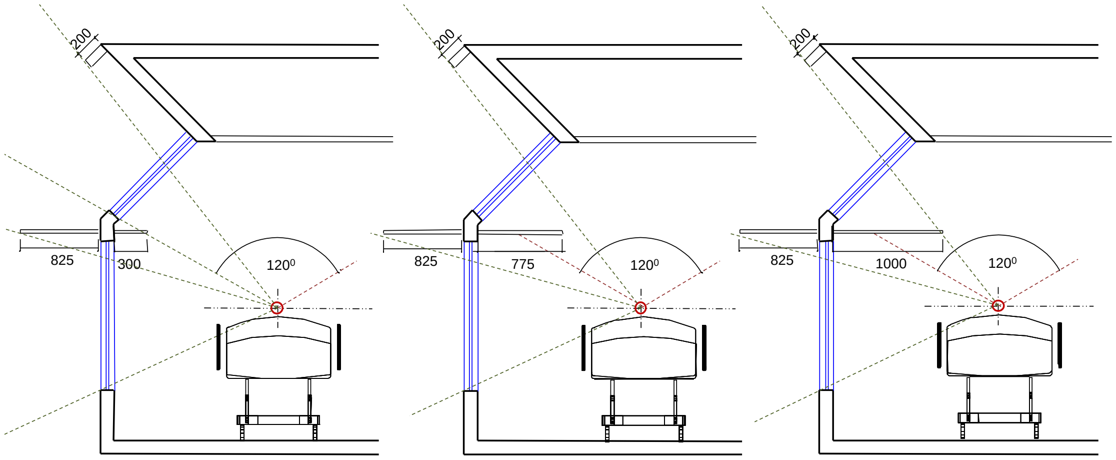
5.7.3. Internal light shelf

Light shelves are typically placed just above the eye levels to reflect daylight into the interior ceilings and to use the ceilings as a light-reflector for deeper parts of the rooms. However, light shelves are not efficient in terms of raising daylight levels under overcast sky conditions (Eagan et al., 2002; Littlefair, 1996; Christoffersen, 1995; Aizlewood, 1993), but can be used to reduce glare and can ensure a better and uniform distribution of light throughout the interior space (Joarder, 2007). As the sky conditions of London is majorly governed by overcast sky, introduction of light shelf at any height will result a decrease in daylight intensity. Thus, light shelves can be used to reduce glare and enhance the quality of daylight in a space located at London.

In a simulation study under overcast sky condition, it was found that light shelves at a height of 2m above floor level within a 3m high ceiling, performed better to enhance the quality of daylight in the interior spaces compared to other studied alternative locations, including the alternative where no light shelves were present (Joarder, 2007). The light shelves were located at a two-third (2/3) height of the room height. For present case of in-patient room, the height of the ceiling is 2700mm. Therefore, the locations of light shelves were fixed at two-third of the heights of the rooms which is 1800mm from finished floor levels and just above the viewing windows. In this exercise, the impact of the changes of the depths of internal light shelves on DA and UDI>2000 were observed at test points for south orientations.

The ranges of depths of the internal light shelves for this analysis was fixed by considering the viewing angle of the patients, when lying with their spine on bed in the case room at a distance of 1500mm from the window. The minimum depth was fixed to 300mm (Figure 5.26(a)), so that the light shelf itself is out of the visual field of the patients, when lying with their spine on the beds and looking straight towards the ceilings (adult visual field extends to approximately 60^0 toward the nose for each eye). The maximum depth of the light shelf was fixed as1000mm (Figure 5.26c), so that while patients lying with their spine on the beds, the light shelf will completely restrict the view of sky through sky windows, as a result no direct daylight will hit the test point through sky windows. A number of alternative depths of internal light shelves were studied to observe the impact on DA and UDI>2000 between 300mm to 1000mm (Appendix D). Finally, a light shelf with 775mm depth satisfied both the requirements of DA and UDI>2000 levels. The material of light shelf was the same as the material of the wall. Figure 5.26 shows three critical alternative depths of internal light shelves.

Figure 5.27 shows that with the increase of the depth of light shelves, both the DA and UDI>2000 were reduced. A light shelf below 300mm have little impact on decreasing DA and UDI>2000 at test point. For a 775mm light shelf, DA reduced 5% and UDI>2000 reduced 9%. To provide a more detailed observation on the impact of the depths of the light shelves on illumination levels at test points, highest illuminations on an axis through the test point (XX' axis in Figure 3.23) were compared for the brightest sunny day (28 June at 10:30 AM) and most overcast day (13 November at 11:30 AM) for the typical sky condition of London.



a) 300mm light shelf *b) 775mm light shelf* *c) 1000mm light shelf*

Figure 5.26: Sections show three alternative depths of internal light shelves for south orientations.

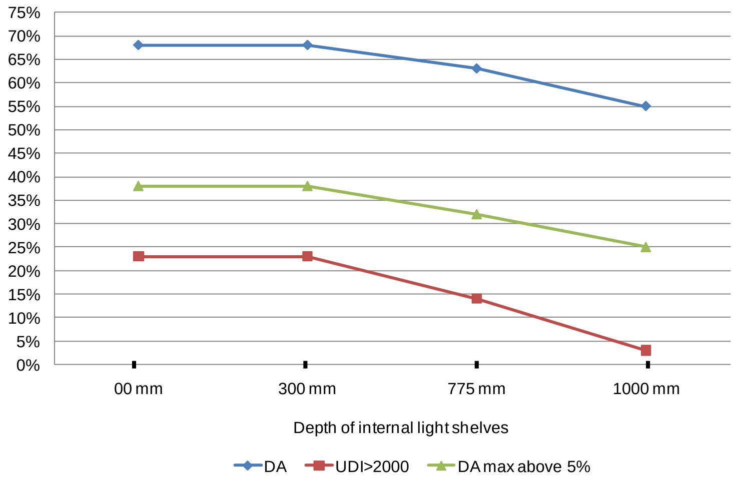


Figure 5.27: Increase of the depth of light shelf decreases both the DA and UDI>2000 respectively for south orientations.

Figure 5.28 shows daylight illumination in lx from window to the back of the room for three depths of light shelves for the brightest sunny day, including the option without any light shelf for south orientations. The sensors were placed at 500mm interval on a line perpendicular to the window plane and go through the test point. In the brightest time, for the studied depths of light shelves, the illuminations were much higher than the benchmark (190 lx) at 1500mm distance from the window. It was apparent that without light shelf, the daylight level near window is as high as 39,764 lx while the target was to achieve 190-2000 lx only at 1500mm distance from windows. This high illumination near window could create excessive glare, heating and discomfort inside the rooms. Introduction of light shelves reduced illumination on individual points near windows for presented three depths of light shelves. Light shelves with a depth below 300mm had little impact on decreasing the light level after 1000mm distance from windows. The high illumination levels were significantly reduced near windows and further reduced towards the test points for other two depths of light shelves: 775mm and 1000mm. For 775mm light shelf, the illumination at 1500mm (test point) was higher than the illumination at 1000mm distance from window, although 1000mm is nearer to the window.

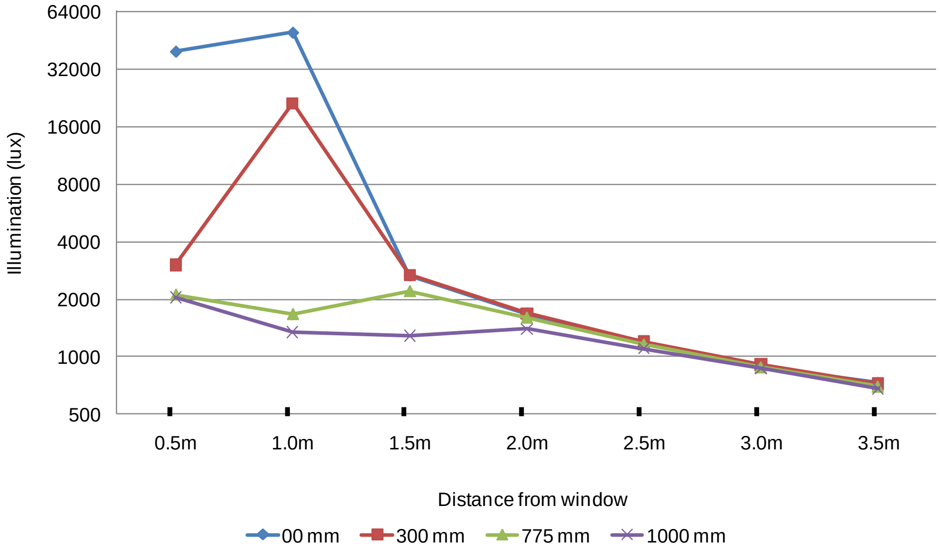


Figure 5.28: Comparisons of highest illuminations on an axis through the test point for the brightest sunny day (28 June at 10:30 AM) for three alternative depths of internal light shelves with the case of without light shelf.

For overcast sky conditions, none of the options were able to achieve the benchmarks (190-2000 lx) at a distance of 1500mm from windows (Figure 5.29). In the absence of any light shelf, daylight level decreases gradually from window towards the test point. For 300mm light shelf there is a sudden raise of daylight level observed at a distance of 1000mm from window, for 775mm light shelf at 1500mm (test point) and for 1000mm light shelf at 2000mm from windows. Therefore, decreases of the depths of the light shelves increased daylight levels near windows during overcast sky conditions.

It was evident from overall analysis of the changes of the depths of the internal light shelves for the climate of London that light shelves reduced the direct illumination at test points more than the increase by reflection; however, there were significant usefulness of light shelves to reduce excessive illuminations (UDI>2000) near windows, which normally were much higher than target levels (190- 2000 lx), and the illuminations at deeper parts of the rooms. Therefore, light-shelves can be used to ensure a more balanced luminous environment, with less contrast, discomfort and glare for south orientations. Considering both the collective performance of the whole year and single performance on brightest and overcast days of the light shelves, it was evident that a light shelf with a depth of 775mm performed better among the studied alternatives and satisfied the target levels of DA and UDI>2000 for south orientations. In this research, a 775mm deep light shelves were recommended for south windows.

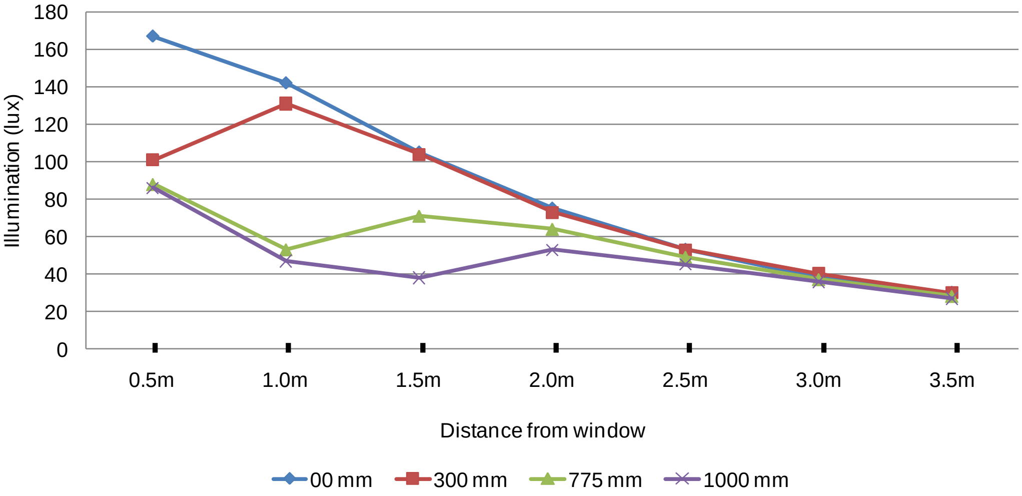


Figure 5.29: Comparisons of highest illuminations on an axis through the test point for the most overcast day (13 November at 11:30 AM) for three alternative depth of internal light shelves with the case of without light shelf.

5.7.4. Surface of internal light shelf

In the previous exercise, it was found that introduction of light shelves reduced the daylight illumination at test point for London climate. To observe the possibility to increase the illumination levels uniformly, highly reflective stainless steel metal sheets (with 90% specular reflectance) were added on the top of three alternative depths of light shelves studied in Section 5.7.3 (300mm, 775mm and 1000mm). From Figure 5.30, it is evident that introduction of highly reflective materials had no impact on increasing the annual DA at the test point for 775mm deep light shelf, and 2% increase in 300mm and 1000mm deep light shelves. To provide a more detailed observation on the impact of the material of the light shelves on test points, highest illuminations on an axis through the test point were compared for the brightest sunny day and most overcast day for the typical sky condition of London.

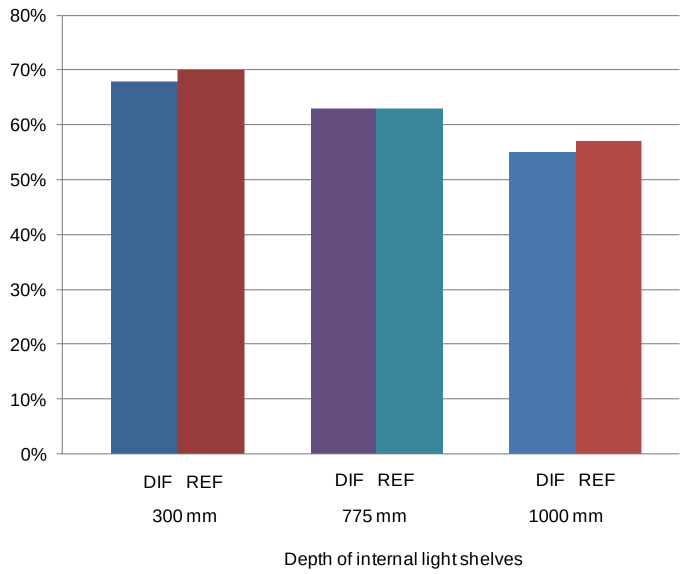


Figure 5.30: Introduction of highly reflective material has no impact on increasing the annual DA at test point for 775mm deep light shelf.

Figure 5.31 and 5.32 compare daylight illumination from window to the back of the rooms for 775mm deep light shelves with diffuse and reflective surfaces for south orientations for the brightest sunny day and the most overcast day. Though the high reflective light shelf have no impact on raising annual DA for 775mm internal light shelf, but when focussed on the illuminations on individual points near windows, daylight levels raised for the studied points. As diffused plaster boards were used for suspended ceilings of the rooms and the overcast sky is dominant in London climate, reflected light from the top of light shelves became diffused after incident on the ceiling and had little contributions on DA to the test point located on the test plane. A specular reflective ceiling could be advantageous for an office space, where the eyes are mostly directed to test plane, but for in-patient rooms a specular ceiling might create more discomfort, as the direction of the eyes of the patients are mostly upward. Though the reflectance of light shelves has impact on raising the illuminations on individual points near windows, when considered annually, little or no change was observed in DA. In this research, light shelves of the same material of the wall are suggested for London climate.

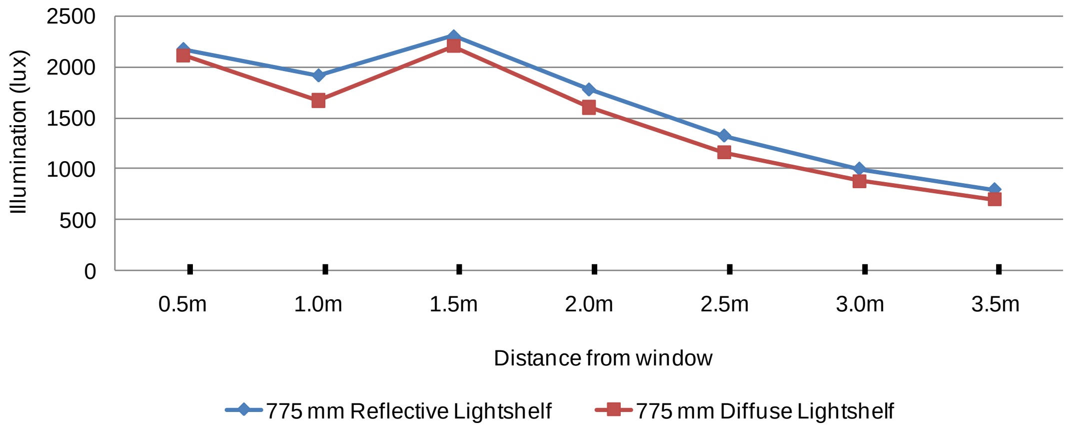


Figure 5.31: Comparisons of highest illuminations on an axis through the test point for the brightest sunny day (28 June at 10:30 AM) for 775mm deep light shelf with and without reflective surfaces.

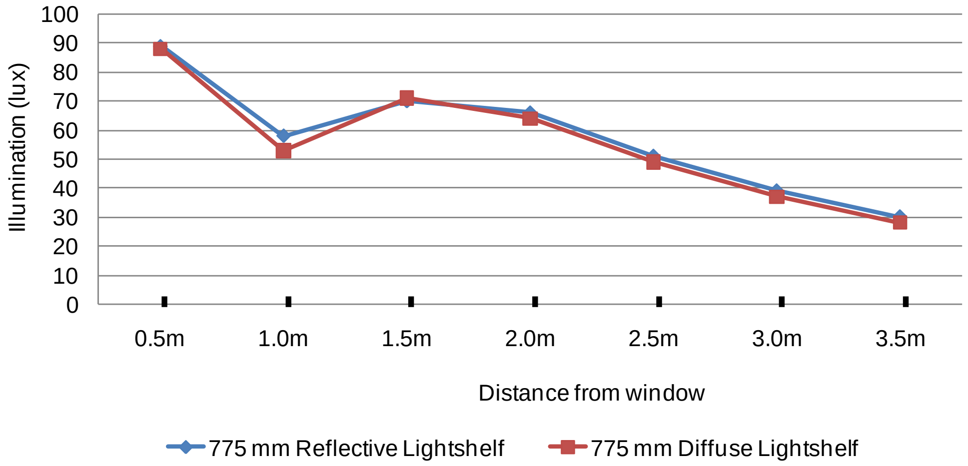


Figure 5.32: Comparisons of highest illuminations on an axis through the test point for the most overcast day (13 November at 11:30 AM) for 775mm deep light shelf with and without reflective surfaces.

5.7.5. Material of sky window

Instead of internal light shelves, tinted glasses can be used for sky windows to reduce glare on the test points. Tinted glasses with 30%, 50%, 70%, and 90% normal visible transmittance were studied for sky windows, in this exercise.

Figure 5.33 shows the daylight performance metrics for sky windows with tinted glass with alternative transmittance value for south orientations. It is evident from the analysis that increasing the transmittance value of the glass, results increase of both the DA and the UDI>2000. A glass with 50% transmission value meet both the requirements of the DA (63%) and UDI>2000 level (13%) for south orientations. So, a sky window with clear glass and 775mm light shelf can be replaced by a tinted glazed sky window with 50% transmittance value to achieve similar DA and UDI>2000 levels. To find out the differences between these two options, highest illuminations on an axis through the test point were compared for the brightest sunny day and most overcast day for the typical sky condition of London.

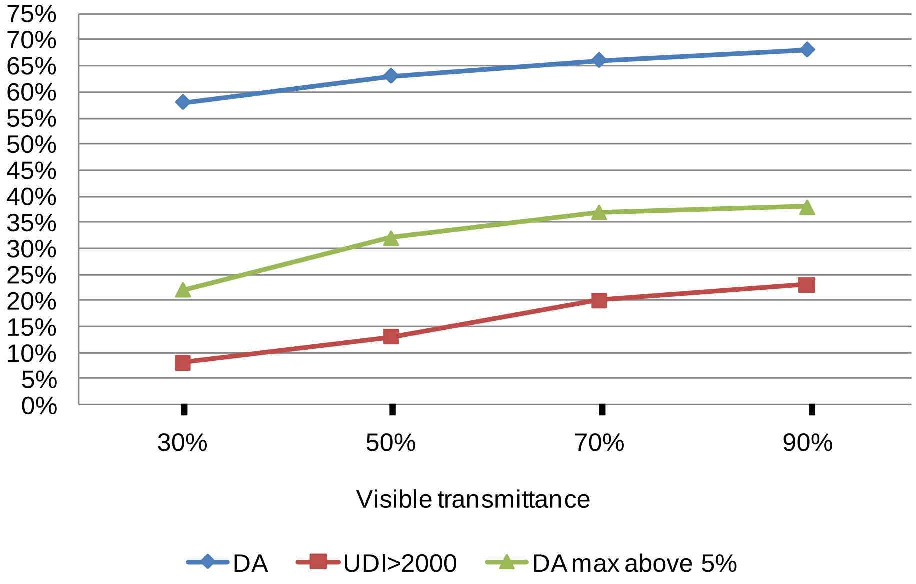


Figure 5.33: Increase of the visible transmittance of sky window glasses increases both the DA and UDI>2000 respectively.

Figure 5.34 and 5.35 shows daylight illuminations in lx from windows to the back of the rooms when the sensors were placed at 500mm interval on a line perpendicular to the window plane and go through the test points. Though the DA, UDI>2000, and illumination level at test point (1500mm from window) in sunny and overcast days are similar for two options, tinted option had a higher illumination near windows and drops gradually towards back. Light shelf had dramatic contribution to reduce higher illuminations near windows and raised illumination level at back of the rooms. Therefore, considering the individual and annual illumination of the rooms, a sky window with clear glass and light shelf was preferred compared to 50% visible transmittance glasses.

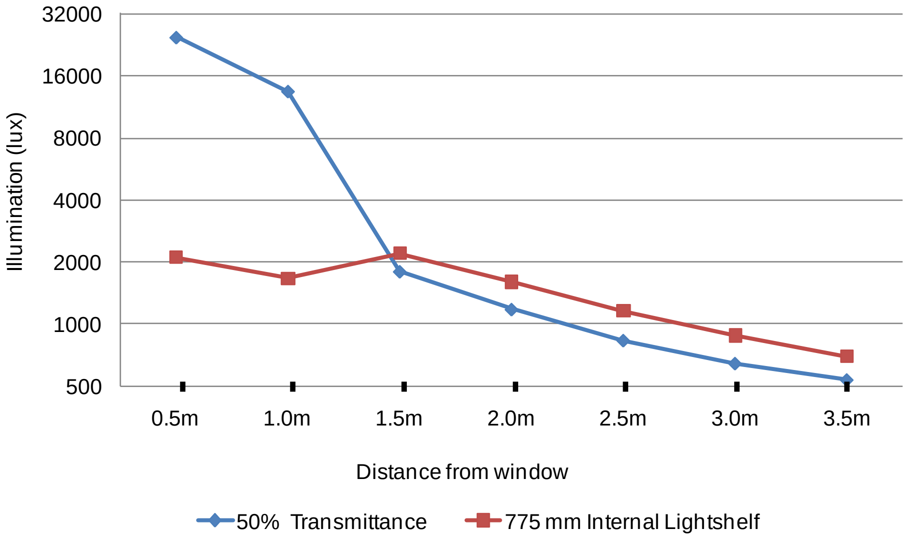


Figure 5.34: Comparisons of highest illuminations on an axis through the test point for the brightest sunny day (28 June at 10.30 AM) for 775mm deep light shelf and tinted sky window glasses with 50% normal visible transmittance.

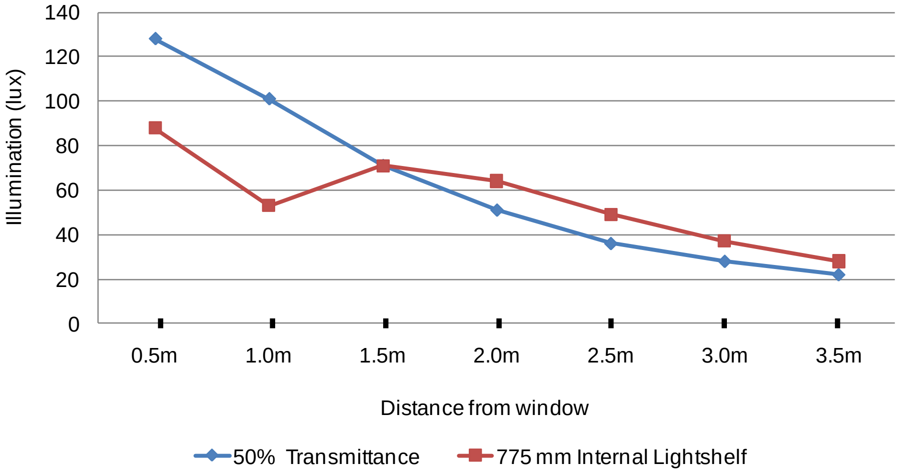
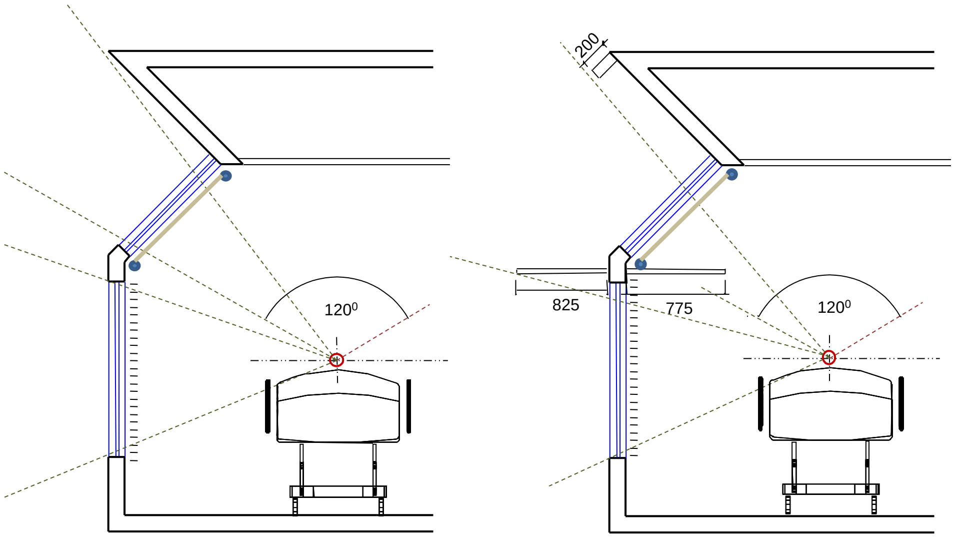


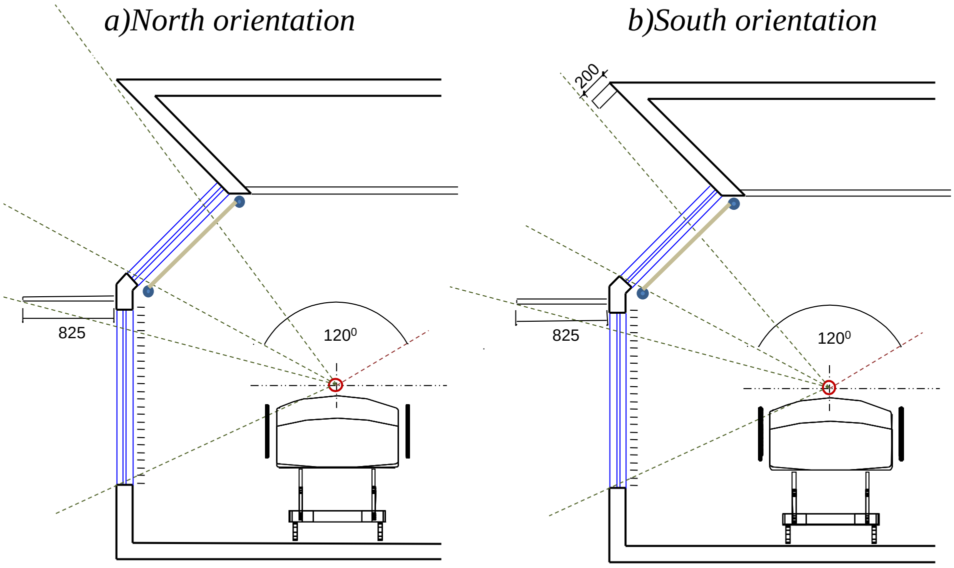
Figure 5.35: Comparisons of highest illuminations on an axis through the test point for the most overcast day (13 November at 11.30 AM) for 775mm deep light shelf and tinted sky window glasses with 50% normal visible transmittance.

5.7.6. Internal venetian blinds and operation

Venetian blinds can block or divert the direct sunlight to reduce the glare. The advantage of venetian blinds is that it can be raised when the sun control is not needed. The shading requirements to protect direct sunlight vary throughout the day for south orientations and literally, no shade is required for north orientations to protect direct sun for London climate. As the sun is in the east during the morning and in the west during evening, shades are required to protect direct sunlight only in east during the morning and west in the afternoon. As a result, a movable internal blind is a preferable solution, which could be dropped in east orientations at early mornings and late afternoons in west orientations.



a)North orientation *b)South orientation*



c)East orientation *d) West orientation*

Figure 5.36: Sections show position of internal blinds with developed shading for four orientations.

Although, the developed fixed shading devices (sunshade, overhang and light shelf) were capable to meet the target of DA and UDI>2000, recommended in Section 3.5.1(g) for the in-patient rooms, the scenario of a hospital in-patient room window without blinds is unrealistic. Therefore, an internal blind was installed for four orientations with the developed shading devices. The design of installed venetian blinds ensured that, it will not allow the direct sunlight into the space and will transmit 25% of diffuse daylight compared to the case when the blinds will be removed. This is a generic blind system model supported by DAYSIM under the simple dynamic shading device mode. The blinds will be fully lowered to avoid glare as soon as direct sunlight above 50W/m^2 will hit the test point and will be re-opened as soon as the sunlight will reduce below 50W/m^2. Figure 5.36 shows the locations of internal blinds for different orientations with fixed shading devices developed in earlier sections.

The performances of internal blinds depend mostly on the behaviour of the users who operate and control blinds. Reinhart (2002) identified two basic user behaviour for blind control based on field studies: active user and passive user. An active user opens the blinds in the morning, and partly closes them during the day to avoid direct sunlight. A passive user keeps the blinds partly closed throughout the year to avoid direct sunlight. Both types of users were considered in this section separately.

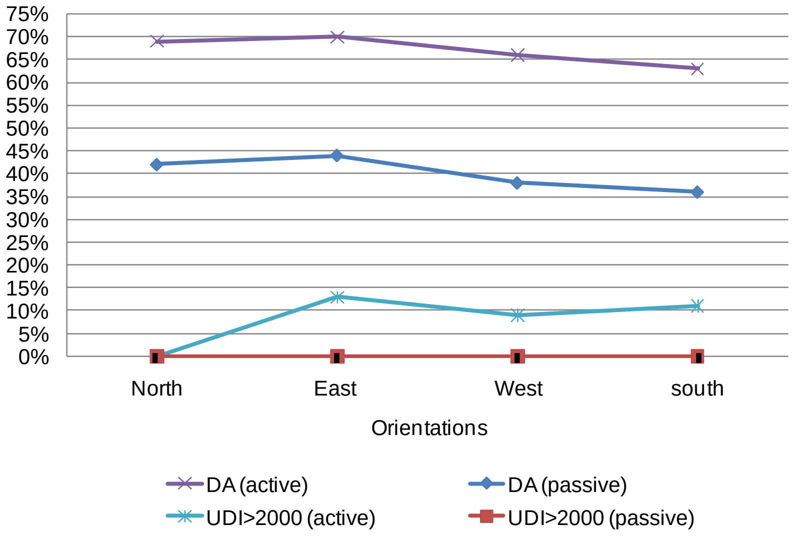


Figure 5.37: An active blind user can decrease the UDI>2000 levels without decreasing the DA levels.

Analysis showed that the impact of blind controls to reduce UDI>2000 is the maximum for west orientations (Figure 5.37). An active user can decrease the UDI>2000 level, kipping the DA levels constant to a situation without any blind. At the same time, a passive user may decrease the DA level significantly and can make the space darken (Figure 5.37).

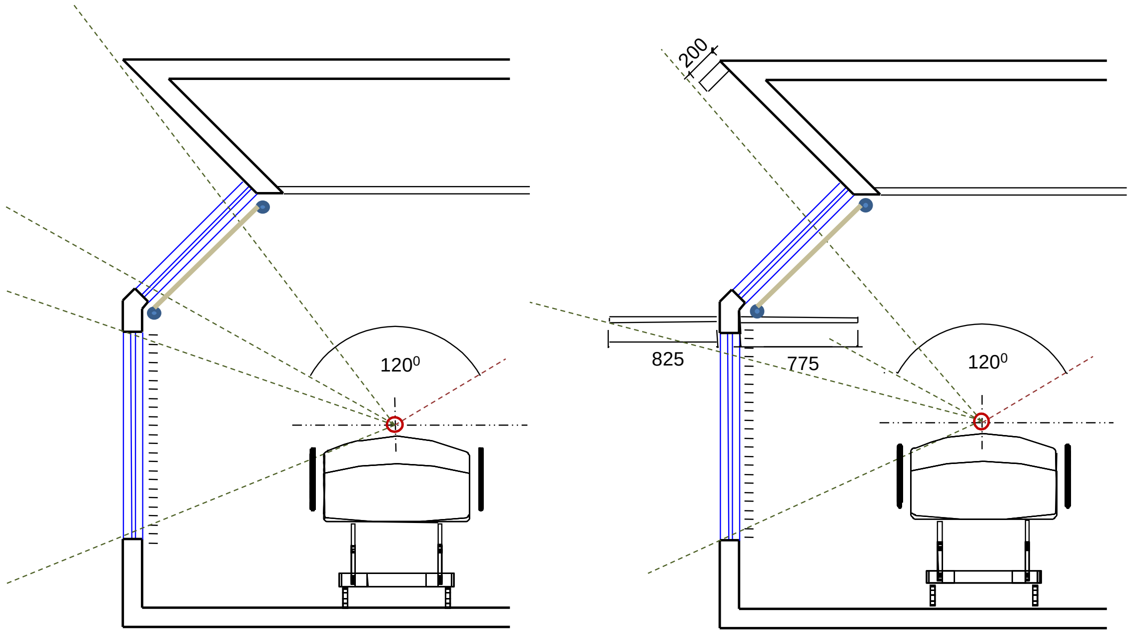
5.7.7. Recommendation of shades for sky window configurations

Figure 5.38 shows the developed design of sky window configurations with shading devices by parametric simulation analysis, for a single storey hospital building with external en-suite layout and without any surrounding obstructions. Table 5.2 summarises the recommendations and results of the analysis. The recommended depth of shading devices can be considered as a reference depth for NHS model space for single in-patient units with respect to London climate. In the absence of external en-suite, the depth of the shading devices can be increased (analysed in Section 5.9). For multi-storey hospital buildings, in conjunction of mutual shading by the building itself (projected upper floors and shading of upper floors) and/or presence of surrounding obstruction (for example other buildings and trees), the depth of the shading devices can be reduced further (impact of surroundings has been discussed in Section 5.8).

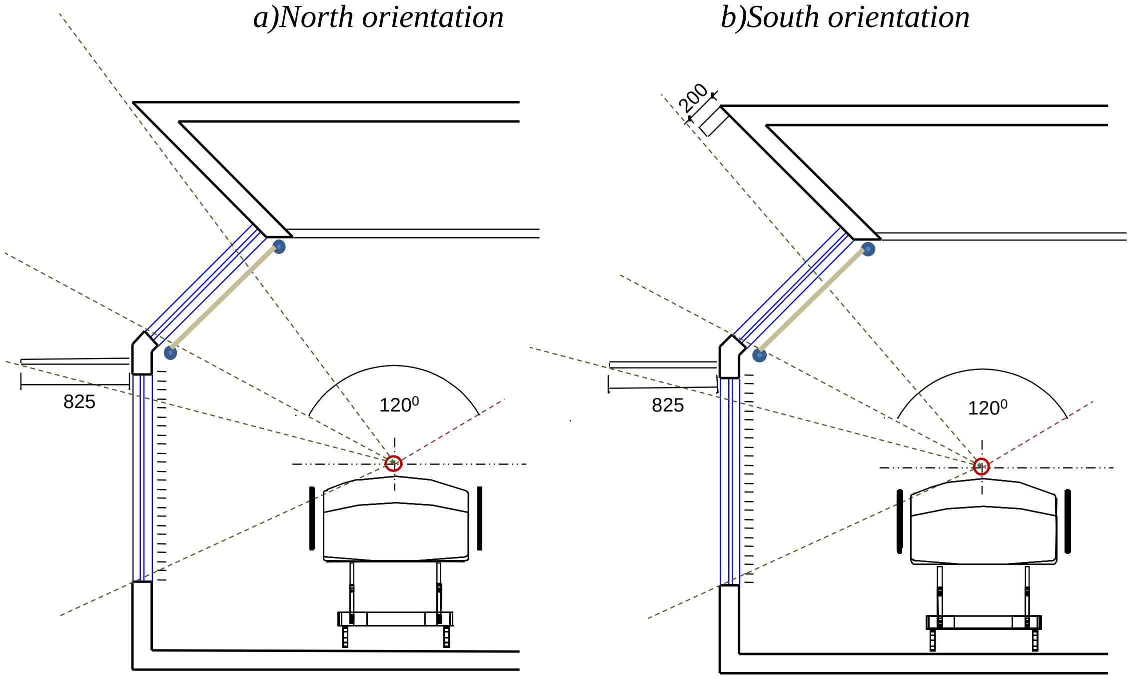
It needs to be mentioned that the designs of shading devices were developed in such a manner that the fixed shading devices (sunshades, overhangs and light shelves) were sufficient to keep UDI>2000 level in 14%. Introduction of internal blinds with active control helped to reduce the UDI>2000 further without reducing the DA levels. If the blinds are kept open for 24 hours, it will not affect to achieve the target level; in addition to that, an active operation of internal blind will enhance the comfort of patients.

Table 5.2: Recommended shading devices for sky window configurations for different orientations.

Orientation of sky window configurations	Depth of external sunshades (mm)	Depth of 45^0 angled external overhangs (mm)	Depth of internal light shelves (mm)	Internal venetian blinds control	DA (%)	UDI>2000 (%)
North	-	-	-	Active	69	-
East	825	-	-	Active	70	13
West	825	200	-	Active	66	9
South	825	200	775	Active	63	11



a)North orientation b)South orientation



c)East orientation d) West orientation

Figure 5.38: Sections show the recommendations of shading for sky window configurations for four orientations.

5.8. Contribution of building massing and surroundings

A recent tendency in the UK hospital architecture has been to arrange the in-patient units into multi-storey wings separated from treatment and diagnostic facilities to allow more consistent planning with increased flexibility, and enables to carry out easy maintenance and refurbishment (HBN 04-01, 2008). Considering the advantages of multi-storey buildings, daylight design in this research for therapeutic purpose was developed in a manner that, the concept is also applicable to multi-storey buildings. The proposed design of in-patient rooms with integrated sky window configurations and shading devices can be placed horizontally spread over large floor area or stacked into towers.

In a multi-storey hospital building, the upper floors can have impact on both reducing and/or increasing the daylight levels of the lower floors, by blocking or reflecting sunlight from the same building façades. In previous exercises, the case space was located at the ground floor of a single storey building. If the space is located in the intermediate floors of a multi-storey building, the upper floors, especially the projected en-suites might block some daylight for south orientations. In this exercise, the case space was placed in an intermediate floor (5th floor) of a multi-storey (10 storey) hospital building with typical floor plan in pairs of two adjacent rooms (Figure 5.39), and the performance for different orientations were observed.

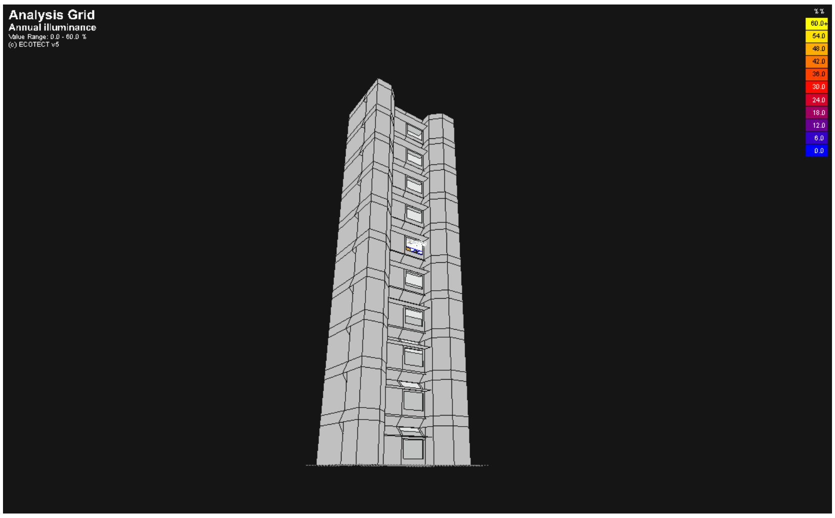


Figure 5.39: 3D model of 10 storey building (ECOTECT model).

It is evident from Figure 5.40 that for north orientations, there were no contribution of upper floors. The impact of upper floors was highest for south orientations and contribution to west and east orientations were in-between. It was found in the exercise of this section and previous sections that south is the most critical one for both DA and UDI>2000. The location of the space in the building for south orientations should be considered with greater importance.

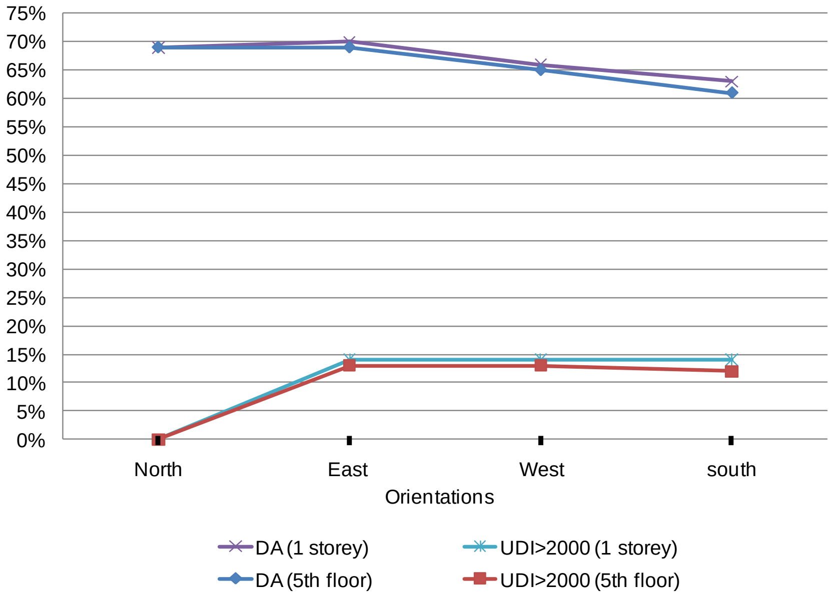


Figure 5.40: There is no contribution of upper floors to change DA and UDI>2000 for north orientations and the change is the maximum for south orientations.

In the next exercise, the case space was placed in three alternative levels (i.e. in ground floor, an intermediate floor (5th floor), and the top floor) of a multi-storey (10 storey) hospital building with typical floor plan with a group of two rooms for south orientations. Figure 5.41 shows the location of case space in the building for three alternative levels in south orientations.

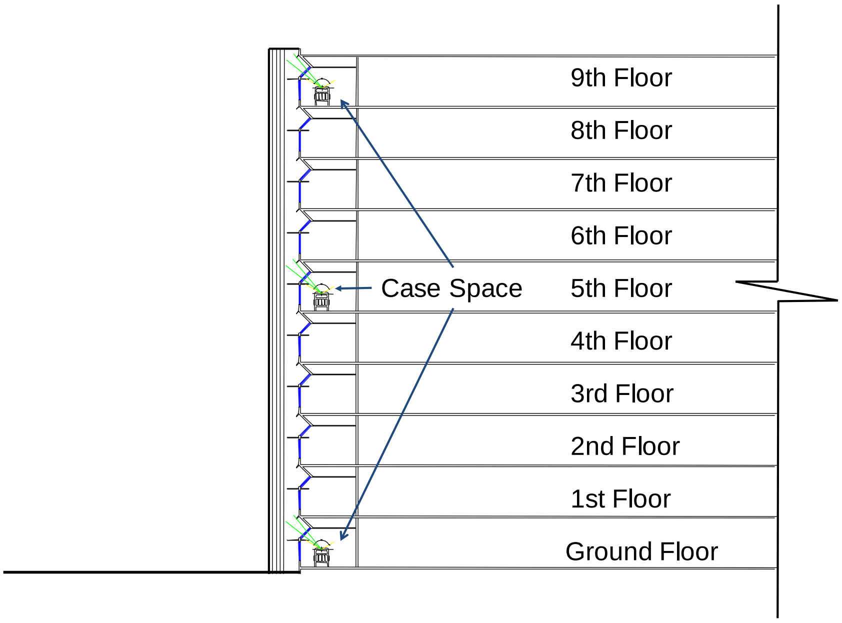


Figure 5.41: Section shows the alternative locations of case space in a 10 storey hospital building for south orientation.

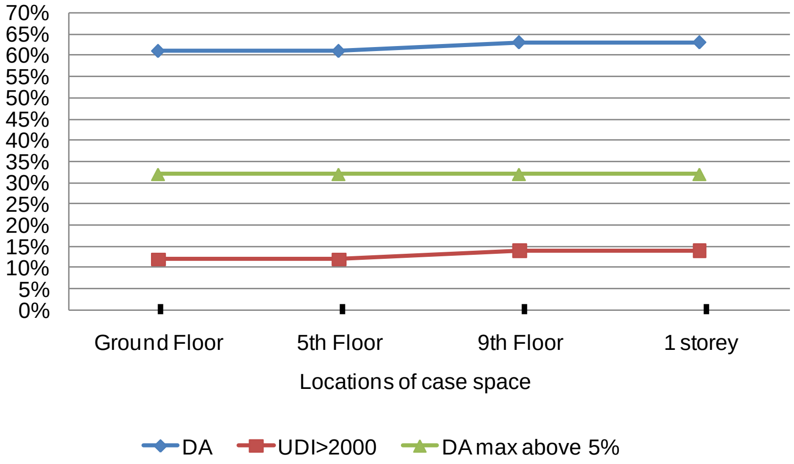


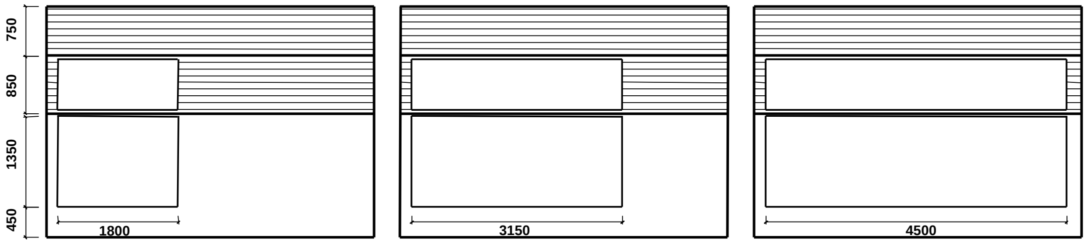
Figure 5.42: Introduction of upper floors on case space reduces both DA and UDI>2000 levels.

Figure 5.42 shows comparison of three alternative locations of the case space, on daylight levels on test points with respect to single storey case. The performance of the case space is same when located on the top floor (9th floor) of a 10 storey building or the ground floor of a single storied building. When located in 5th floor both the DA and UDI>2000 reduces 2%. When the case space is placed on the ground floor no further reduction on DA and UDI>2000 level is observed. It can be concluded that the immediate upper floors might have some contribution to reduce the lighting levels of the case space.

The impact of surrounding (e.g. other buildings and trees) is significant on the daylight level of an interior space. The building may be placed on a vacant field, adjacent to a tree, or the distance with the next building may be zero (adjacent to the next building). In each case, the impact can varied widely and should be considered separately as case specific. Daylight simulation, in this regard, can be the unique solution to conceptualise the impact of actual surroundings on the daylight potentiality of the space before construction.

5.9. Performance of sky window configurations for other en-suite layouts

In previous exercises, the designs of sky windows with shading devices were developed for the external en-suite layout (Figure 3.15(d), option 4), among four example layouts illustrated in HBN 04-01 (2008). In external en-suite layout, the en-suite occupied nearly half of the outer walls of the in-patient rooms and kept the other half of the outer wall free for placing a window. This was the worst en-suite layout among four layouts considering viewing and daylighting potentiality of the space. For other three options, the outer wall is totally free for placing a window anywhere in the outer wall; even window can occupy the entire external wall. In this exercise, three windows with alternative widths were placed on the en-suite free outer walls applicable to other three options of HBN 04-01 (2008) for south orientations and the impact on daylight levels at the test points was observed. The installed shading devices were the same as recommended for external en-suite layout (825mm sunshade, 200mm overhang, and 775mm light shelf with active internal blind control). The sill heights, lintel heights, and heights of the windows were the same as to the previous ones. Only the widths of the windows were changed, as a result window-to-floor ratios were changed. The minimum width of window was fixed as the same as the width of the previous ones (1800mm), and the maximum width was fixed to 4500mm occupying the maximum outer surfaces of the rooms. The other width selected for observation is 3150mm, which is the midpoint between the minimum and the maximum widths. The three windows were started from the head side of the patient beds to ensure the maximum daylight on test point. Figure 5.43 shows the size and location of three alternative widths of the windows. Table 5.3 shows the details of three investigated window sizes.



a) 22.3% *b) 39.0%* *c)55.6%*

Figure 5.43: Three elevations of alternative window-to-floor ratio due to change of the window width.

Table 5.3: Particulars of studied three configurations of window sizes for south orientation with shading.

Window width (mm)		Sill height (mm)		Window height (mm)		Total window glass area (m^2)	Served floor area (m^2)	window-to-floor Ratio (%)
View	Sky	View	Sky	View	Sky			
1800		450	1850	1350	1000	4.23	19	22.3
3150						7.40	19	39.0
4500						10.57	19	55.6

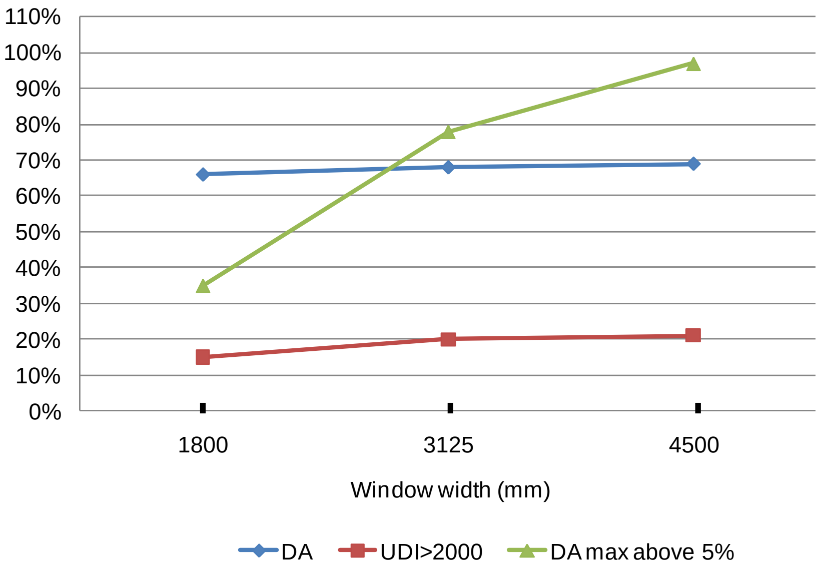


Figure 5.44: Increase of the width of the windows raised DAmax above 5% significantly compared to DA and UDI>2000 levels.

When the en-suite is removed from the outer wall, both DA and UDI>2000 were increased (DA is increased by 3% and UDI>2000 by 1%) for 1800mm width windows. The projected en-suites blocked part of the daylight and, therefore, reduced the effectiveness of window width. Figure 5.44 shows with the increase of the width of the windows, both DA, UDI>2000, and DAmax above 5% increased. Between the maximum (4500mm) and the minimum (1800mm) width of the windows, the increase of DA was 3%, increase of UDI>2000 was 6% at test point, and increase of DAmax above 5% was 62% on test plane. It seemed that the impact of increasing the width of the window is much on increasing the overall glare of the room than to increase the DA at test points.

Relating the findings of the impact of increased window-to-floor ratios of this section with Section 5.4, it is evident that, increasing the width of both the windows (viewing and sky window) more than twice from 1800mm to 4500mm results 33.3% increase in window-to-floor ratio; as a result DA increases by 3% at test point. When sky window was placed in the place of high window, a 2% increase in window-to-floor ratio resulted 4% increase in DA (Figure 5.3) at test points. Therefore, increasing the window-to-floor ratio to a higher level by increasing the aperture size in any direction, does not guarantee a higher DA at test points as well as increase of the therapeutic benefit of daylight on hospital patients. The overall analysis of increasing the window-to-floor ratio by increasing the aperture size in three directions (horizontal in this section, vertical for high window, and diagonal for sky window) also proofs that the concept of sky window configurations might be a very strong design element to enhance DA as well as daylight intensity at test points to enhance therapeutic benefit of daylight inside hospital in-patient rooms.

5.10. Impact of climate change on indoor daylight

Assessments of existing buildings show that many buildings are at the risk of being uninhabitable in the future without additional protection in building service design. This can be expected to have significant impact on the building industry; therefore, refurbishment is necessary for the existing buildings to meet the challenges of climate change. At the same time, it is necessary to keep in mind that during new construction the design must satisfy the demand to cope with climate change.

Climate change thus introduces several new issues to the knowledge gaps in daylighting research. Rapidly accelerating climate change, which is mainly associated with GHG emissions, is responsible for many dangerous regional and global environmental events. Climate change has the potential to decrease cloud cover (HPA, 2002) and change in sunshine duration. As a result, changes in incident global, direct and diffuse radiation is expected. Figure 5.45 shows the changes in average direct, diffuse and global radiations, based on DSYs and TRYs, described by UKCIP02 derived from CIBSE (2008) weather files. It is evident from Figure 5.45 that average diffuse radiation is higher for TRYs and average direct radiation is higher for DSYs in each the present and the future climate change time slice. The differences between DSYs and TRYs are much higher in average direct radiation then to average diffuse radiation. As a result, global radiation is higher for DSYs.

Based on DSYs, the average global radiation increases 1.0W/m^2 from 1989 to 2020s and increases further 1.5W/m^2 per 30 years till 2080s under low emission scenarios. While under high emission scenarios, the increase of average global radiation level is 3-4W/m^2 per 30 years from 2020s to 2080s. As a result, the average global radiation can raise a maximum 8.30W/m^2 in the future (2080s) compared to the present (1989). Based on TRYs, average indoor illumination can raise a maximum 8.31W/m^2 in the future (2080s) compared to the present (1983-2004). As an influence of the changes of radiation values, changes in ambient outdoor and indoor daylight levels are expected. The simulation of this phase was based on the data summarised in Figure 5.45.

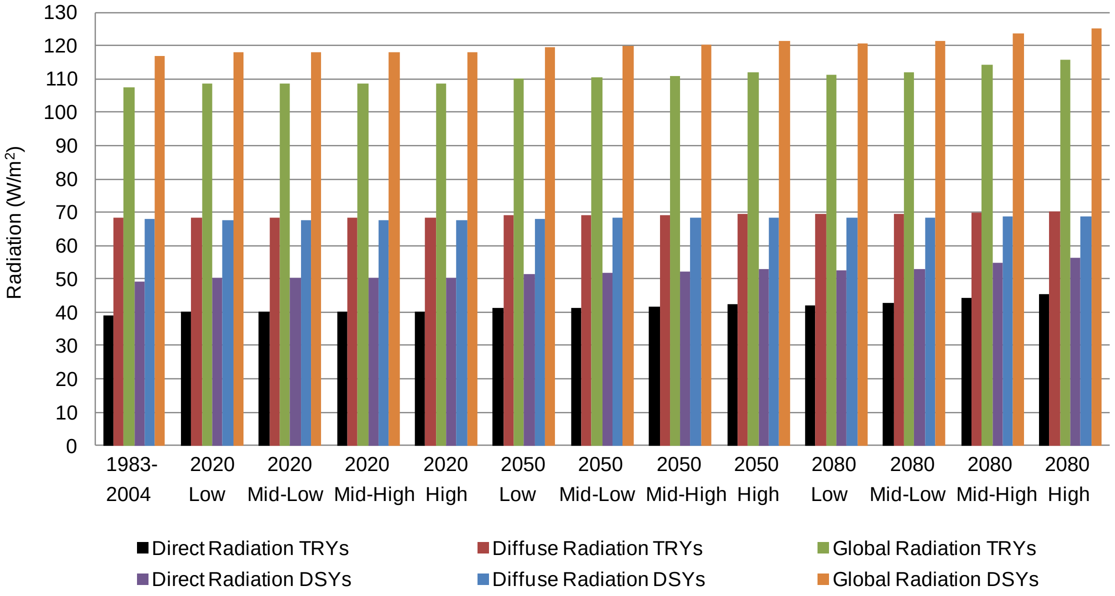


Figure 5.45: Changes in average direct, diffuse and global radiation projections described by UKCIP02.

5.10.1. Simulation parameters to evaluate the impact of climate change

In this second part of prospective simulation study, analysis were done to conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit environment, designed for therapeutic purpose, by evaluating the performance of sky windows. The quantitative and qualitative evaluations of climate change were based on the following parameters discussed in Section 3.5.2.

Location: Heathrow, West London, United Kingdom.

Longitude: 0.45 W

Latitude: 51.48 N

Ground reflectance: 0.2

Duration: Whole Year

Sky model: Perez sky model (Perez, 1990; 1993)

Design illumination: Minimum 190 lx daylight for south orientation (Pechacek et al., 2008)

Discomfort level: Above 2000 lx (Rogers, 2006; Nabil et al., 2006; 2005)

Single-bed in-patient room area: $19m^2$ (4800mm x 3960mm)

External en-suite area: 4.5m^2 (2285mm x 2100mm)

Clear height of the room: 2700mm

Height of the void space above ceiling: 750mm

Test plane height: 1150mm above floor level

Internal grid size for illumination measurement: 500mm x 500mm

Distance of core test plane sensor from window: 1500mm

Orientation of window: South

Window-to-floor ratio: 22.3 %

Window one: Viewing window (2.43m^2): 1350mm (height) x 1800mm (width) with a sill height at 450mm.

Window two: 45^0 angled sky window (1.8m^2): 1000mm (height) x 1800mm (width) started at a height of 1850mm from finished floor level, placed above the viewing window

Depth of external sunshade: 825mm

Depth of external 45^0 angled overhang: 200mm

Depth of internal light shelf: 775mm

Internal blind control: Active

5.10.2. Impact of climate change on indoor daylight level

In this section, simulations were done to calculate the hourly illumination at 63 intersecting grid points of the example space for the whole year. Figure 5.46 summarises the increase of average indoor illumination level from the present (1983 - 2004) to the extreme future (2080s under high emission scenarios) considering the average of 24 hours and selected 12 hours (06:00 AM to 06:00 PM) of daylighting. It is evident from Figure 5.46, that increases of illumination levels were higher for DSYs cases. Based on DSYs, the average illumination level increased 1% from 1989 to 2020s and increased further 1% per 30 years till 2080s under low emission scenarios. While under high emission scenarios, the increase of average illumination level was 2% per 30 years from 2020s to 2080s. As a result the average indoor illumination can raise a maximum 5% (average 16.58 lx considering 24 hours, and 33.23 lx considering 12 hours) in the future (2080s) compared to the present (1989). Based on TRYs, average indoor illumination can also raise a maximum 5% (average 17.33 lx considering 24 hours, and 34.39 lx considering 12 hours) in the future (2080s) compared to the present (1983-2004).

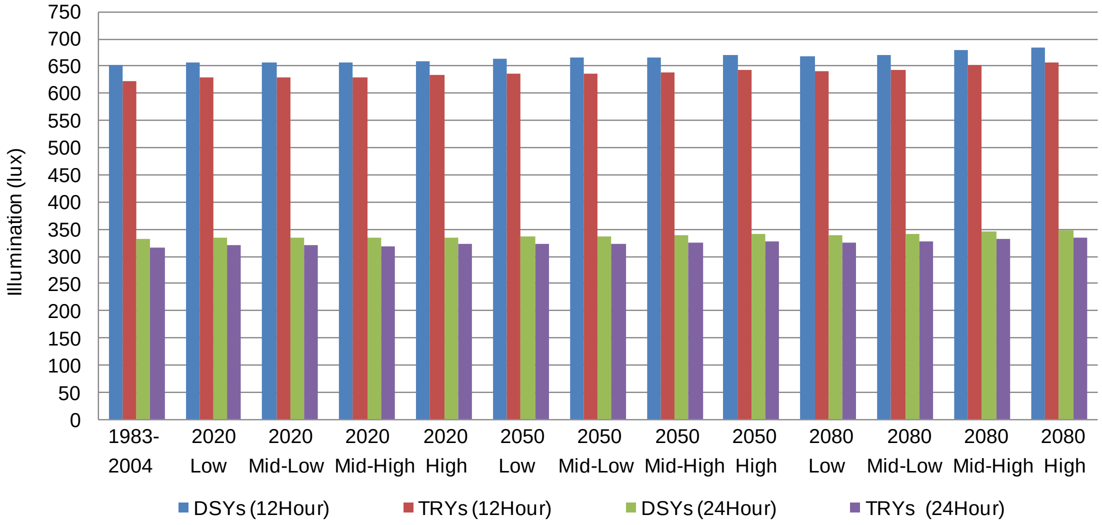


Figure 5.46: Increase of average indoor illumination level due to climate change.

Figure 5.47 compares the present and the extreme future hourly illumination profiles, averaged for 63 points, under DSYs. Comparisons of yearly (Figure 5.47) and monthly illumination profiles (Figure 5.48) show that the variations between the present and the future illumination were not constant. A closer observation of 24 hours daily illumination profile (Figure 5.49) revealed that the average difference between the future to the present could vary from -595.54 lx (27 January at 1:00 PM) to 579.03 lx (26 January at 1:00 PM) on a particular date. It is important to consider how this large amount of variation will be incorporated in the therapeutic design of daylighting.

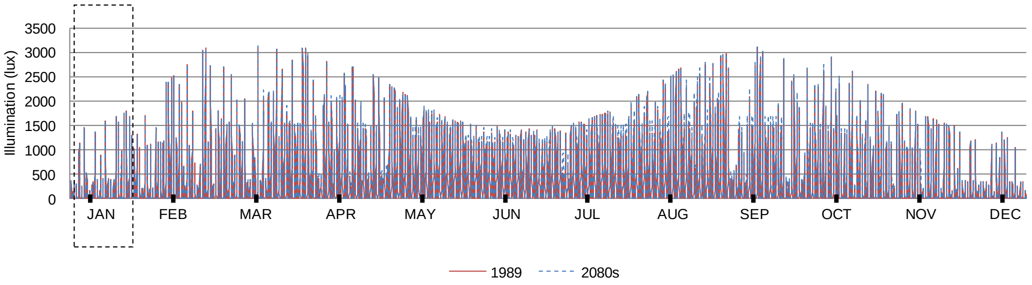


Figure 5.47: Comparison of yearly illumination profiles between 1989 and 2080s (DSYs).

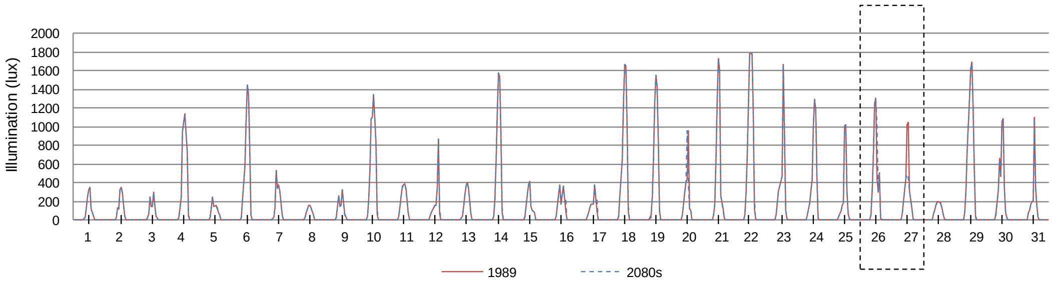


Figure 5.48: Comparison of monthly illumination profiles between 1989 and 2080s for the month of January (DSYs).

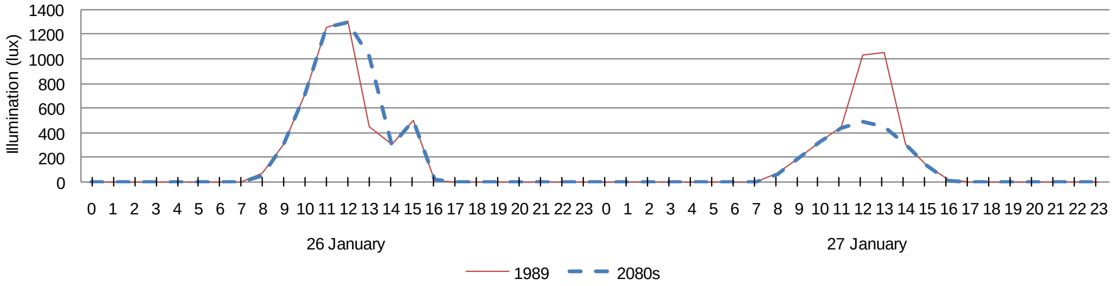


Figure 5.49: Comparison of 24 hours illumination profiles between 1989 and 2080s on 26 and 27 January (DSYs).

5.10.3. Impact of climate change on daylit space designed for therapeutic purpose

To understand the contribution of indoor daylight level on therapeutic potentiality of the patient, a comparison between the current illumination levels with the future illumination at test point (patient's head) will be sensible. Figure 5.50 summarises the increase of average indoor illumination level from the present to the extreme future considering the average of 24 hours and selected 12 hours of daylighting for core test plane sensor placed at patient's head (Figure 3.28). It is evident from Figure 5.50, that increases of illuminations were higher for DSYs cases for core test plane sensors. Based on DSYs, the average illumination level at test point increased 2% from 1989 to 2020s and increased further 3% per 30 years till 2080s under low emission scenarios. While under high emissions scenarios the increases of the average illuminations at test points were 3% per 30 years from 2020s to 2080s. As a result the average indoor illumination could raise a maximum 8% (average 62.56 lx considering 24 hours and 126.46 lx considering 12 hours) in the future (2080s) compared to the present (1989). Based on TRYs, average indoor illumination can also raise a maximum 7% (average 51.90 lx considering 24 hours and 104.82 lx considering 12 hours) in the future (2080s) compared to the present (1983-2004).

Figure 5.51 shows the illumination profiles comparison between the present and the extreme future under DSYs at test points. Comparison of yearly (Figure 5.51) and monthly (Figure 5.52) illumination profiles showed that the variations between the present and the future illuminations were not constant. A closer observation of 24 hours daily illumination profiles (Figure 5.53) revealed that the differences between the future to the present could vary from - 995 lx (27 January at 12:00 PM) to 3706 lx (24 August at 12:00 PM) on a particular date.

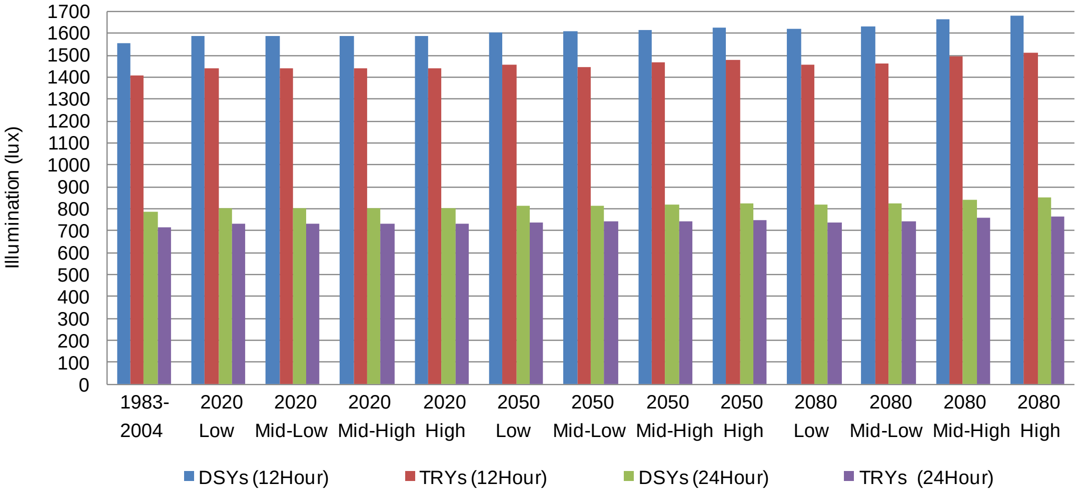


Figure 5.50: Increase of average indoor illumination levels at core test plane sensors due to climate change.

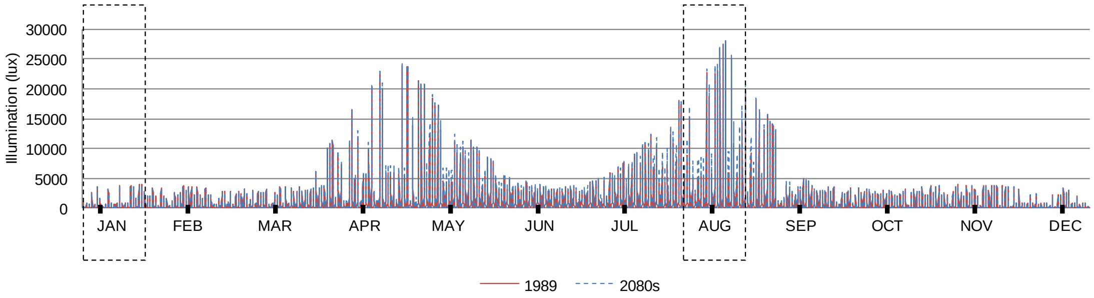


Figure 5.51: Comparison of yearly illumination profiles between 1989 and 2080s (DSYs) at core test plane sensor.

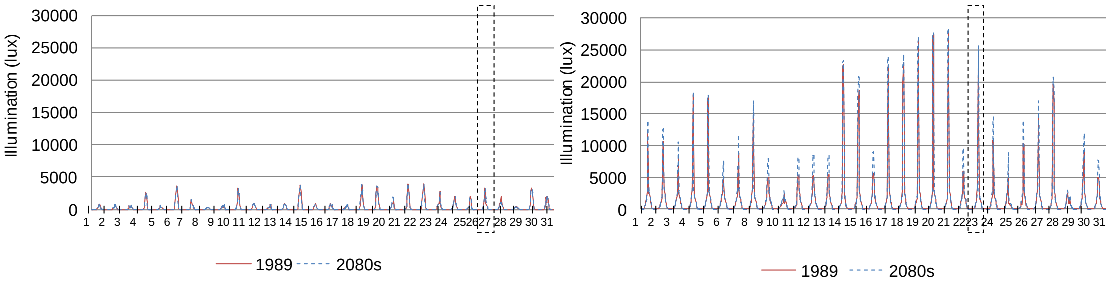


Figure 5.52: Comparison of monthly illumination profiles between 1989 and 2080s for the months of January (left) and August (right) (DSYs) at core test plane sensor.

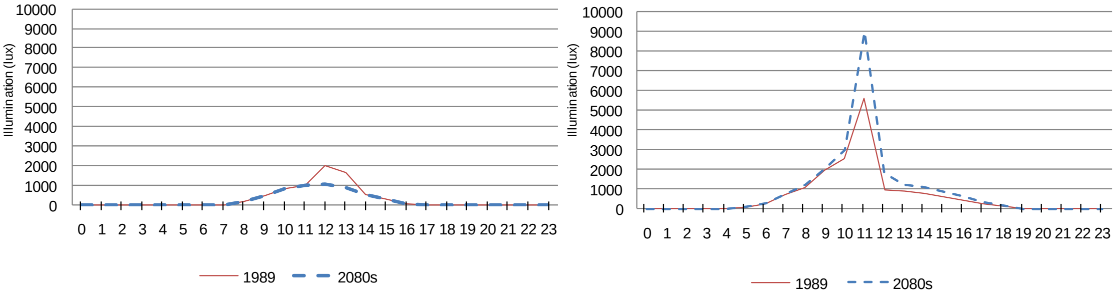


Figure 5.53: Comparison of 24 hours illumination profile between 1989 and 2080s on 27 January (left) and 24 August (right) (DSYs) at core test plane sensor.

Comparison of illumination profiles revealed that in most of the time, the illumination levels will be higher than the present which results an overall 8% increase in average daylight levels at test points. For some few cases, the illumination levels can be less than the present (e.g. 27 January at 12:00 PM). It is also apparent from detail observation of a single day illumination profiles (Figure 5.53), that illumination levels varied mostly around noontimes (12:00 – 1:00 PM) when both the present and the future daylight levels are much higher (exceeds the comfort level) then the benchmark (190- 2000 lx). In other times of considered daylight hours (between 06:00-11:00 AM, and between 02:00- 06:00 PM) the light levels increased gradually.

Comparing the average illumination increase in test point (core test plane sensor) to the average increase of the room illumination (average of 63 intersecting points at test plane), it seemed that average increase in illumination at test point is 3% higher than the average room illumination due to the close location of patient beds near windows. There are both advantages and disadvantages of the increase of illumination levels. The present illumination levels, which are lower than 180/190 lx at a particular time, might be increased to a therapeutic level, at the same time the present therapeutic illumination at a particular time can cross the limit of comfort (2000 lx) and can create discomfort.

5.10.4. Performance of sky window configurations under the future climate

The impact of the increase of indoor daylight levels were observed by evaluating the performance of south sky windows with recommended shading devices. The evaluation of 24 hours daily illumination profiles suggested that a shift change/adjustment in blind control/operations might be a suitable option to keep the duration and amount of illumination levels nearly constant for therapeutic purpose. In this case the opening and closing of venetian blinds should be earlier in the morning, and re-opening of the blinds in the evening should delay from the present schedule of blind operation. In this simulation analysis, the same generic blind system model of DAYSIM was used as Section 5.7.6.

Figure 5.54 shows the impact of blind operations on indoor daylight metrics when the blinds are operated by an active user who opens the blinds in the morning, and partly closes them during the day to avoid direct sunlight. It is evident from Figure 5.54, that under active blind control it will be possible to keep the present DA level constant for both DSYs (76%) and TRYs (75%). The glare level on test point (UDI>2000) remained constant under TRYs (18%), while under DSYs varied 1% (19% - 20%). The overall glare level (DAmax above 5%) on test plane sensors varied up to 2% (between 35% - 37%) for both DSYs and TRYs. It was evident from the analysis of daylight metrics that the proposed designs of sky window configurations with the integrated shading systems were capable to protect the increased level of indoor daylight illumination due to climate change.

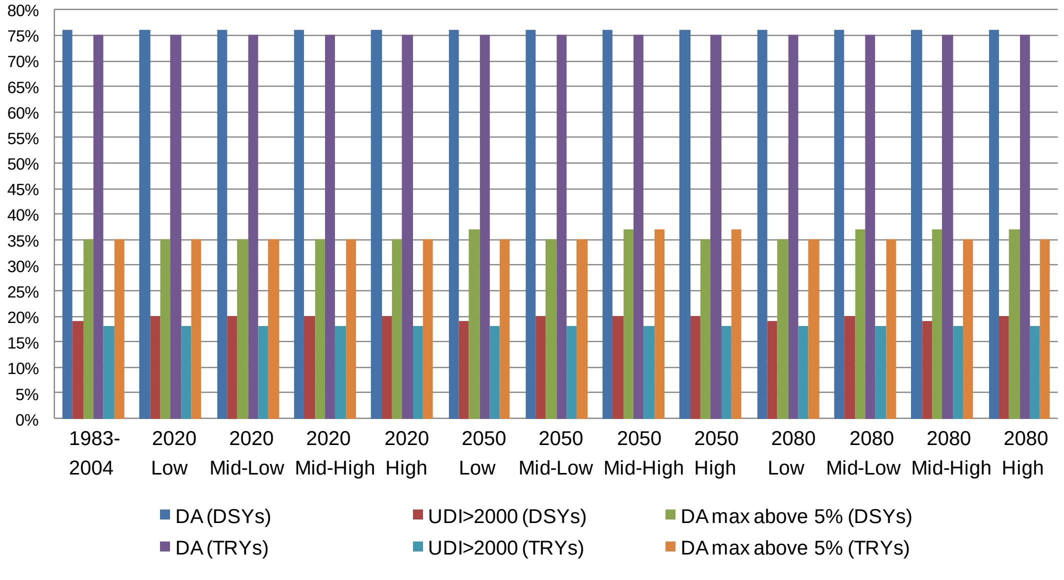


Figure 5.54: Under active blind controll the DA will remain constant; UDI> 2000 and DAmax above 5% changes slightly (1-2%).

Figure 5.55 shows a summary of yearly blind operation schedule to keep the DA levels constant under DSYs and TRYs, simulated for this study. To keep the DA level constant under the extreme future compared to the present, it needs to keep the blinds downward 28% more in a year for DSYs, and 40% more for TRYs.

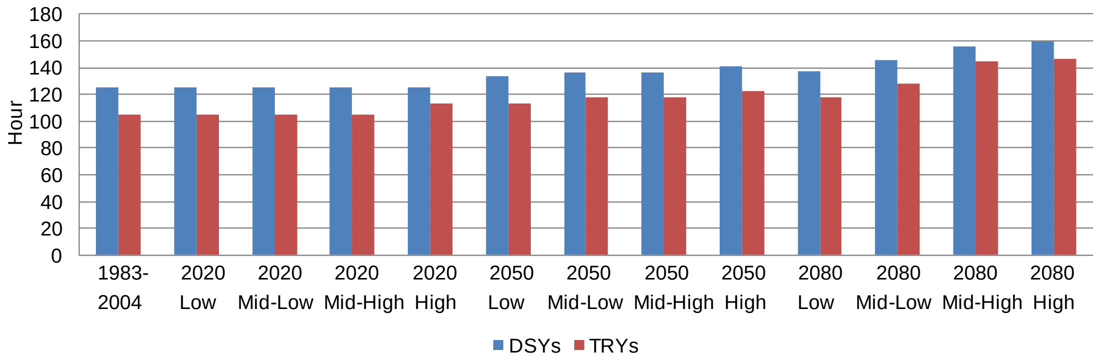


Figure 5.55: Total number of hours that the blinds need to be kept downward to keep the DA level constant under DSYs and TRYs.

5.11. Summary

This chapter has achieved the fourth and fifth objectives of the research.

The fourth objective has been achieved by presenting a concept (sky window configurations) as a possible option for incorporation of therapeutic effect of daylight in the design of hospital in-patient room, in a more effective way. Prospective simulation study helped to evaluate and compare the therapeutic potentiality of standard, traditional hospital window configurations with sky window configurations. The comparison revealed that the performance of sky window configurations was better than the traditional ones to enhance the therapeutic potentiality of the space by daylighting. Simulation exercise was also done to identify better location of bed inside patient rooms and to develop the design of sky window configurations (e.g. angle, material and optimum shading devices) for different orientations.

The fifth objective has been achieved by evaluating the performance of sky window configurations under the future climate scenarios. Though the design of the sky window configurations was fixed in this chapter at the beginning by simulation analysis, the performance of sky window configurations are not expected to be constant in the future due to climate change. It was come out from the analysis of the future climate data that the global incident radiation can be increased up to 8.3W/m^2 in the future. As a result, the average indoor illumination can raise a maximum 5% and increase of illumination at test point (patients' heads) could be 8%. Though, the proposed design of sky window configurations with integrated shading systems were capable to protect the increased level of indoor daylight illumination but to protect the increased level, internal blinds will be needed to shut down more often/times during day hours, which might create negative impact on patients’ clinical improvement, due to lack of outdoor views. The experiences and results of simulation analysis helped to identify parameters that can help to increase the therapeutic effect of daylight on hospital patients and to produce strategies in next Chapter 6.

CHAPTER 6
Strategies and Discussion

6.1. Introduction

This chapter discusses the strategies to incorporate therapeutic effect of daylight in the architectural design of in-patient rooms with reference of the developed MLR models from retrospective field investigation data described in Chapter 4, and experiences of prospective simulation study done in Chapter 5 of this thesis, with consideration of some issue, such as vitamin D metabolism and UVR protection, highlighted in the literature review of Chapter 2. The strategies are based on simple passive technologies and easily applicable in the design of hospital in-patient rooms. In this chapter, the strategies are grouped under the key activities of this research and are presented in six segments: to support architectural decisions in case of critical situations between daylight and POV; to identify daylight intensities within which reduction of patient LoS are expected; to enhance therapeutic benefit of daylight inside hospital in-patient rooms; to consider the effect of climate change on therapeutic performance of daylit in-patient rooms; to ensure vitamin D metabolism for hospital patients; and to protect patients from higher levels of UVB when inside hospital rooms. This chapter ends with the information of expected additional benefits of incorporation of therapeutic effect of daylight in hospitals (e.g. energy savings of the building and performance of stuff), based on the findings of previous researchers. The next Chapter 7 concludes the thesis by presenting a summary of this chapter with respect to the aim and objectives of this research and recommends areas for further research.

6.2. Background

In this research a triangulation research method was applied where theories were developed qualitatively in Chapter 2 and Chapter 3, and tested quantitatively in Chapter 4 and Chapter 5.

In Chapter 2, the impact of daylight has been described under two phases: direct and indirect. Direct impact is observed when daylight incident on the skin and cause photochemical reactions within the tissues, as a result production of vitamin D and dissociation of bilirubin starts. Indirect impact is observed when daylight incident on retina and photoreceptor cells create neural or neuroendocrine signals. Exposure to daylight increases concentration of serotonin from the pituitary gland and serotonin mixed directly into the blood stream. Once in the blood stream, serotonin goes to the heart, and heart circulate the hormone to different parts of the body, and affect certain specific target cells that are capable to catch the messages. Serotonin regulates sleep, reduces pain and appetite, and generally calms down and improves patient mood. With the reduction of light and exposure to darkness, serotonin converted to melatonin. The action of melatonin is opposite to serotonin. Higher level of melatonin increase stress, fatigue and sleep. Both the hormones are equally important to run the body function properly, as patients need sleep, at the same time continuous sleep/inactiveness is not expected. Again, with the introduction of light, melatonin converted to serotonin and it reverse at night. A kind of rhythm or cycle continues in human body that is regulated by external light. Serotonin and melatonin work combine to control the body’s internal clock or circadian rhythm. Without sufficient daylight, circadian rhythms are affected, which results into mood and sleep disorders. On the other hand bright light improves patients’ feelings, emotions and sleep, and reduces SAD, agitation and depression. The functions of pituitary gland, pineal gland, and internal regulatory mechanism, e.g. the nervous system and endocrine system, are affected by different wavelengths of daylight. The psychological benefits from daylight may catalyse clinical recovery of patients. As a result, it was hypothesised that patients’ exposure to daylight inside in-patient rooms might cause reduction to patient LoS in hospitals.

Field investigation of this research established the impact of daylight on reducing patient LoS inside in-patient rooms by developing MLR models, presented in Chapter 4. In this chapter, the researcher tried to illustrate how this knowledge (MLR models) can be incorporated in architectural decision support processes in critical situations to consider POV and daylight potentiality of a design.

Field experiments of Chapter 4 also confirmed the range of daylight intensities within which reduction of patient LoS are expected and the outcomes have been described in this chapter as strategies to identify benchmarks for daylight illumination to enhance therapeutic benefits for hospital patients.

The experiences and results of simulation analysis done in Chapter 5 helped to identify the design parameters that can be considered to enhance the therapeutic benefit of daylight inside hospital in-patient rooms, and to develop architectural design strategies for hospital in-patient rooms in this chapter.

Literature review of Chapter 2 showed that, due to the global climate change, individual environmental variables are expected to be changed. As a result, daylight design strategies should not only meet the current requirements but also should take accounts of future demands. It was evident from the climate change simulation analysis of Chapter 5 that, as the ambient outdoor daylight levels are expected to be increased due to climate change, future climate will probably offer a greater potential for the use of daylight for therapeutic purpose. Strategies for the protection from the increased level of daylight in the future, and how this increased level of daylight could be used to enhance the therapeutic benefit of daylit in-patient rooms, were discussed in this chapter.

Literature review of Chapter 2 revealed the necessity of direct daylight to be incident on the skin that cause photochemical reactions within the tissues, as a result production of vitamin D and dissociation of bilirubin starts which is also important for skeletal health and calcium metabolism. Psychological benefits (indirect impact) of daylight can be substituted by high intensity artificial light (Wirz-Justice et al., 1996), though it is complex and costly to match with human circadian system. Physiological promotion of daylight on health due to light incident on skin and production of vitamin D (direct impact) is quite difficult to obtain by artificial light. On the other hand, excess daylight might be harmful to individuals' health. To ensure therapeutic benefit of daylight for hospital patients, it was important to know the expected duration of direct daylight exposure which is only positive for health. Strategies to ensure vitamin D metabolism for patients, during their stay time in hospitals, were included in this chapter, based on previous research.

The literature review of Chapter 2 also ended with highlighting the consequences of climate change on human health due to the increased amount of UVR in daylight. The outcomes of literature, helped the researcher to develop the strategies in a balanced way and not biased by only one side of daylight (psychological and physiological benefits), but comprehend the overall impact of daylight on human health. Strategies of this chapter included the available techniques to protect patients from higher levels of UVR when inside in-patient rooms in hospitals.

For an overall progress of patients' health under hospital environment psychological, physical and physiological improvements are necessary. Strategies of this thesis tried to satisfy psychological, physical and physiological needs of daylight for patients during their LoS in hospitals. Following sections describes the strategies for architects to incorporate therapeutic effect of daylight in the architectural design of in-patient rooms as extended output of literature review, retrospective field investigation and prospective simulation study.

6.3. Strategies to support architectural decisions in critical situations

Both clinician and non-clinician researchers conduct experiments to identify the therapeutic effect of daylight on hospital patients. Due to clinicians association with hospital environment and control on sample groups (i.e. patients), the research conducted by clinicians (such as Walch et al., 2005; Oren et al., 2002; Lewy et al., 1998 and Lovell et al., 1995) are more robust and strong compared to the research conducted by non-clinician (such as Dutro, 2007 and Choi et al., 2012). However, in most of the cases, the findings of the clinicians are confined to the patient's health perspective only, and without linking the results to the hospital daylight environment design. The scientific research related to the impact of daylight on individuals strike clinicians interests from 1880s (HEL, 1885) to present, but their contribution to the design of hospital visual environment is not notable, except strengthening the previous knowledge. On the other hand, the first study of the impact of visual environment on hospital patients, conducted by a non-clinician, was published in 1984 by Prof. Roger Ulrich that is a milestone and one of the most referred article in daylight research related to therapeutic environment, till now. In the application of in-patient room design, the findings of the non-clinicians' research were topped although the qualities and acceptance of their research is questionable due to lack of clinical variables in their analysis and their control in healthcare settings, compared to clinicians' ability.

Unfortunately, in the description of the clinicians' research the architectural details, for example window size, bed position, outdoor views, quality of daylight other then intensity, for example discomfort and disability glare possibilities; uniformity and diversity of illuminations, were absent. In Walch et al. (2005) article, even no in-patient room layout plan or photographs of the in-patient rooms were included to express an idea about the visual character of studied rooms. In his study variables other than indoor daylight levels were not considered for indoor environment, for example outdoor views, room temperature and humidity were not considered. In the design of research methodology, the intention of clinicians are to include more uniform patient group in the study, but provide less attention to variables associated with visual/built environment of the spaces. The major weakness found in past research was in selection of variables (discussed in Section 3.4(b)) and procedure of daylight measurement (discussed in Section 3.4.1).

This research considered 33 variables during data collection of field surveys, including 21 clinical, five demographical and seven environmental variables. Application of MLR enabled the study of the relationship among daylight and POV with other clinical variables (e.g. LoS, blood pressure and heart rate). MLR models first allowed defining the relationship among different variables (Table 4.4, 4.6, 4.8 and 4.9). The Un-standardized Coefficients (B), Standardized Coefficients (Beta) and t-statistics or *p-value*s of the explanatory variables in the regression models determined the importance of the explanatory variables to reduce patient LoS and can be used as a reference to determine the significance of particular element on hospital in-patient room designs. Once it become possible to identify the importance and impact of environmental variables independently, it is possible to apply the findings to support an architectural design decision in critical and/or conflicting situations.

It was evident from the model based on the pilot study data that between two room variables daylight and POV (Table 4.4), daylight was more significant (t=-1.995, *p value*=0.055). Comparing the standardized coefficients (Beta) of two room variables, it was apparent that average daylight intensity of the room was more important than POV (Beta -0.245 for daylight to Beta -0.198 for POV) in relation to the recovery process of heart surgery patients.

It was also evident from MLR model generated from principal study data (Table 4.6) that daylight was more significant (t=-2.425, *p value*=0.016) between two environmental variables daylight and POV. Comparing the standardized coefficients of two environmental variables, it was apparent that daylight intensity near a point above patient's head is more important than POV (Beta -0.127 for Daylight to Beta -0.114 for POV) in relation to the recovery process of CABG surgery patients.

The results of MLR models from the pilot and principal studies confirmed that both daylight and POV are important to cause reduction in the patient LoS. Comparing the standardized coefficients (Beta) of two environmental variables it was apparent that daylight was more important than POV in relation to the recovery process (Table 6.1). The reason would be that, in most of the cases it is quite impossible to provide an outdoor view in inner rooms/beds if located far from external peripheral walls, but increase of daylight inside rooms (e.g. 100 lx) is relatively easier to achieve by design. Based on estimated MLR models, it can be concluded from an architectural decision support perspective that rooms with more daylight but less outer views are better than rooms with better views but less daylight. The provision of skylight for more daylight in deep planned single storied hospital buildings or the top floors of multi-storey hospital buildings can be an effective solution in dense urban context to enhance therapeutic benefit of daylight inside in-patient rooms, effectively. In case of sky window configurations, developed in this research, if the blinds are shut down for viewing windows (for privacy), the daylight through sky window will have some positive impact on patients' recovery process without affecting much on privacy.

Table 6.1: Comparison between statistical importance of daylight and POV in pilot and principal study.

	Pilot study		***Principal study***	
	Daylight (lx)	*POV*	*Daylight (lx)*	*POV*
Un-standardized coefficients(B)	-0.040	-13.495	-0.073	-17.437
Standardized coefficients (Beta)	-0.245	-0.198	-0.127	-0.114
t-statistics	-1.995	-1.636	-2.425	-2.100
*p-value*s	0.055	0.112	0.016	0.037

6.4. Strategies to identify daylight intensities for patient LoS reduction in hospitals

In the 2nd phase of principal study, experiments were done to verify the range of daylight intensities within which positive health outcomes are expected, by generating the third MLR model. It was evident from the model that LoS of the patients for two daylight categories, used as explanatory variables for the model (lx<190 lx and lx>2000 lx), were significantly higher compared to the reference group who experienced moderate levels of daylight (190-2000 lx) in the maximum time of their stay inside in-patient unit. This result of the analysis confirms the recommendation of previous researchers on circadian illumination (Pechacek, 2008) and useful daylight levels (Rogers, 2006; Nabil et al., 2006; 2005).

The coefficient estimates of third MLR model (Table 4.8), based on the output of pilot study data to identify the range of daylight intensities within which reductions of patient LoS inside in-patient rooms are expected, showed that while holding the other explanatory variables constant, being in lower daylight group added 42 hours and being in higher daylight group added 29 hours in patient LoS compared to the group experienced moderate levels of daylight. Comparing the standardized coefficients (Beta) of two categorical variables for daylighting, it was apparent that patients experiencing lower daylight level have greater possibilities to stay more time in hospital rooms (Beta -0.138 for lx <190 to Beta -0.093 for lx>2000) than patients experiencing higher daylight level, implying that patients deprived from daylight are more likely to suffer compared to patients who enjoys higher amount of daylight inside in-patient rooms. The estimation of fourth MLR model (Table 4.9), confirmed that increase of daylight intensity (under moderate level: 190- 2000 lx) at patients' heads can reduce patient LoS inside hospital in-patient rooms more significantly.

6.5. Strategies to enhance therapeutic benefit of daylight inside in-patient rooms

Although, windows are the primary building elements that allow entry of daylight into rooms, research has shown that a room with a window is no guarantee of adequate daylight to ensure therapeutic benefits (Pechacek et al., 2008). The findings of field studies and literature review also revealed 'the more the better' philosophy does not work to enhance therapeutic effect of daylight in the design, and increasing aperture sizes do not necessarily support to gain therapeutic benefit of daylight for hospital patients. Unnecessary increases of window-to-floor ratios by increasing glazing areas of the in-patient rooms might be threat to health and cause discomfort, glare, UVR gain and additional energy consumption to the space. The increase of aperture sizes should follow the appropriate direction and design in order to meet the therapeutic purpose of hospital patients. To ensure therapeutic benefit of daylight for hospital patients, efforts need to be concentrated on the design of windows from the beginning of the hospital building projects at conceptual/sketch level to avoid demolitions, renovations and adjustments after construction and to achieve therapeutic quality more economically.

The purpose of the simulation exercises in this PhD research was to show an option of, how therapeutic effect of daylight can be incorporated more effectively in the architectural design of hospital in-patient rooms, than to specify a concrete and complete design solution to achieve therapeutic effect of daylight for a typical hospital in-patient room located in London. The idea of doing the simulation exercises was to develop some architectural design strategies for the incorporation of therapeutic effect of daylight inside hospital rooms from the experience gained of the analysis. The strategies based on the outputs of simulation studies are discussed below.

To meet the therapeutic requirement, windows should provide the maximum daylight on patient beds and uniform daylight over the room without creating much discomfort to patients. Traditional windows without any aids provide the maximum daylight (extremely high) near windows, which decreases quickly towards the back of the rooms. Daylight inclusion through roof to lit deeper parts of the room is not possible for intermediate floors of most of the multi-storey buildings (which is common in modern hospital design). This research tried to introduce a different architectural form by introducing sky window configurations for hospital in-patient rooms to incorporate higher levels of daylight intensities on hospital beds through part of the ceilings. Comparisons between standard traditional hospital window configurations and sky window configurations showed that, under similar restrictions, sky window concept provide higher intensity of daylight on test points (patients' heads) than traditional high windows. This result emphasised that, extra efforts need to be concentrated in the design of hospital windows to support biological systems of patients more effectively. The exercise of simulation study also showed it was beneficial to start hospital windows from the head side of the patient beds to ensure the maximum daylight (without discomfort) towards patient’s head and better outdoor views for bedridden patient. The popular practice of placing windows in hospital rooms is at the centre of the external walls (for example, Leeds Nuffield Hospital, UK, (Appendix F.1); and Northwestern Memorial Hospital, Chicago, US, (Appendix F.9)) and in some cases on leg sides of the patients (for example St. Joseph Regional Health Centre, Texas, USA, (Appendix F.31); Lee Memorial Hospital, Fort Meyers, USA, (Appendix F.16); and Methodist Health Center, Sugarland, USA, (Appendix F.17)).

It was evident from the distribution of daylight on a horizontal and vertical plane going through the patient eyes by simulation studies that horizontal plane with a sensor point upwards receives higher intensities of daylight. Thus patients themselves can also control the amount of daylight incident on their retinas by changing the gesture and posture of the body. For example to protect from higher intensities of daylight on eyes, patients can rest on their back and if they prefer higher illumination, patients can lay with their spine.

As, the intensity of daylight falls rapidly from the window towards the opposite wall, single-bed in-patient unit with a minimum room depth (distance from window to back/corridor wall) is more preferable to ensure therapeutic benefit of daylight for individual patient than deeper multi-bed rooms. It is preferable to locate en-suites in inner sides of the hospital buildings, keeping the outer walls of the in-patient rooms unoccupied, to achieve greater flexibility for placing and varying sizes of windows. Verandas could also be provided as a place to enjoy direct exposure to sunlight during some parts of the day (discussed in Section 6.7). Bed should be placed as close as possible to window with a minimum clear space on window side for clinical activity and considering glare possibilities. The common practice of placing hospital beds are at the middle of the room (for example Digne and Montceau Hospital, France, (Appendix F.4 and F.5); Charmes Hospital, France, (Appendix F.3); Northwestern Memorial Hospital, Chicago, US, (Appendix F.9); and Vail Valley Medical Center, Ambulatory Surgery Center & Women & Children Center, Vail,US, (Appendix F.24)), or in some cases far from the window (for example Methodist Health Center, Sugarland, US, (Appendix F.14); IHC McKay Dee Medical Center, Ogden, US, (Appendix F.19); La Rabida Children's Hospital, Chicago,US, (Appendix F.22); Florida Hospital, Flagler, US, (Appendix F.25) and Montceau Chbre, France, (Appendix F.5)).

It was found during simulation analysis that the shading requirements varied for different orientations. With only a particular design of shading devices (e.g. sunshade with fixed depth) for the entire hospital building, it was not possible to satisfy the comfort levels with sufficient daylight for therapeutic purpose for different orientations and shading should vary with orientations. However, it is common in architectural design to repeat a window with same shading configurations (for example sunshade) for the entire building without considering the orientation and potential for daylighting (Pechacek, 2008), and in some cases totally different design of the windows for different orientations. This research recommends to keep the design of a particular type of shading device fixed for different orientations for the whole building and add separate shades in different levels of windows where more shades are required than to change the design and depth of the same shading devices for different orientations. For the studied case space, the glare possibility increased in an order from north, east, west and south. The number of shading devices were added gradually higher in north (only internal venetian blinds) to east (internal venetian blinds and external sunshades) to west (internal venetian blinds, external sunshades, and external overhangs) and finally to south (internal venetian blinds, external sunshades, external overhangs and internal light shelves). This principle for developing shading devices for sky window configurations for a hospital in-patient room can also be used to develop shading systems for other types of windows for different kinds of buildings. The dimensions of shading developed in this simulation exercise can be taken as a reference for shading design for sky window configurations for London. The case presented here can be a starting point for further simulation studies to fix the dimension of shading devices for other locations.

The shading design developed for sky window configurations in this research could be one of the way to achieve the minimum 80% of outdoor DA with a maximum 20% UDI>2000 for an imaginary location in central London. Based on the practicality, surrounding conditions and available outdoor daylight, both the target for indoor DA and UDI>2000 can be changed. It was evident from simulation exercise that, same DA and UDI>2000 can be achieved by a different combination of light shelves, overhangs, sunshades and internal blinds. For example to achieve the target level of DA and UDI>2000, the depth of internal light shelves and depth of external overhangs could be inversely proportional for south orientations. Means, if the depth of overhangs are increased, the depth of internal light shelves were necessary to be decreased to maintain the DA and UDI>2000 level constant. In the simulation exercise, the suitability of a 775mm internal light shelf with a 200mm overhang was shown for the ground floors of single story hospital buildings for south orientations. It is possible to achieve the same DA and UDI>2000 by 275mm overhang with 600mm internal light shelf, (see Appendix D). It is also possible to omit one type of shade (e.g. external overhang) by increasing the depth of other type of shade (e.g. internal light shelf). The researcher preferred to maintain the depth of overhang constant for all orientations of the same building for uniformity as mentioned above. It was evident from the simulation study that, for London climate, north and east are better orientations for in-patient units compared to south or west in terms of achieving therapeutic effect of daylight. Extra care should be concentrated for the design of south windows in hospital buildings to achieve daylight for therapeutic purpose, without glare and discomfort. The occurrences of direct penetration of higher intensities of daylight through north windows are uncommon and less critical in terms of glare control and shading requirements.

The shading adjacent to the windows primarily govern the performance of the windows. Immediate upper floors and building surroundings can have a greater influence on the daylight potentialities of the space and should be considered and studied during design development phases. Simulation can be a useful tool for conceptualising the performance of architectural shading and building surroundings during design phase before construction. Comparing the impact of upper floors on reducing DA and UDI>2000 with the analysis of the impact of shading designs showed that, the addition of five floors below the case space and four floors above the case space, causes similar impact on test points, resulted by 200mm change in over hang depths or 100mm change in the depths of internal light shelves.

The options of tinted glass (50% transmittance value) were rejected and clear glass windows with light shelves (775mm depth) was recommended in this research. A lower depths of light shelf (less than 775mm) with a window glass of higher transmission value (above 50%) can also contribute the same level of DA and UDI>2000. These types of precise decisions/options/combinations can be left to the architect's individual preference. The researcher prefers clear glass to facilitate outdoor view and better daylight distributions inside patient rooms. Tinted glass might be essential to protect UVR in some geographical locations where the ambient outdoor UVR is extremely high (discussed in Section 6.8.1). Highly specular reflective surfaces should be avoided both inside and outside of the hospital buildings to reduce glare and uncomfortable views (discussed in Section 6.8.2).

Among thousands (even millions) of options, the configurations of particular design elements recommended in this research in some cases was primarily governed by researcher‘s (with architectural background) own aesthetic and intuitive judgements. E.g., for the angle of the overhang, a 45^0 angle was chosen as it matches well with a 45^0 angled sky window better than other angles. It is not possible to test each option simultaneously against all combinations of every other option. Due to the limitations of time and parametric simulation technologies, some of the preliminary decisions can be based on solar control criteria, line of vision, aesthetic, or intuitive judgements of the designer, and the other could be fixed by simulation study. Appendix D presents a total 123 numbers of simulation results with different shading configurations exercised in trial and error process during this research time and only 43 numbers were included in the discussions of Chapter 5, based on which most of the design decisions were supported.

A hospital window, located at in-patient room, without blind is unrealistic. It was evident from simulation study that the concerns and benefits of special window design can be diminished under occupants' passive blind operations. Therefore, someone in the hospital premise should take the responsibility to control the blinds actively. Recently published research on the same issue of daylighting and LoS, recommends that, 'shading devices that can be controlled by the patients may provide a positive effect on their physiological and psychological conditions' (Choi et al. 2012: p 17). It is difficult for hospital patients to be active in blind control. This research recommends hospital nurses to be active in blind operation and maintain a schedule for opening and closing the blind similar to provide timely medications to patients to maximise daylight inside patient rooms without glare (therapeutic effect of daylight on patients are similar to the effect of medicine). As nurses are available 24 hours and have frequent access to patient rooms for care purpose almost each hour, active control of venetian blinds by nurses is more practical compared to control by patients who are mostly physically weak. The model used for this PhD research considers active control as opening the blinds in the morning, and partly closing them during the day to avoid direct sunlight. Therefore, the nurses need to be concerned for blind operation in two or three times a day, which is not very significant considering the working load of nurses in hospitals (which usually varies for different wards for different hospitals), but the benefit is significant, i.e. under passive control the DA level might be reduced to 30% on average for different orientations (Figure 5.37). Means of operation for patients to control curtains or blinds for privacy and comfort should be included near bed (e.g. motorised curtains for non-ambulatory patients). Fully automated blind control is the least option as it uses active energy continuously i.e. electricity. Passive design and technology should be used in the therapeutic design of hospital in-patient rooms to save energy.

It was found during simulation analysis that, though thousands of lx varied on test points for a particular variation of a single design element, it is difficult to achieve 1% of increase/decrease in DA and UDI>2000 at test point annually. It is assumed that based on the steps and methodologies adopted in the simulation studies of this research, the proposed design of sky window configurations will be more comfortable than the quantitative credit it achieved by DA and UDI>2000 numbers. For example, under DAYSIM analysis, 2001 lx to higher (e.g. 50,000 lx) will be considered as UDI>2000, but in reality 2500 lx is much less uncomfortable then 50,000 lx. In this research, considering the highest illuminations in critical days such as brightest sunny days and most overcast days, the illumination levels were tried to keep nearer to the benchmark (190 – 2000 lx).

The outputs of simulation exercise in this research is an advanced to the previous research (Gochenour et al., 2009; Pechacek et al., 2008) in a sense that this research presents new architectural forms as a conceptual solution to enhance therapeutic effect of daylight by introducing and implementing sky window configurations in the architectural design of hospital in-patient rooms. This research also confirmed the suitability of sky window configurations for achieving therapeutic benefit of daylight for hospital patients more effectively compared to traditional standard hospital window configurations. Still there are further scopes to develop the design of sky window configurations and evaluate its performance in terms of heat gain or heat loss associated with energy usage of the hospital buildings. It is also possible to introduce other concepts to achieve therapeutic benefit from daylight for hospital patients more effectively using the methodology demonstrated in this research.

6.6. Strategies to consider effect of climate change on daylit in-patient rooms

The analysis of the therapeutic daylighting performance of the proposed sky window configurations under different future emissions scenarios revealed that, average indoor illumination at test point (patients' heads) can raise a maximum 8% (average 62.56 lx) in the future (2080s) compared to the present (1983-2004) based on CIBSE (2008) database and the differences can vary - 995 lx to 3706 lx.

It was also evident that, the difference in indoor daylight levels between the present and the extreme future is due to increase of higher illumination during noontimes (Figure 5.53) and, extra protections are needed during this time periods. The design of sky windows in this research was developed in such a manner that the service space (and/or upper floors) itself provides complete shade of sun during noontimes when the sun is near zenith (Figure 6.1) and UV is highest in the environment as well (Section 6.8.3, Figure 6.9).

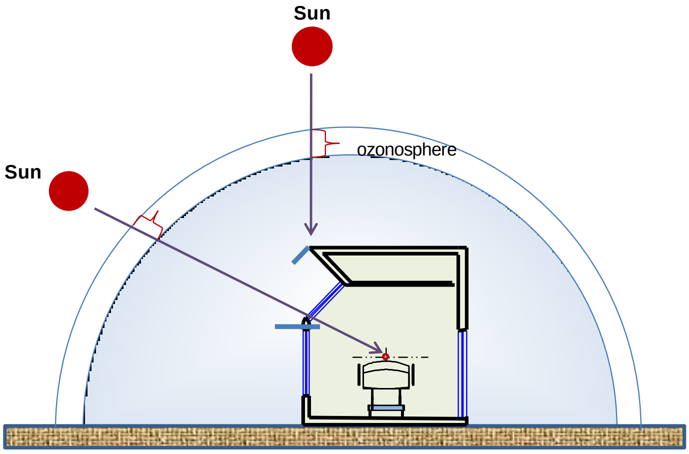


Figure 6.1: The service space above sky window provides complete shade to the sun during noontimes when the sun is near zenith.

The simulation analysis showed that the proposed design of sky window configurations, with integrated shading systems with active controls are capable to protect the increased level of indoor daylight illumination due to climate change. But, to protect the indoor from increased daylight levels, internal blinds were needed to shut down more often/time during day hours, which might create negative impact on patients' clinical improvement due to lack of outdoor views.

The design of simulated venetian blinds did not allow the direct sunlight into the space and transmitted 25% of diffuse daylight compared to the case when the blinds were removed. That was a generic blind system model, supported by DAYSIM, under the simple dynamic shading device mode. The blinds remained fully lowered to avoid glare as soon as direct sunlight above $50W/m^2$ hits the test point and re-opened as soon as the sunlight reduced below $50W/m^2$. It is also possible to enjoy the maximum use of increased daylight level by using specially designed blinds which will not generic in nature but interactive/change continuously (not fixed to $50W/m^2$) and allow 0%-100% of outdoor daylight throughout the daylight hours to increase DA levels without increasing glare. It is also important to consider that with higher daylight illumination, high heat gain and UVR can enter through the windows into the space and could be harmful to patients.

6.7. Strategies to ensure vitamin D metabolism for hospital patients

Individuals are always physiologically and psychologically keened to enjoy the rhythms and changes of the outdoor world. Individual's preference for daylight does not always justified by the estimation of energy savings and/or comfort perception. It is well known from research that when individual have to interact with nature, they are tolerable to a wider range of environmental conditions. Natural ventilation, outdoor views and daylight give to the occupants a sensation that they are in closer contact with nature and for that reason, they are more tolerable to a wider range of conditions (Gallou, 2005). Being a full spectrum light, the natural quality of daylight is highly desirable (Kim, 1997) for hospital patients and should not be ignored while designing hospital buildings.

One of the clearest beneficial effects of exposure of sunlight on skin is the production of vitamin D (DE, 1996), which is important for skeletal health and calcium metabolism (Kovats, 2008). There is a possibility that over exposure to sunlight can cause suppression of the immune system (Kovats, 2008; Longstreth, et al., 1998) and other health hazards for example skin cancer (Kovats, 2008), cataract (Taylor et al., 1988), sunburn and suntan (HPA, 2002). Determination of how daylight can be maintained for inhabitants of a building without the adverse consequences of exposure to damaging UVR from sunlight, involves a high degree of complexity. A number of studies have investigated the role of UVR in maintaining vitamin D levels and the clinical importance of vitamin D (ICNIRP, 2006; Holick, 2004); further research is needed to investigate the associations and to define the optimum levels of vitamin D for individuals. Researchers are trying to estimate the amount of the sun exposure individuals actually need, but the number of successful research is few and the results are inconsistent. It is too early to certain how much vitamin D people exactly need and how levels can best be increased (Kovats, 2008).

Washington University School of Medicine conducted a study on a population of normal white adults living in St. Louis and found some 70-90% of the vitamin D activity in blood samples was accountable to vitamin D received from sunlight. The investigators concluded that sunlight was vastly more important than food as a source of vitamin D (Wurtman, 1975). Recently, Dr. Holick from Boston University describes, ‘Sensible sun exposure can provide an adequate amount of vitamin D... Exposure of arms and legs for 5 to 30 minutes (depending on time of day, season latitude, and skin pigmentation) between the hours of 10:00 AM and 3:00 PM twice a week is often adequate’ (Holick, 2007: p.277). Therefore, the requirement of daylight for vitamin D metabolism can be easily fulfilled by individuals who spent some parts of the day in outdoor activities, but it is critical to meet the physical need of daylight for individuals who spend several days into indoors continuously, for example hospital patients. This PhD research recommends to provide scope of getting direct contact of sunlight, in the design of hospital buildings by incorporating semi-open or open to sky spaces (e.g. verandas, and roof top or terrace gardens) with in-patients rooms, or connected with common public spaces (e.g. corridors and lobbies). During field survey, the researcher observed many patients walking into the corridors of the in-patient units to overcome the post-operative dilemmas. A veranda or roof top garden on the podium which is easily accessible to patients could be a perfect place to release patients' trauma, as well as meet the requirement of vitamin D metabolism (Figure 6.2 and Figure 6.3).

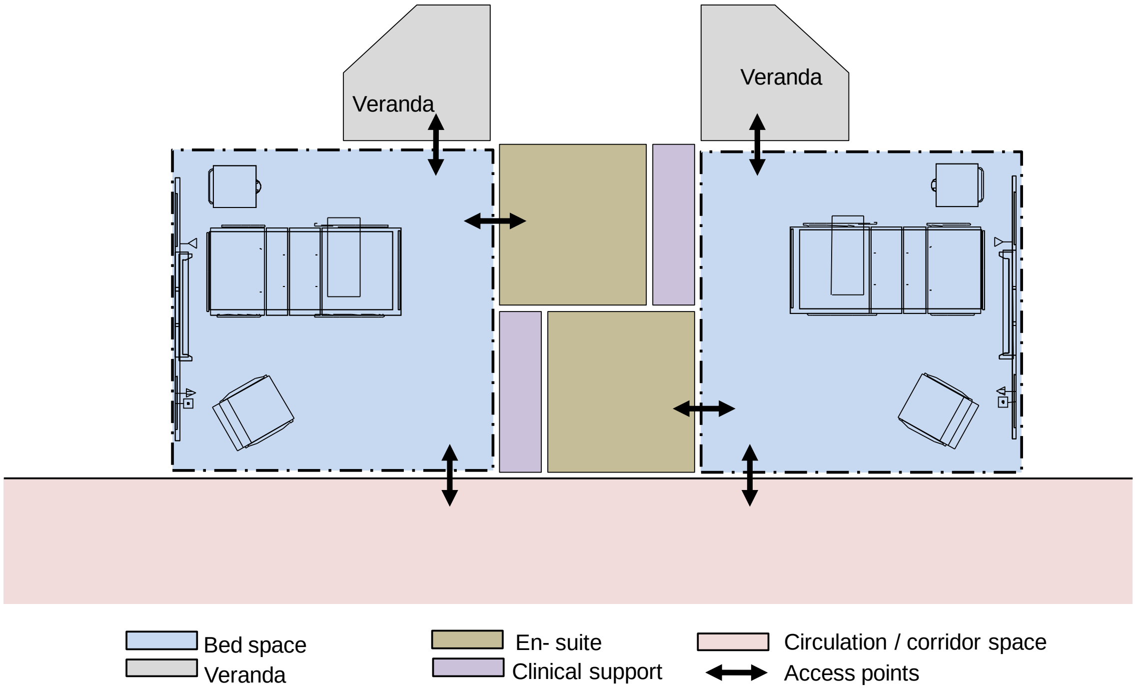


Figure 6.2: Verandas connected with inpatient rooms.

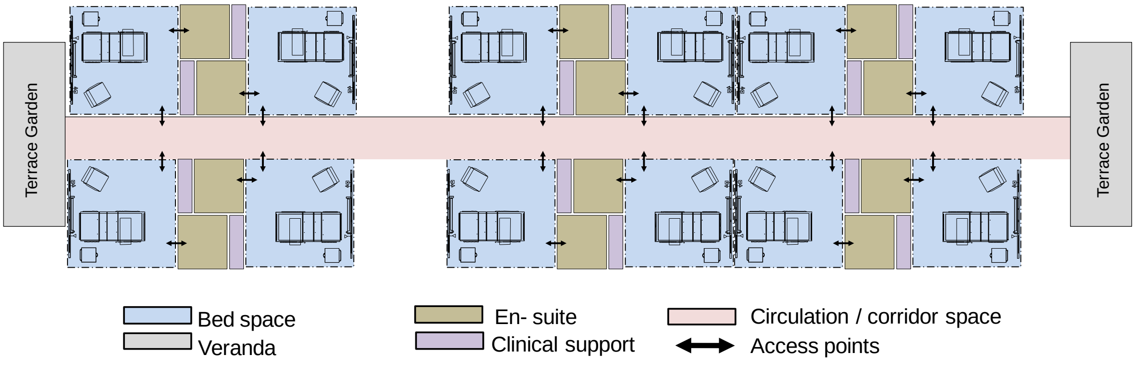


Figure 6.3: Terrace gardens connected with common public spaces(corridoors).

6.8. Strategies to protect hospital patients from higher levels of UVB

Although, the main source of UVR is the sun, different elements in the environment can act as reflector of UVR, emitted from the sun, for example sky, cloud, hills, surrounding buildings and ground (Figure 6.4). Individuals' exposure to UVR is not always proportional with the ambient UVR levels in the environment but depends more on their behaviour and protection measures adopted (CIESIN, 2008; HPA, 2002). For example participation in outdoor activities or wearing lighter clothing can increase the risk, on the other hand, wearing a wide-brimmed hat, use of the sun cream, avoidance of the sun and staying under the shades could be highly beneficial (ONS, 1997) and mitigate the effects of the anticipated increase in UVR levels within the environment. As the increase of UVR in outdoor environment has possibility to increase the indoor UVR exposures, daylight designers and researchers need to consider how this increased level of indoor UVR can be taken into account during the daylight design of interior environment. The issues of increased levels of UVR are more important when it is related to the therapeutic design of daylight environment of hospital rooms where patients can spend long times close to windows (Figure 6.5), and have risk to receive long time exposure of UVB. The threat of UVR is more prominent to individuals, because UVR cannot be seen similar to visible radiation (as light) or even felt similar to infrared radiation (as heat), but it can cause damage to the biological organism of the patients.

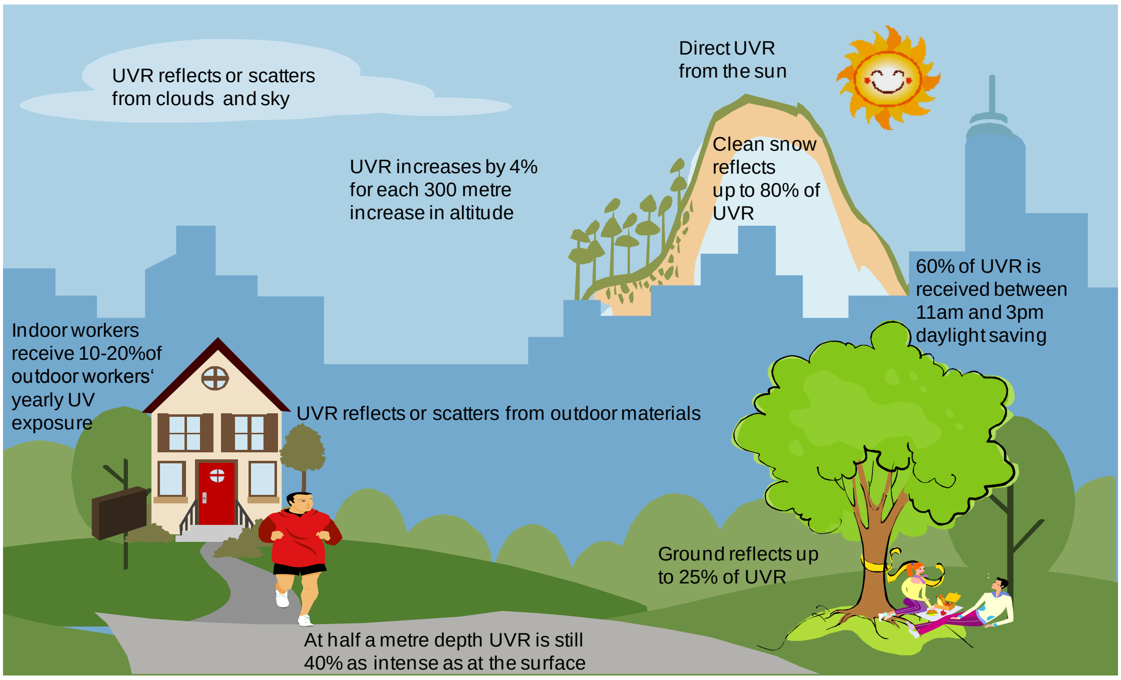


Figure 6.4: Different elements in the environment that can act as direct or indirect source of UVR exposure (adapted from: CCV, 2004).

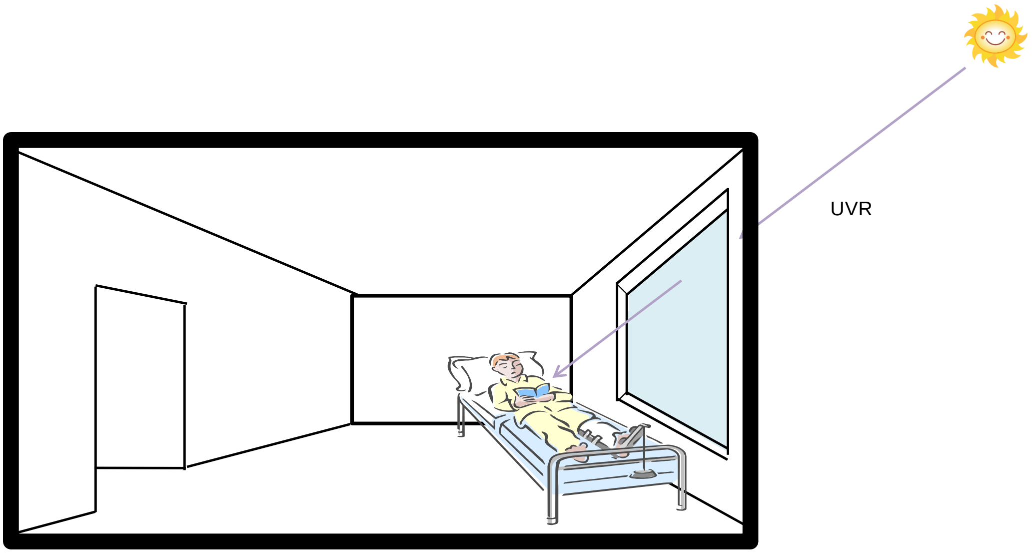


Figure 6.5: Patients might spend long times close to window in hospital rooms and have risk to receive higher UVB.

Patients inside hospital rooms can receive UVR from three significant sources: directly from the sun; reflected from the environment; and scattered from the open sky/cloud (Figure 6.6). It is evident that, if a patient is not directly under the sun and stays far away from windows, there is still a possibility to be exposed to substantial UVR from reflected surroundings and open skies. Brief descriptions of available techniques are mentioned below to protect individuals from UVR when inside hospital rooms.

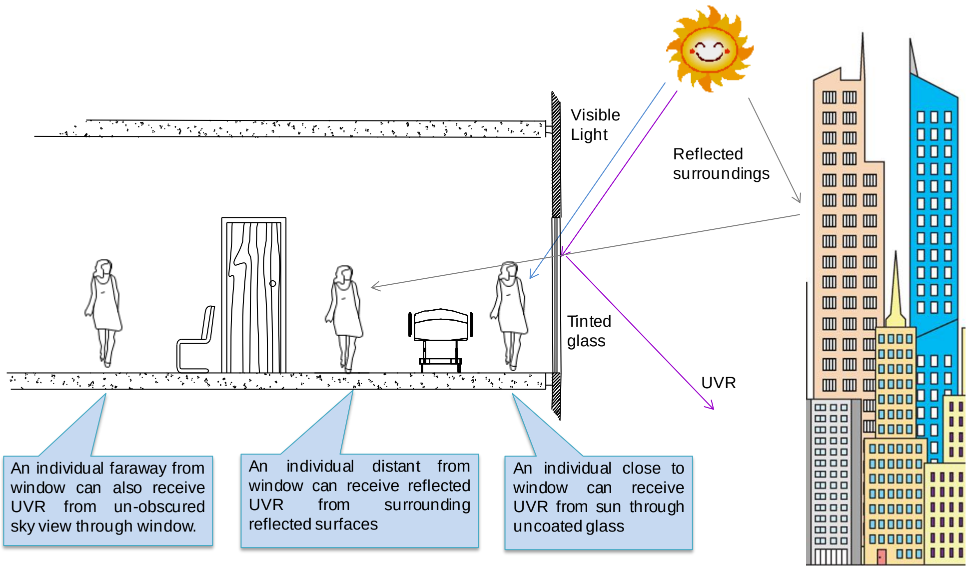


Figure 6.6: Individuals inside in-patient rooms can receive UVR from different distances from window; however, tinted glass can be used to allow visible light to pass but screen out UVR.

6.8.1. Window protection

The potential of receiving UVR through windows depend largely on the, how much time the occupants spent near windows. In a hospital in-patient room, patients who are largely stationary on beds, if stay long time continuously near windows, the risk to UVR over-exposure is considerably higher than a person in a residential building who spent little time near windows. Tinted window glasses can be used to filter out UVR as illustrated in Figure 6.7 as much as 99.9%. How much tinting is required can be assessed according to the potential risk of users. According to Australian Radiation Protection and Nuclear Safety Agency (ARPANSA, 2008), the rating for ultraviolet protection factor (UPF) is 10 for house window glass (10% of solar UVR will pass through and the glass will absorb 90% UVR) and this glass will create only moderate protection against solar UVR. UPF of 50+ is recommended for office building glass, means less than 1% of UVR will pass through and 99% will be absorbed. This glass provides excellent UVR protection. According to the functions of the buildings, specific type of glasses should be used. Appropriate type of glasses can also reduce the energy cost of the buildings by coordinating lighting and heating requirements.

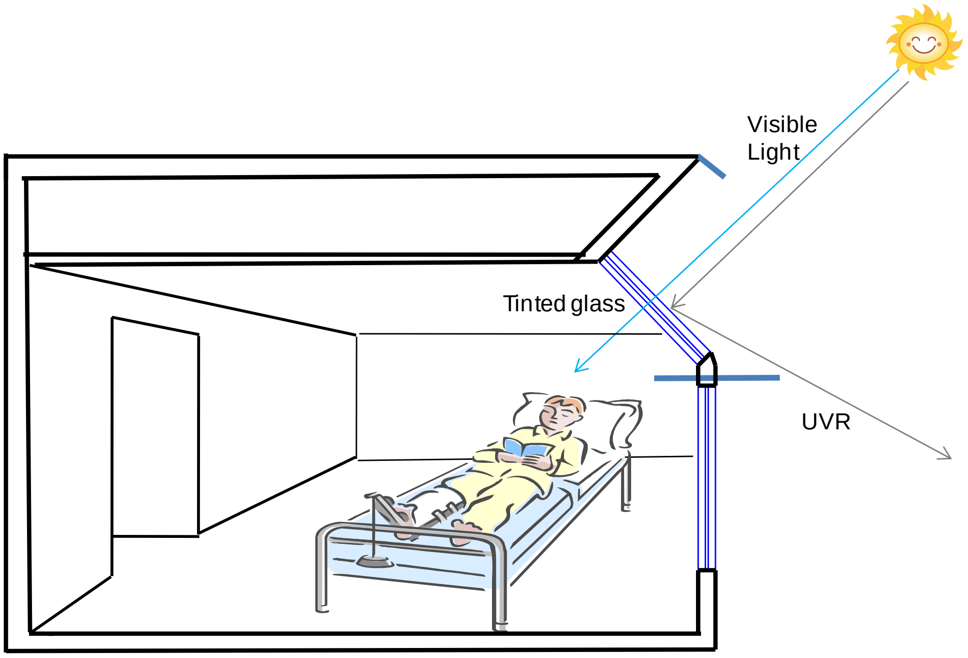


Figure 6.7: Tint should allow as much daylight as possible and reflect as much UVR as possible.

Considering the importance of daylight for hospital patients and location of hospital beds near to windows, it can be concluded that a higher protection of UVR is required by tinting, however, a higher amount of tint will also reduce the amount of daylight passing through windows. Colour tints are more effective but will reduce the indoor daylight level severely and have possibility to reduce the therapeutic potentiality of the space. Larger windows will be required with tinting glasses to achieve the same therapeutic potential. The colour of tint is also important. For example, bluish tint is more preferable compared to bronze or gray tint (Pechacek, 2008). Tint should allow as much daylight as possible and reflect as much UVR as possible (Figure 6.7). The reflected UVB could be a threat for a neighbour building, if not sufficiently protected, and/or individuals working outdoors (discussed in Section 6.8.2).

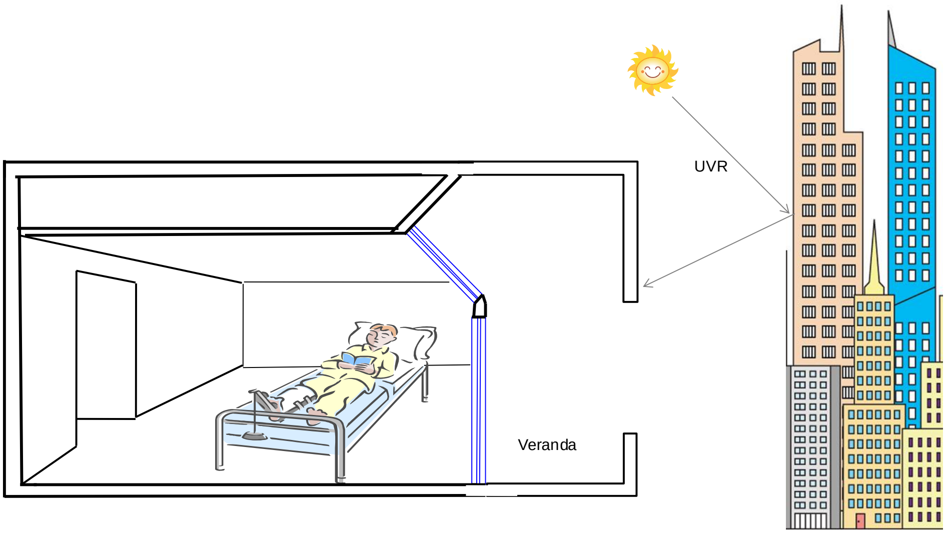


Figure 6.8: Veranda in front of the windows or openings can protect UVR but will reduce the available daylight of the room.

6.8.2. Protection from reflected surroundings

In urban areas, many vertical and horizontal surfaces can act as reflectors of UVR to patients who are inside the hospital rooms (Figure 6.6). Reflective surfaces such as concrete, metal, snow and water can bounce off a considerable amount of UVR. Therefore, white painted facades, light coloured concrete, polished aluminium, reflecting glasses and other types of metallic surfaces which could act as a reflector should be avoided as exterior building material. These reflective surfaces can reduce the effects of other protection measures (e.g. tinting). In a built urban environment it is difficult to control the character of neighbour buildings. As an alternative, UVR protection can be done by additional movable and temporary shade structures for openings made of tinting films, clothes or plastic roofing materials. Permanent protection of openings can be done by shading, ranges from simple shades (e.g. shade screens, fins, venetian blinds, miniature louvers and roller shades) to complete verandas. However, a complete veranda in front of the windows or openings can also reduce the available daylight level in the space and will reduce therapeutic potentialities of the space.

6.8.3. Design window shades with consideration of the period of UV index

The threat of UVR exposure for a location is highly related to the sun elevation, which is fixed with time of day in a particular date of the year, and less on the temperature of the day. The outdoor temperature of a sunny day at 12:00 PM and 4:00 PM may be same or even higher at 4:00 PM but potential risk of UVR exposure is higher at 12:00 PM. It is necessary to know the critical hours when the UV index is the maximum in environment.

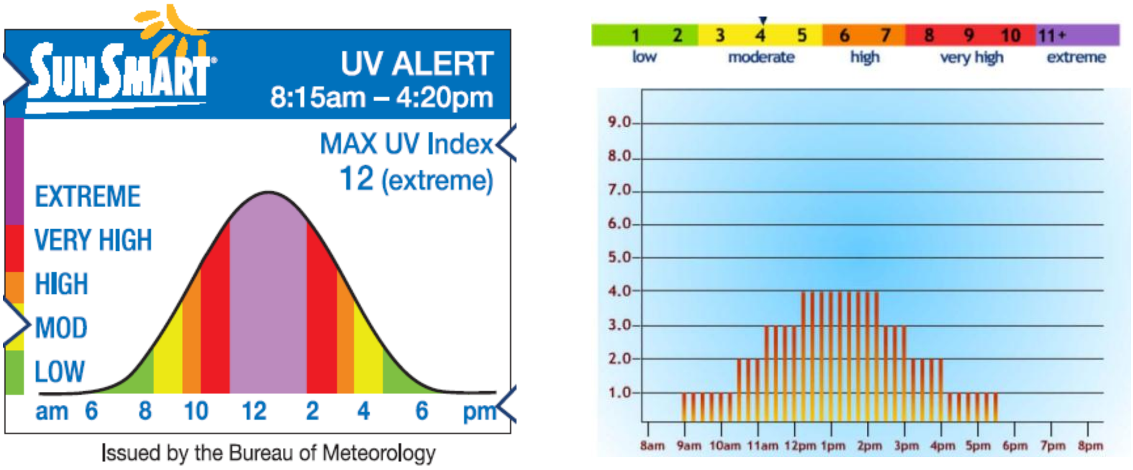


Figure 6.9: The SunSmart UV alert for critical hours of UV for Australia (at left; adapted from: CA, 2009) and recent trend of presenting UV index in full numbers(at right; adapted from: WN, 2011).

In the left-hand side of Figure 6.9 shows a typical SunSmart UV alert for Australia which is reported daily on Australian Government’s Bureau of Meteorology website (CA, 2009). The recent trend of presenting UV index is as a full number similar to a diagram shown in the right hand side of Figure 6.9. Whatever is the form of representation it is evident from the Figure 6.9 that UV is high during noontimes (11:00

AM to 03:00 PM) and peak at 12:00 PM. The reason is, UVR rays need to pass through thicker layers of ozonosphere during mornings and evenings compared to noontimes (Figure 6.10). Architectural shading systems e.g. sunshade, overhangs, light shelves, vertical and horizontal blinds need to be designed to protect the interior during UV peak times with compliance with local climate. Shading devices can be positioned outside the glazing, between the glazings, or at the interior surface. The systems can be static or operable, controlled either by occupants or with motorized, automated controls with respect to time (Joarder, 2007). The design of sky window configurations under this research was developed in such manners that the sky window will be protected from direct sunlight during noontimes when the sun is near zenith (Figure 6.10).

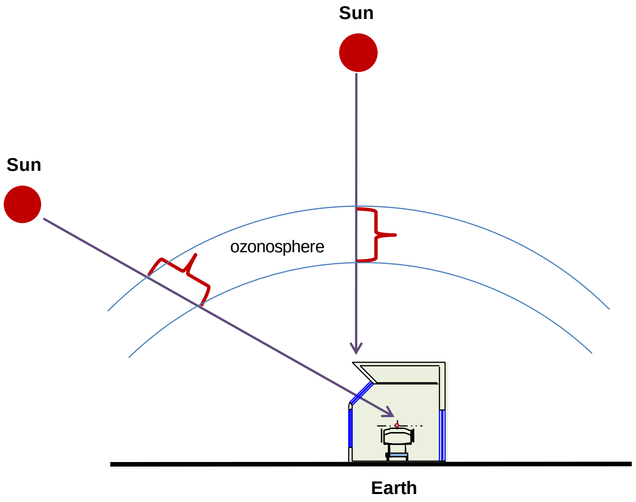


Figure 6.10: UVR rays need to pass through thicker layers of ozonosphere during morning compared to noontimes.

6.8.4. Protection by plantation surrounding the hospital buildings

Individuals, far away from the windows, still have possibilities to be exposed to UVR from un-obscured sky. Shade trees surrounding the buildings can protect buildings and individuals from damaging UVR in a very natural way. Visible and UV radiations reflect from leaves of trees (Figure 6.11; left). Though some of the sun radiation passes through a single leaf, when it tries to pass through the tree crowns, rays need to encounter many leaves and have little chances to reach to the grounds or opposite surfaces (Figure 6.11; right). The presence of trees can thus reduce the amount of UVR exposures to the surrounding people and structures.

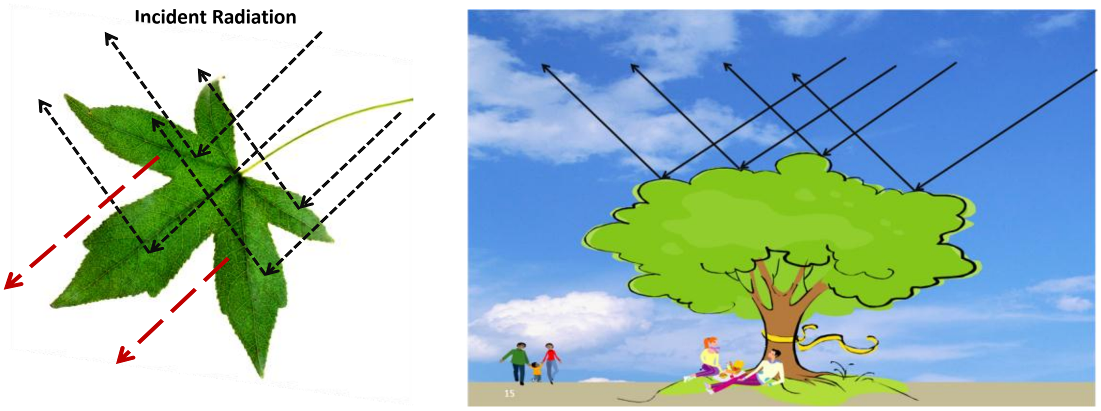


Figure 6.11: Visible radiation and UVR reflects off of a leaf and an individual who is not directly under tree still get protection from UVR as tree blocks scattered UVR across the sky (adapted from MacDonald et al., 2006).

Heisler, et al. (2000) measured the amount of radiation in six types of areas around a tree to find out the reduction of UVB level in sunny and shady areas by special sensor equipment (pyranometer sensor). Table 6.2 summarises the results of his experimental study. It was found that the reduction in UVB radiation was more in sunny areas near a tree (39% for summer measurement) compared to the reduction in visible radiation (3% for summer measurement). The reason behind this was that the UVB radiation scatters widely across the sky, and when individuals stand close to trees but still under the sun, trees block part of the sky. When part of the sky is blocked, some of the UVB radiation is also blocked, even though the visible radiation does not reduce at all (Figure 6.11) (Heisler, et al., 2000). Similarly, when individuals are inside rooms, near or far from windows, they can still be exposed to some part of the sky but trees surrounding the buildings can block/reduce the exposures (Figure 6.12).

Table 6.2: Average percent reduction in the sun visible radiation and invisible UVB radiation below a street tree canopy (source: MacDonald et al., 2006).

Area near tree canopy	**Percent reduction in UVB radiation**	**Percent reduction in visible radiation**
Sunlit areas in Summer (with leaves)	39	3
Shady area in Summer (with leaves)	63	84
Sunlit area in winter (no leaves)	40	6
Shady area in winter (no leaves)	56	73
Sunlit area in winter with a building nearby (no leaves)	59	5
Shady area in winter with a building nearby (no leaves)	70	47

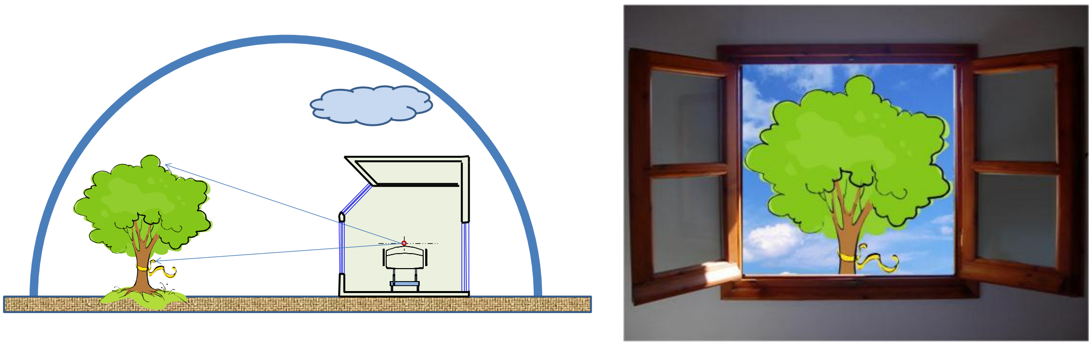


Figure 6.12: An individual who is indoor can get protection from scattered UVB radiation across the sky by a tree.

It is also evident from Table 6.2 that visible radiation on a space can be substantially reduced (84% for summer measurement) if shaded by trees. The distance of the hospital windows from trees should be sufficient, so that the windows are out of the shadow ranges of the trees for the maximum times of the daylight hours, but patients have a good view to the trees and trees will obscure the view of the open sky (Figure 6.12)

An outdoor natural view to plants are also found positive to patients' recovery process psychologically (Kaplan, 2001; Kaplan et al., 1995; Ulrich, 1979), physiologically (Chang et al., 2005; Lohr et al., 1996; Coleman et al., 1995; Ulrich et al., 1991; Doxon et al., 1987; Verderber et al., 1987), emotionally (Adachi et al., 2000; Ulrich et al., 1991; Ulrich, 1981), and in cognitive changes (Tennessen et al., 1995; Cimprich, 1993; Hartig et al., 1991). Several studies also confirmed that presence of nature contributes to reduce stress, pain and analgesics requirements of hospital patients (Park et al., 2004; Diette et al., 2003; Dilani, 2001; Wells-Thorpe, 2001; Lohr et al., 2000; Ulrich, 1997, 1993, 1992). A comparison between the patients looking at a built environment and exposed to nature, shows that later group recovered faster and more completely (Ulrich, 1984). Unfortunately, in urban areas, hospital buildings with natural premises are rare (Choi, 2005).

6.9. Benefits of daylit hospitals in addition to patient LoS reduction

The performance of daylight in a building primarily depends on a combination of building latitude, orientation, form, geometry and environmental factors that block and reflect daylight, e.g. density of built environment and presence of obstructions and trees. The admittance of daylight in a particular room depends on the size and placement of apertures, details of glazing and shading devices, but the design optimized for cloudy conditions needs control to face the bright sunny days. With appropriate architectural detailing, materials and devices, proper control can be achieved. In terms of energy benefit, fully integrated daylighting and electric lighting solutions are needed to minimize energy use and power demand. The physiological, emotional and aesthetic aspects of daylight have to be taken into account during the design process to optimise occupants' health, comfort, performance and satisfaction. To optimise the benefits, daylighting strategies need to consider the factors¸ such as, building type and climate of the region, which are fixed prior to the design phase and factors which may vary after occupancy such as changes of functionality and climate change (GBC, 2004).

In a healthcare facility, patients, visitors, and staff are mostly exposed to artificial lights. In most of the cases artificial lights have deficiency in wavelength (colour) and intensity than the sunlight (White, 2006). Most artificial lights are composed of wavelengths that are concentrated in limited areas of the visible light spectrum for example orange to red end, or yellow to red end of the spectrum (Edwards et al., 2002). The maximum spectral energy distribution can be provided by full-spectrum fluorescent lights, but light levels are much lower compared to daylight levels. The spectra of cool-white fluorescent, incandescent and high-pressure sodium vapour light sources appear to fall short to cover the entire photobiologic action spectra important for human (Hathaway et al., 1992). Sunlight has a continuous spectrum of colours ranging from the short wavelengths of invisible ultraviolet light through blue, green, yellow, and into the infrared waves (Liberman, 1991), which is necessary to run many biological functions properly. As a source of illumination daylight is mostly preferred over artificial lighting by individuals. In situations, where the level of light is same for both daylight and electric light, individuals prefer to work under daylight due to physiological support. Choi (2005: p.17) emphasised, 'for human health reasons, electric light should not be substituted for daylight'. Only the natural light provides the complete spectral energy distribution essential for most of the biological functions essential for human body. According to Pechacek et al., (2008: p.22), 'except for some specific emerging technologies, artificial illumination cannot substitute for the temporal cues (alerting, phase shifting, etc.) of daylighting, and used wrongly may, in fact, confound circadian organization'.

Daylight is one of the most significant natural elements available to architects and designers to enhance the visual appearances of interiors. The place of daylight in therapeutic built environment is highly significant. With respect to hospital buildings, the benefits of sunlight and windows in patient rooms have been acknowledged for more than half a century (Loftness et al., 2006; Karolides et al., 2005; Ulrich et al., 2004). From ancient times, designers have used daylight within buildings to make architectural statements. However, strong arguments for daylight inclusion in building design are associated with health/performance and energy benefits. This research focuses on the benefits of daylight inclusion to reduce patient LoS in hospitals. Hence, inclusions of daylight, as a source of light in addition to therapeutic purpose, have multiple benefits for hospital buildings and its occupants, for example energy, cost, environment, health and performance benefits.

From a global perspective, the finite resources of energy must be conserved (Philips, 2002), and energy consciousness in the design of hospital lighting environment is essential. It is also important to reduce the use of fossil fuel GHG-emitting energy for lighting purpose to reduce the impact of rapid climate change. The primary strategy for energy savings in a building should be to exploit the most abundant source of sunlight (Phillips, 2004). Using daylight for interior illumination, reliance on artificial lighting sources can be minimised, resulting saving on lighting energy (Muneer et al., 2000). With the help of advanced light sources, design strategies and control systems, 25-50% of electric lighting energy use can be reduced, and addition of daylight can reduce this energy further by 75% (Clanton et al., 2004). This reduction in lighting energy represents 5% of total energy consumption of a building and can be achieved by conscious daylighting design (Chapman, 2004). It is also possible to reduce air conditioning loads of buildings by proper controlling in daylighting to reduce use of electrical lighting and minimise solar heat gain (Franzetti et al., 2004). During cooling load periods proper sun shadings can mitigate solar heat gain. During heating load periods, solar heat gains with daylighting can be beneficial. With appropriate daylighting design both the overall heating and cooling loads can be reduced for a building (Rogers et al., 2006). Based on twelve international case studies, CBPD confirmed that 27-88% annual energy loads can be reduced by improved lighting design (Loftness et al., 2006). Integration, automation and optimisation of the daylight, electric light and mechanical systems are, therefore, important for the maximum benefit.

Daylight can be used to reduce the pressure on electrical energy for lighting as well as GHG production, at the same time daylight itself can be a source of electrical energy production without emitting GHG, i.e., use of photovoltatics (PV) can generate electricity from solar energy. PV can generate electricity on cloudy days with the help of only daylight, as direct sunlight is not necessary to run PV.

To estimate the savings from a non-residential building, Ternoey (1999) presented a comparison for 75 years total costs of a perfectly designed daylit building with a professionally designed typical standard building of same footprint (see, Appendix E). Analysis shows that the initial construction cost of daylit building is 10% higher than standard building, but provision of daylighting reduces 61% in air-conditioning tonnage, 56% in installed fan horsepower and 52% in initial mechanical budget, jointly results nearly equal first cost for two possible solutions; however, lifetime maintenance cost drop 16% for daylit building. Finally, by reducing the need of electric lighting during daytime with lowering peak and solar cooling loads annually, the daylit building reduces lifetime utility costs by 57%. As a result, the daylit building reduces 20% of total lifetime costs, where the savings from daylight building is greater than the original construction cost of the standard building (Ternoey, 1999).

Daylight is indispensable both as a primary source of illumination as well as an ingredient of drama, excitement and as dynamism in the architecture and aesthetics of spaces (Ahmed and Joarder, 2007). Proper interior lighting design balanced with daylight, can improve productivity (Wilkins, 1993). With reducing energy consumption of the building, daylight plays a central role to provide views and contact with the outside world and limits psychological and physiological threat creates by lack of light (Steemers, 1994). There is a growing acknowledgement that daylight produces positive impact on individuals’ physiology and psychology (Robbins, 1986). Daylight can create enjoyable interiors with variety in brightness, refreshment and relaxation with an outside view (Bell and Burt, 1995). As a result, individuals actually perform better when exposed to daylight (Boyce et al., 2003).

A growing number of references suggest a strong correlation between daylight and performance. Daylit buildings can increase human performance because people enjoy the environment and will stay a little longer and/or return more frequently to work, study or shop. The presences of windows in the workplace and access to daylight have been linked with increased satisfaction with the work environment (Zullo, 2007). Individuals' productivity can be increased 0.7-23% with improved lighting design (Loftness et al., 2006). In some daylit schools, students have been found to have higher standard test scores, noticeably less disciplinary problems and absenteeism (Hathaway et al., 1992). Heschong (2002) found that students near windows with more daylight have scored 7% to 18% higher on standardized tests compared to those with less daylight sited far from the windows in classrooms. In a reanalysis on daylight and human performance, the Heschong Mahone Group (HMG, 2003a; 2003b) reported that students of mostly daylited classrooms progressed 26% faster on their reading examinations and 20% faster on mathematics tests compared to those of least amount of daylited classrooms. Windows in classrooms creates significant differences in stress, concentration and growth hormones that reflect on students' psychological and physical developments (Kuller et al., 1992). In elementary daylit schools children grew on average 2cm per year taller than ordinary schools. Customers' book collections in daylit libraries are used up to 50% more than those in traditional library designs. Retail sales increases of 8-12% were recorded in daylit areas (Ternoey, 1999). Adequate daylight enhances performance of individuals and poor lighting conditions can result in deficiencies (Joseph, 2006).

Therefore, in addition to accelerate patients' recovery, it is expected that daylit hospitals, designed for therapeutic purpose, will also enhance the performance of visual tasks of staff (Joseph, 2006). The quality of daylight influence hospital staff morale and productivity. Hence, the advantages of daylit hospital building have extended beyond the objective achievements of cost and energy to subjective benefits of hospital patients' and stuff health and performances.

However, while designing with daylight, it is important to consider that all the effects of daylight may not be beneficial for the users. Excess light, heat and radiation may enter with the daylight, and in case of hospitals, there are risks of contaminations and cross infections through openings. Ternoey (1999) suggested that many inexperienced daylight designers try to achieve such high amounts of foot-candles with rooms which can create excessive glare within the space with excessive solar heat gains (which increases space cooling loads) thus wiping out savings from electric lighting. Consequently, with the increase of glazed areas risk of glare, overheating, high cooling loads and thermal discomfort increased (USGBC, 2008). An informed balance must be struck between energy saved and therapeutic gain from daylight inclusion in the hospital rooms, and the threat associated with unwanted daylight. Research is ongoing to make daylight more useful source of energy and comfort, and less harmful to the occupants.

6.10. Summary

This chapter has discussed the architectural design strategies for incorporation of therapeutic effect of daylight in the design of in-patient rooms to reduce patient LoS in hospitals with respect to the extended outputs of the developed MLR models from retrospective field investigation data described in Chapter 4, and experiences of prospective simulation study done in Chapter 5 of this research, with consideration of some issue highlighted in the literature review of Chapter 2, i.e. vitamin D metabolism and UVR protection. The discussion has included different strategies to ensure therapeutic benefit of daylight for hospital patients and also to protect patients from adverse effect of excess daylight. This chapter ends with the information of expected additional benefits of daylit hospital in-patient rooms along with acceleration of clinical recovery (e.g. energy savings of the building and performance of hospital stuff) based on the references of previous literature. This chapter leads to the presentation of the achievement of the research objectives in next Chapter 7, which concludes the thesis with key contributions to knowledge, limitation of this research and recommendations for further research.

CHAPTER 7
Conclusion

7.1. Introduction

The first chapter introduced the thesis. The literature review of Chapter 2 described the positive and negative impacts of daylight on patient health and wellbeing considering the present and the future climates, and highlighted the existing knowledge gap on sound evidence based relationships between daylight intensities and patient LoS. The third chapter elaborated the detail steps of the two methodologies applied in this thesis: field investigation and simulation study. Chapter 4 presents the activities and findings of field studies to establish the statistical relationship between daylight intensity and patient LoS in a general hospital environment from two month pilot and 12 month principal study. Additional field experiments were done to use the principal study data to identify the range of daylight intensities within which reduction of patient LoS is expected and based on these exercise goals for simulation study were fixed for Chapter 5. In Chapter 5, the researcher developed and implemented a design concept to enhance therapeutic effect of daylight in the architectural design of a hospital in-patient room, effectively, by prospective simulation study. The simulation study was also done in Chapter 5 with the future climate data to conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit, hospital in-patient rooms, designed for therapeutic purpose. Chapter 6 elaborated the development of the architectural design strategies as the extended outputs of the activities done in Chapter 2, Chapter 4 and Chapter 5. This chapter includes the key strategies as a summary of Chapter 6. This chapter concludes the thesis by summarising main findings, limitations and areas for further research.

The following sections present the achievement of the objectives of the research.

7.2. Achievement of the objectives

The objectives of the research, developed in Chapter 1, are re-stated as:

Objective 1: To understand the impact of daylight (positive and negative) on patients’ psychological, physical, and physiological health.

Objective 2: To establish quantitative relationship between daylight intensities and patient LoS under a general hospital environment.

Objective 3: To identify the range of daylight intensities within which patient LoS inside in-patient room is expected to be reduced.

Objective 4: To develop a concept to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, effectively.

Objective 5: To conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose.

7.2.1. Objective one

The first objective was *to understand the impact of daylight (positive and negative) on patients’ psychological, physical, and physiological health*. In order to achieve this objective literature review on the effect of daylight on the individuals was conducted. The literature review confirmed that daylight: improves sleep (Lahti et al., 2006; Roenneberg et al., 2003) and circadian rhythms (Burgess et al., 2006); treats SAD (Wirz-Justice et al., 1996); reduces agitation among elderly patients with dementia (Lovell et al., 1995); reduces depression (Ljubicic, et al., 2007); and reduces the stay time of patients with unipolar (Kecskes et al., 2003) and bipolar (Benedetti et al., 2001) disorder, and with severe depression (Beauchemin et al., 1996). The psychological benefits from daylight may catalyze clinical recovery of patients (Pechacek, 2008). Daylight reduces LoS for hospital patients (Choi et al., 2012). Studies show that, elective cervical and lumbar spinal surgery patients exposed to an increased intensity of daylight (average 46% higher) experienced less perceived stress, marginally less pain, took 22% less analgesic medication per hour and 21% less pain medication costs (Walch et al., 2005).

The Lighting Research Centre at Rensselaer Polytechnic Institute has revealed that exposure to daylight in a moderate level can slow non-skin cancer cell development (Bullough et al., 2006) and reduce hospital mortality from NHL (Hughes et al., 2004), ovarian (Lefkowitz et al., 1994), colon, prostate (Freedman et al, 2002), breast, and lung cancer (Lim et al., 2006); however, the epidemiological evidence in support of this is weak and controversial (de Gruijl, 1997). Exposure to daylight also reduces hospital mortality, experiencing myocardial infarction (Beauchemin et al, 1998) and reduces the risks of rickets in childhood, and of osteomalacia and fractures in adults (Whyte et al., 2005; Holick, 2004; Utiger, 1998).

In contrast, the literature review also emphasised that, excess daylight has possibilities to do more harm than good. Among the negative impact: there is a possibility that UVB exposure of daylight can cause suppression of the immune response (Kovats, 2008; Longstreth et al., 1998), cataract (UNEP, 2003), sunburn and skin cancer (HPA, 2002). There is also a risk to increase the adverse impact of daylight due to climate change. Rapidly accelerating climate change may deplete the stratospheric ozone layer, decrease cloud cover and reduce the green. As a result, there are possibilities that more downward shortwave radiation will reach to the earth in the future. As, indoor occupants have a possibility to receive 10-20% of UVR (CCV, 2004), compared to outdoor workers, this 10-20% UVR inside the buildings can be a threat for some particular geographical locations in some periods of the year.

As a summary, it can be concluded from the outcomes of literature review that, for an overall healthy progress of hospital patients both psychological and physiological improvements are necessary. Impact of daylight on patients’ psychology and physical diseases related to bones and cancers are well established. The physiological impact of daylight on patient health during hospital staying periods were needed to be established based on sound evidence. To establish sound evidence field investigations were done in this research. The literature review also emphasised that the strategies for incorporation of therapeutic effect of daylight in the architectural design of hospital in-patient rooms should consider both positive and negative effects of daylight.

7.2.2. Objective two

The second objective was *to establish quantitative relationship between daylight intensities and patient LoS under a general hospital environment*. In order to achieve this objective two field investigations were done to collect data from an existing hospital building (Square Hospital, Dhaka, Bangladesh): pilot study and principle study. As outputs of two field investigations, this research presents two MLR models.

The first MLR model is the output of the pilot study continued for two months. Expressed in terms of the variables used, the MLR equation can be written as Equation 7.1. The coefficient estimates of MLR model derived from pilot study data shows that, while holding the other explanatory variables (POV, MAP, HR, DM, SPO2 and FBS) constant, the increase of 100 lx of average daylight intensity of the room reduces heart surgery patient LoS by, on average 4 hours.

$$\begin{aligned} LoS &= 1086.209 - 0.04(Daylight) - 13.495(POV) - 2.365(MAP) - 1.444(HR) \\ &\quad + 38.049(DM) - 5.839(SPO2) - 10.517(FBS) \end{aligned} \tag{7.1}$$

The second MLR model is the output of twelve month (one year) principal study. Expressed in terms of the variables used, the MLR equation can be written as Equation 7.2. The coefficient estimates of MLR model derived from principal study data shows that, while holding the other explanatory variables constant (rent of the rooms, POV, MAP, HR and DM), LoS reduced by 7 hours per 100 lx increase of daylight intensity near a point above CABG patient head.

$$\begin{aligned} LoS &= 289.891 - 0.073(Daylight) - 17.437(POV) + 0.015(Rent) \\ &\quad - 1.703(MAP) - 1.162(HR) + 73.313(DM) \end{aligned} \tag{7.2}$$

Comparing the standardized coefficients (Beta) of two room variables of both the MLR models derived from pilot and principal study (Table 4.7), it was evident that daylight is more important than POV in relation to the recovery process. The reason may be that, daylight has psychological, physical and physiological impact on patients, but outer views only have psychological effects. It was assumed that the reduction of patient LoS was due to psychological, physical and physiological improvement; as, psychological improvement consequently accelerates the rate of physiological recovery.

7.2.3. Objective three

The third objective was *to identify the range of daylight intensities within which patient LoS inside in-patient room is expected to be reduced*. In order to achieve this objective additional field experiments were conducted to use the principal study data to develop a third MLR model to confirm the daylight intensities which might be useful for hospital patients, identified from literature review.

Analysing the photobiology and daylight literature, it was attained that a minimum of 190 lx is needed to be incident on patient retinas to stimulate circadian rhythm (Pechacek et al., 2008) and illumination higher than 2000 lx will create visual and thermal discomfort (Nabil et al., 2006; 2005). The estimation of third MLR model (Equation 7.3) confirmed that the CABG patients who experienced higher (above 2000 lx) and lower (below 190 lx) levels of illumination in the maximum time inside in-patient rooms, stayed significantly higher (extra 29- 42 hours) times than the patients who experienced moderate levels of daylight (190 - 2000 lx) in the maximum time of their stay in hospital rooms. It was concluded that the range of 190-2000 lx can be considered as daylight intensities within which reduction of patient LoS is more likely to be happened. This benchmark was considered as a goal for prospective simulation study done later in this research.

$$\begin{aligned} LoS &= 242.596 + 42.337\,(lx<190) + 28.592\,(lx>2000) - 24.079\,(POV) \\ &\quad + 0.013\,(Rent) - 1.392\,(MAP) - 0.965\,(HR) + 71.310\,(DM) \end{aligned} \tag{7.3}$$

A fourth MLR model was generated by the data of the patients who experienced recommend (190 to 2000 lx) level of daylight in the maximum time of their stay in hospital rooms. Expressed in terms of the variables used, the MLR equation can be written as Equation 7.4. The coefficient estimates showed that while holding the other explanatory variables constant (rent of the rooms, MAP, HR and DM), patient LoS reduces by, on average, 8 hours per 100 lx increase of daylight intensity near a point above patient head.

$$\begin{aligned} LoS &= 159.140 - 0.082(180\ to 2000 lx) + 0.004(Rent) - 0.498(MAP) \\ &\quad - 0.428(HR) + 63.428(DM) \end{aligned} \tag{7.4}$$

7.2.4. Objective four

The fourth objective was *to develop a concept to incorporate therapeutic effect of daylight in the design of hospital in-patient rooms, effectively*. In order to achieve this objective the concept of sky window configurations was introduced for hospital rooms, and prospective simulation was done to compare and evaluate the performance of the sky window configurations with respect to the traditional standard hospital window configurations.

Most of the windows in buildings, including hospitals, are designed to satisfy the visual needs of the occupants for example light to do visual activities and enjoy outdoor views. To satisfy therapeutic needs, higher intensity of daylight is needed to be incident on patient retinas to start biological stimulation inside human body. As patients are largely stationary in hospital rooms, architects should take the opportunity to improve the design of hospital windows to concentrate higher intensity of daylight in one location.

To the best knowledge of the researcher the concept and configurations of sky window (Figure 7.1) is a new one for achieving higher intensity of daylight inside in-patient rooms to enhance therapeutic effect of daylight on hospital patients. The design of sky window configurations was developed in this research in a modular architectural form that can be implemented in single-bed in-patient unit which can be arranged both horizontally and vertically to enhance therapeutic benefit of daylight inside patient rooms. The form is not familiar to current hospital design practice (see Appendix E for current examples). As, traditional window configurations do not guarantee sufficient daylight for therapeutic purpose, sky window configurations could be a better option for achieving therapeutic benefit of daylight compared to traditional ones. To encourage the new idea (extra efforts in window design to support patients' physiological health) and give an identity (not to misinterpret with skylights) of the new concept, the term Sky Window was proposed to define the developed window system. The advantage of sky windows over skylights is that the service space (and/or upper floors), itself provide complete shade to sky window during noontimes when the sun is near zenith, and thus reduce the potentiality of excessive glare, UVR and solar heat gain during noontimes. With greater window-to-floor ratios and providing daylight from multiple directions (through facade and ceiling) sky window configurations performed better than high window configurations in increasing therapeutic effect of daylight for an imaginary patient lying on the bed far from the window. The limitation of sky window configurations is that, this option is not applicable to residential buildings and suitable for commercial buildings (e.g. hospitals, shopping centres and offices) with a void space above ceiling available for such type of modifications.

The researcher confesses that sky window configurations is neither the only nor the best solution for inclusion of therapeutic effect of daylight inside patient rooms, but better than traditional high windows to achieve therapeutic effect of daylight more effectively. It is evident from the research that changes in design of hospital windows are expected to meet the therapeutic purpose of daylight more effectively for patients. Although, this change is also likely to affect other associated factors such as cost and energy, the analysis of those is beyond the scope of this present research.

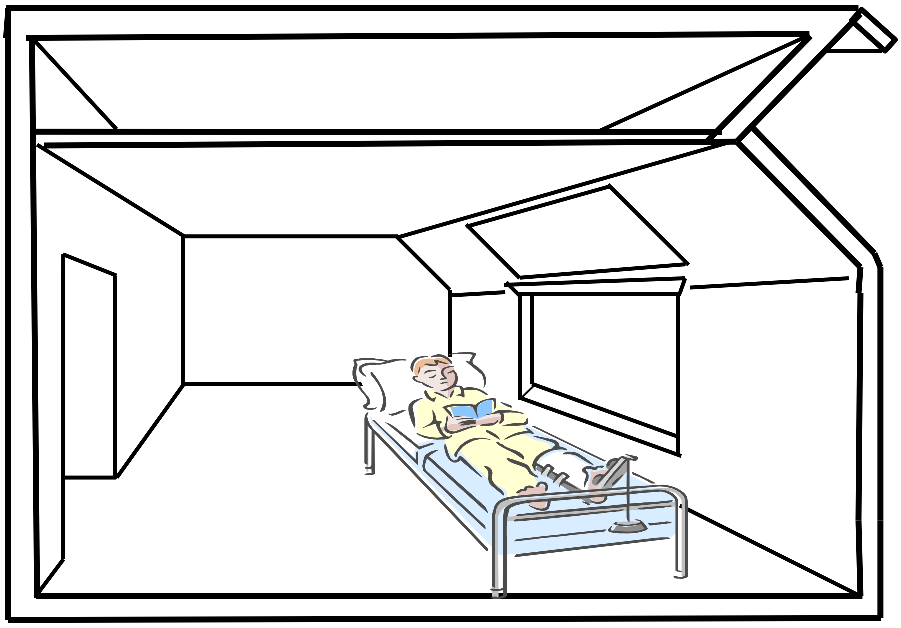


Figure 7.1: Sky window concept.

7.2.5. Objective five

The fifth objective was *to conceptualise the impact of climate change on indoor daylight levels and its contribution to daylit in-patient rooms, designed for therapeutic purpose*. In order to achieve this objective, prospective simulation study was done to evaluate the performance of the sky window configurations under different future emissions scenarios (high, medium-high, medium-low and low) under UKCIP02.

The average global radiation can raise a maximum 8.3W/m^2 in the future (2080-2100) compared to the present (1983-2004) based on CIBSE (2008) database. As a result, the evaluation of the daylighting performance of the proposed sky window configurations under different future emissions scenarios revealed that there is a possibility to increase the average indoor room illumination by a maximum 5% (average 16.58 lx considering 24 hours, and 33.23 lx considering 12 hours from 06:00 AM to 06:00 PM) in the future compared to the present with a difference from -595.54 lx to 579.03 lx.

The average indoor illumination at test point (patient head) can raise a maximum 8% (average 62.56 lx considering 24 hours and 126.46 lx considering 12 hours) in the future (2080s) compared to the present (1989) with difference from - 995 lx to 3706 lx. Comparing the average illumination increase in test point to the average increase of the room illumination (average of 63 intersecting points), it seems that average increase in illumination at test point is 3% higher than the average room illumination due to the location of patient beds near the windows.

The sky window configurations with active blind operation can protect the interior from increased daylight levels. To protect the indoors from increased daylight levels, internal blinds will be needed to shut down more often/time during day hours compared to the present, which might create a negative impact on patients' clinical improvement due to lack of outdoor views. Both daylight and POV have a significant impact on patient LoS, which was found by the analysis of field data of this PhD research.

7.3. Strategies for incorporation of therapeutic effect of daylight in the design

As the extended outputs of the synthesis of literature review, developed MLR models from retrospective field investigation data and evaluation of sky window configurations by prospective simulation study in this research, the following architectural design strategies are recommended below for effective incorporation of therapeutic effect of daylight on the design of hospital in-patient rooms.

7.3.1. Strategies for in-patient room design

- Single-bed in-patient room with a minimum depth (distance from window to back/corridor wall) is more suitable to enhance therapeutic benefit of daylight for individual patient compared to deeper multi-bed rooms.

- Beds should be placed as close as possible to windows with a minimum clear space on window side for clinical activities, and considering glare possibilities.

- Locate windows at the head sides of the patient beds to ensure the maximum daylight (without discomfort) on patient heads and better outdoor view for patients, when lying on the bed.

- While increasing window-to-floor ratios of the in-patient rooms, especial consideration should be provided to reduce discomfort, glare and solar heat gain, and to ensure uniform daylight over the rooms.

- It is preferable to locate en-suites in inner sides of the hospital buildings, keeping the outer walls of the in-patient rooms unoccupied, to achieve greater flexibility for placing and varying sizes of in-patient room windows.

- Provide easy access to semi-open or open to sky spaces (e.g. verandas) adjacent to in-patient rooms for patients to get into direct contact of daylight for some periods of the day (i.e. 5 to 30 minutes) to ensure vitamin D metabolism for patients.

7.3.2. Strategies for window design

- Design and place windows to increase the daylight intensity (under moderate level: 190- 2000 lx) at the location of patient heads inside in-patient rooms to enhance therapeutic benefit of daylight.

- In a conflicting/critical situation between daylight and POV, windows with more daylight but less outer view is preferable to windows with better views but less daylight.

- Considering the importance of daylight for hospital patients and location of hospital beds near to windows, a higher protection of UVB coating is recommended (for example, UPF above 50+) for hospital window glasses. The glass should allow as much daylight as possible with a maximum UVB protection.

- Sky window concept (with its principle to provide the maximum daylight on patient's head without discomfort and glare) can be introduced above viewing windows or in place of high windows of hospital in-patient rooms to enhance therapeutic effect of daylight more effectively.

7.3.3. Strategies for the design of window shades and blind operations

- Varying requirements of shadings for different orientations of the hospital windows should be satisfied with keeping similarities in design and sizes of the individual shades to ensure the uniformity of the architectural character of the hospital buildings, and to facilitate modular constructions.

- Design window shades with consideration of the periods of UV index. Shading devices should provide the maximum protection to interior, when the outdoor UVR is highest (i.e. noontimes). Additional movable and temporary shade structures might be necessary to protect reflected UVR from surroundings.

- To get the benefits of higher daylight intensity, due to the climate change, specially designed interactive blinds are needed to be developed which will allow 0%-100% of outdoor daylight through windows without discomfort.

- Hospital nurses should be active in blind operations and maintain a schedule for opening and closing the blinds similar to give medications to patients, to maximise daylight inside patient rooms without glare (therapeutic effect of daylight on patients are similar to the effect of medicine).

7.3.4. Strategies for the design of in-patient room surrounding

- Avoid reflective surfaces such as white painted facades, light coloured concrete, polished aluminium, reflecting glass and other types of metallic surfaces as exterior building material surrounding hospital buildings, which might be a source of reflective UVR and glare for patients staying inside in-patient rooms.

- Plant shade trees surround the hospital buildings at a reasonable distance, so that the patients can enjoy the view of the tree crowns while inside in-patient rooms, but the trees should not create shade on windows during most of the daylight hours.

7.4. Contribution to knowledge

There are key contributions to knowledge that are the outcome of this research. These comprise the following areas.

7.4.1. Contribution to theory

The research adds to the body of literature that, the LoS of patients reduced by 4-8 hours per 100 lx increase of daylight inside hospital in-patient rooms. These findings are based on evidence from real-world field analysis data rather than theories, reviews, references, tools, and models (i.e. equivalence chart of Pechacek et al., 2008). In the previous research, daylight data was collected by using light meters (for example Walch et al., 2005; Choi et al., 2004 and Beauchemin et al, 1998) or generated by building simulation tools (Choi et al., 2012), whereas, in this research indoor data loggers were installed for first time inside patient rooms to record daylight intensities. As a result, the impact of the rapid changes of outdoor daylight intensities with the change of cloud cover and the sun positions, and impact of patients' internal blind controls were possible to be considered in the statistical models more accurately. It was also possible to use the daylight data of the loggers in the MLR models as continuous variable instead of categorical/ordinal variable (used widely by previous researchers) and quantify the change in patient LoS with respect to the unit change of daylight for the first time. The architects should take advantage of this evidence to motivate the owners and policy makers to invest on, and incorporate therapeutic effect of daylight in the architectural design of hospital in-patient rooms.

7.4.2. Contribution to practice

In terms of application, this research attempt to incorporate therapeutic effect of daylight in the architectural design of in-patient rooms to reduce patient LoS in hospitals. In previous clinical research, therapeutic effect of light was mostly provided by devices/lighting fixtures (i.e. light boxes by Eagles, 2004; Partonin et al., 2000; Lovell et al. 1995 ; Kripke et al., 1992) rather than architecture (Pechacek, 2008; Choi et al., 2004), or more recent research on healthy lighting by building technology groups (e.g. MITDL, 2011) have started to evaluate the therapeutic potentialities of existing/standard daylit spaces (Gochenour et al., 2009; Pechacek et al., 2008). This research superseded those by demonstrating how to develop and implement a design concept to ensure therapeutic effect of daylight more effectively in the architectural design of a hospital in-patient room by presenting sky window configurations as an option. The configurations of sky window, recommended in this research, is neither the only nor the best, even inclusive solution to achieve therapeutic effect of daylight inside patient rooms, but the first attempt to design therapeutic daylit space by introducing different architectural forms for hospital in-patient room. It is expected that, the example presented in this research will help and encourage architects to incorporate therapeutic effect of daylight in hospital design, and generate new ideas for incorporating therapeutic effect of daylight inside in-patient room more effectively.

7.5. Limitations and areas for further research

There are several limitations in this research. They are mainly associated to the subjective issues of therapeutic effect of daylight, clinical recovery and actual estimation of daylight, which are discussed below. Recommendations for further research are also offered.

- This study is the objective analysis of the effect of daylight on heart surgery patients (e.g. CABG) where indoor data loggers were first time used to incorporate the rapid change of outdoor daylight with the impact of internal blind controls on statistical models to quantify the change of patient LoS with respect to unit change in daylight. This research might be replicated to confirm the presented results. This research may also encourage interior designers and architects to conduct similar studies that examine the effect of daylight on other types of patients and impact of other built environment elements (e.g. temperature, air quality, acoustic and aesthetics) on the healing process of hospital patients.

- The statistical relationship between daylight intensities and patient LoS in hospital rooms was assumed linear in this research and presented by simple MLR models. These models are the first MLR models on therapeutic effect of daylight related to patient LoS. Based on these initial and primary models, it is possible to develop more complex, significant and detailed models to describe the statistical relationship more specifically and confidently.

- The researcher tried to establish not only the impact of daylight and outdoor views on hospital patient LoS by MLR models, but also illustrated how this knowledge can be incorporated in architectural decision support processes in critical situations between outdoor view and daylight potentiality of a design. As the field study was based on a single hospital building, most of the architectural features of the space were same, for example shading, room colour scheme, furniture layouts, partition height and opacity, ceiling height and design, basic room geometry, internal blind systems and building materials. By including samples from a number of hospitals with different architectural features (for example presence of atriums or courtyards inside hospital building, or high windows and skylights in patient rooms), it is possible to come to a decision about other architectural features of the hospital buildings.

- It was evident from the analysis of MLR models generated from field study data of this research that, an increase of daylight intensity near patient heads as well as overall increase of daylight inside hospital rooms contribute to reduce patient LoS. The other related attributes of daylight except intensity (for example direction, pattern, photic history and spectrum) are needed to be identified that might reduce patient LoS. The targets should be specified to generate a comprehensive daylighting model to ensure therapeutic benefit for human health that could be applied in therapeutic design of hospital in-patient rooms.

- The evaluation processes of daylighting for indoor built environment by simulation study are at crossroads between static and dynamic daylight simulation methods (Mardaljevic, 2008). The earlier studies in this research were based on static method (i.e. radiosity based) and latter dynamic methods (i.e. climate based) were adopted for daylight calculations. In this research a workflow was proposed and followed to set targets for indoor dynamic daylight metrics (e.g. DA and UDI>2000) based on outdoor DA and UDI>2000 in absence of any standard for hospital in-patient rooms. Realistic targets to achieve the therapeutic effect of daylight should be fixed for a location considering the surrounding environments, the available outdoor natural light, sunshine hours, sky conditions and daylight hours of the geographical location of the hospital building site. A standard for evaluation should be fixed and the technique applied in this research is in need for further review and upgrading.

- Most of the simulation tools are capable to do intensity-based calculations only. New tools and/or up-gradation of existing tools are necessary to calculate and evaluate the other expected attributes of daylight needed for therapeutic purpose in addition to intensities (such as spectrum).

- It was evident from the climatic analysis of this research that, the potentialities of achieving therapeutic effect of daylight differ for different geographical locations. For example the potentialities of achieving therapeutic benefit of daylight are much higher for Dhaka (Bangladesh) than London (UK). Additional therapeutic illumination can be provided by artificial light to satisfy patients' therapeutic needs, after the maximum and effective use of daylight. An artificial lighting system of changing light levels and tints throughout the day (for example warm at dawn; bright with a bluish cast at midday and rosy at dusk) is needed to be developed to ensure therapeutic benefit of daylight for hospital patients, located in places with insufficient daylight hours.

- In this research, the integration of sky window configurations in hospital facade design was found beneficial to achieve therapeutic effect of daylight more effectively inside patient rooms compared to traditional standard window configurations under the present and the future climate scenarios. There are still scopes for evaluation and development of the design of sky window configurations in terms of cost, maintenance, heat gain and heat loss, ventilation, glare protection and climate change factors other than daylight (e.g. temperature and relative humidity).

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Appendices

Appendix A explains the key terms and concepts relevant to this thesis in the field of architecture, biology, statistics and lighting. It will help the readers to distinguish between simple terms (e.g. daylight and sunlight) to technical terms (e.g. radiance and irradiance), which sometimes used synonym in daylight literature. The definition of commonly used terms (e.g. physical, psychological and physiological) and unfamiliar terms (e.g. ambient resolution, specular threshold and direct sampling) have been included. The basic concepts to understand CBDM simulation technique (such as backward raytracing, daylight coefficients and Perez sky model) have been discussed in this appendix (pp. 253-264).

Appendix B presents example layout for a single-bed room and four options for en-suite locations illustrated in HBN 04-01 (2008) (pp. 265-266); and

Appendix C provides ADB room data sheet B0303, which describes the detail specification of the single-bed room (e.g. furniture and surface finishes), based on which the case space for parametric simulation analysis was developed in this research (pp. 267-271).

Appendix D compiles a total 123 number of simulation results with different shading configurations exercised in trial and error process during this research period (pp. 272-273).

Appendix F presents a comparison for 75 years total costs of a perfectly designed daylit building with a professionally designed typical standard non-residential building of same footprint (Ternoey, 1999) (p.274).

Appendix F shows hospital room images with windows to reveal the existing practice of hospital in-patient room design in different countries, such as UK, USA, France and Korea (pp. 275-294).

Appendix G presents the list of Journal and Conference papers, and posters published by the researcher during this PhD course. The list of conferences/seminars/workshops where the researcher presented the outcomes of the research was also mentioned (pp. 295-297).

Appendix A: Definition of key Terms and concepts

ARCHITECTURE

Window Configurations – A configuration is the way a system is set up, or the assortment of components that make up the system. Window configurations record the entire layout of one frame, e.g. all windows, their sizes, how those windows are fixed in the frame and other window parameters.

Window-to-floor ratio – is the percentage of total unobstructed glass area of window to total area of floor served by the windows.

BIOLOGY

Human physiology – is the science of the mechanical, physical and biochemical functions of humans in good health, their organs, and the cells of which they are composed. Physiology focuses at the level of organs and systems. Most aspects of human physiology are closely homologous to corresponding aspects of animal physiology, and animal experimentation has provided much of the foundation of physiological knowledge. Anatomy and physiology are closely related fields of study: anatomy, the study of form, and physiology, the study of function, are intrinsically tied and are studied in tandem as part of a medical curriculum.

Mean arterial pressure (MAP) – is a function of systolic and diastolic blood pressure. Calculated as, MAP = [(2 x diastolic) + systolic] / 3.

Physical – means having to do with the body.

Physiology – is the study of the mechanical, physical, and biochemical functions of living organisms.

Psychology – is the study of the mind.

STATISTICS

Confidence interval – gives an estimated range of values which is likely to include an unknown population parameter. It is also called margin of error. The estimated range is calculated from a given set of sample data. For example, if a confidence interval of 4 is used and 47% percent of sample picks an answer then it is certain that if the question is asked to the entire relevant population, between 43% (47-4) and 51% (47+4) would have picked that answer. Conversely, there is a 5% chance (when the confidence level is 95%) that fewer than 43% of population or more than 51% of population would not pick that answer. The width of the confidence interval gives some idea about the uncertainty about the unknown population parameter. A very wide interval may indicate that more data should be collected before anything very definite can be said about the population.

Confidence level – is the probability value (1-α) associated with a confidence interval. It is expressed as a percentage and represents how often the true percentage of the population who would pick an answer lies within the confidence interval. For example, α=0.05=5%, then the confidence level is equal to (1-0.05) = 0.95, i.e. a 95% confidence level. With a 95% confidence level, there is a 5% chance of being wrong.

Hidden nominal variable – is the nominal variable that groups together two or more observations. For example, in a regression of height and weight, the hidden nominal variable is the name of each person.

Independent vs. dependent variables – If a cause-and-effect relationship is being tested, the variable that causes the relationship is called the independent variable and is plotted on the X axis, while the effect is called the dependent variable and is plotted on the Y axis.

Measurement variables – are things that can be measured. An individual observation of a measurement variable is always a number. Examples include length, weight, pH, and bone density.

Nominal variables – classify observations into a small number of categories; also called "attribute variables" or "categorical variables”. A good rule of thumb is that an individual observation of a nominal variable is usually a word, not a number. Examples of nominal variables include sex (the possible values are male or female), genotype (values are *AA, Aa,* or *aa*), or ankle condition (values are normal, sprained, torn ligament, or broken).

Parameter – is a value, usually unknown (and which therefore has to be estimated), used to represent a certain population characteristic. Within a population, a parameter is a fixed value which does not vary. Each sample drawn from the population has its own value of any statistic that is used to estimate this parameter. For example, the mean of the data in a sample is used to give information about the overall mean in the population from which that sample was drawn.

Sample vs. population – A sample is a group of units selected from a larger group (the population). By studying the sample it is hoped to draw valid conclusions about the larger group. A sample is generally selected for study because the population is too large to study in its entirety. The sample should be representative of the general population. For example, the population for a study of infant health might be all children born in the UK in the 1980's. The sample might be all babies born on 7 May in any of the years.

Statistic – is a quantity that is calculated from a sample of data. It is used to give information about unknown values in the corresponding population. For example, the average of the data in a sample is used to give information about the overall average in the population from which that sample was drawn. Statistics are often assigned Roman letters (e.g. m and s), whereas the equivalent unknown values in the population (parameters) are assigned Greek letters (e.g. μ and α).

Statistical Inference – makes use of information from a sample to draw sensible conclusions (inferences) about the population from which the sample was taken.

LIGHT SOURCES

Daylight – is the light received from the sun and the sky, which varies throughout the day, as modified by the seasons and the weather.

Skylight – is the light received from the whole vault of the sky as modified by the weather and time of day, ignoring sunlight.

Sunlight – is the light received directly from the sun, as opposed to that derived from the sky.

LIGHTING TERMINOLOGY

DA (Daylight Autonomy) – is the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone.

DAcon (Continuous Daylight Autonomy) – is the percentage of the minimum illuminance requirement met by daylight alone at the sensor during the full occupied times of the year. The metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial. For e.g. if the design illuminance is 300 lux on core work plane sensor, and 180 lux are provided by daylight alone at one sensor point during the whole office hours of the year; a partial credit of 180lux/300lux=0.6 (60%) is given to that sensor point.

DAmax (Maximum Daylight Autonomy) – is the percentage of the occupied hours when the daylight level is 10 times higher than design illumination; represents the likely appearance of glare.

Daylight coefficients – calculate indoor lighting levels due to outdoor natural light levels under arbitrary sky conditions. Tregenza (1983) first proposed the concept of daylight coefficients. In this concept, the celestial hemisphere is theoretically divided into disjoint sky patches at the beginning. Then, total illuminance at a point in a building is calculated by summing the contribution of each sky patch individually (Figure A.1). After, calculating a complete set of daylight coefficients on a sensor point for a building geometry, it is possible to couple the daylight coefficient with an arbitrary sky luminance distribution and calculate the total illuminance on the specified point by a simple linear superposition. So, using this simple algebraic equation, DAYSIM calculates daylight levels annually considering the short-time-step variances of the outdoor available natural light simultaneously with a time variation of minutes to hours. Reinhart and Herkel (2000) compared six different RADIANCE-based (backward raytracer) dynamic daylighting simulation concepts, and found that daylight coefficient approaches is the most reliable and fastest methods to define the short-time step illuminance change in a building.

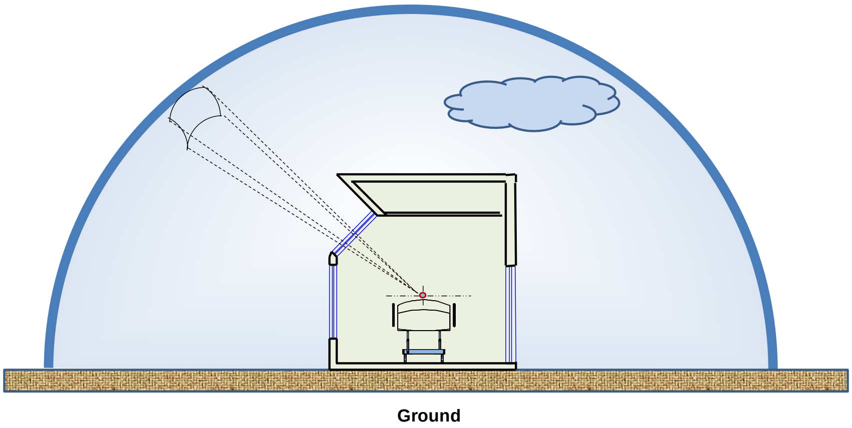

Figure A.1: Contribution of an individual sky patch on the illuminance at a point inside a room (after, Reinhart, 2006).

Daylight factor (DF) – is the ratio of the daylight illuminance at an interior point to the unshaded, external horizontal illuminance of the building under a CIE overcast sky condition.

Diffuse radiation – is the total amount of radiation falling on a horizontal surface from all parts of the sky apart from the direct sun.

Direct radiation – is the radiation arriving at the earth's surface with the sun's beam.

Global radiation – is the total of direct solar radiation and diffuse sky radiation received by a horizontal surface of unit area.

Electromagnetic spectrum – is a continuum of all electromagnetic waves arranged according to frequency and wavelength. The sun, earth, and other bodies radiate electromagnetic energy of varying wavelengths. Electromagnetic energy passes through space at the speed of light in the form of sinusoidal waves. Light is a particular type of electromagnetic radiation that can be seen and sensed by the human eye, but this energy exists at a wide range of wavelengths. The micron is the basic unit for measuring the wavelength of electromagnetic waves. The spectrum of waves is divided into sections based on wavelength. The shortest waves are gamma rays, which have wavelengths of 10e-6 microns or less. The longest waves are radio waves, which have wavelengths of many kilometres. The range of visible rays consists of the narrow portion of the spectrum, from 0.4 microns (blue) to 0.7 microns (red).

THIRD-PARTY CONTENT

Figure A.2: electromagnetic spectrum (Source: http://en.wikipedia.org/wiki/Electromagnetic_spectrum)

Illuminance – is the quantitative expression for the luminous flux incident on unit area of a surface. A more familiar term would be “lighting level”. Illuminance is expressed in lux (lx). One lux equals one lumen per square metre (lm/m^2). In Imperial units the unit is the foot-candle which equals lumen per square foot (lm/ft^2).Other units are – metrecandle, phot, nox.

Irradiance – is light power per unit area falling on a surface, computed by integrating radiances of sources and surfaces around $E = dP/ dA$, in W/m^2

Luminance – is the quantitative expression for the amount of light reflected by a surface in a specific direction. A more familiar word is “brightness”, although this term must, strictly speaking, be reserved to describe the subjective impression of luminance on the eye. The luminance of a surface is determined by the illuminance on the surface in question and its reflective properties. Luminance is expressed in candelas per square metre (cd/m^2), referred to as the unit. In Imperial units the unit is the foot-lambert, which is candelas per square foot (cd/ft^2). Other units are – lambert, stilb, apostilb, blondel, skot.

Luminous efficacy – is the ratio between luminous flux and power dissipation, and is expressed in lumens per watt (lm/W). Each lamp type has a different luminous efficacy.

Luminous flux – is the total amount of light radiated by a light source per second. A more familiar term would be “light output". It is expressed in lumens (lm).

Luminous intensity – is the luminous flux radiated by a light source in a specific direction. Luminous intensity is expressed in candelas (cd).

Radiance – is power (energy flux) emitted per unit area into a cone having unit solid angle. The unit is $W/m^2/sr$.

UDI (Useful daylight illuminances) – try to find out when daylight levels are ‘useful’ for the user and when they are not. Based on occupants’ preferences in daylit offices, UDI results in three metrics, i.e. the percentages of the occupied times of the year when daylight is useful (100- 2000lux), too dark (<100 lux), or too bright (> 2000 lux).

LIGHTING METHODS

Ambient accuracy (aa) – value is approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

Ambient bounces (ab) – is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.

Ambient division (ad) – The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of the number of ambient divisions. A value of zero implies no indirect illumination.

Ambient resolution (ar) – determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. The maximum ambient value density is the scene size times the ambient accuracy divided by the ambient resolution.

Ambient sampling (as) – are applied only to the ambient divisions which show a significant change.

Backward raytracing – simulates individual rays from the points of interest to light source or other objects backwardly with respect to a given viewpoint (Figure A.3). It is possible to simulate different basic surfaces (e.g. 100% specular surfaces, lambertian surfaces, transparent surfaces and translucent surfaces) and a random mixture of these basic surfaces under raytracing.

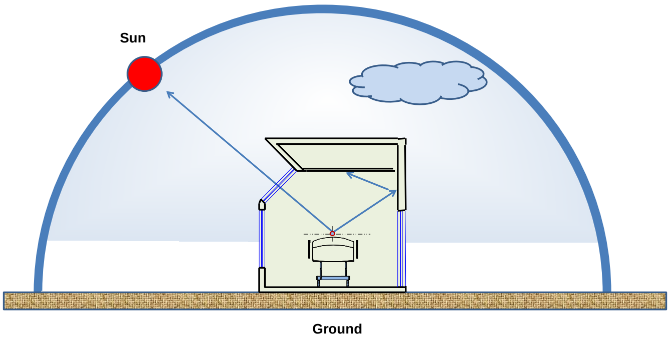

Figure A.3: Backward raytracing simulates individual rays from the points of interest to light source or other objects backwardly (after, Reinhart, 2006).

Control run – provides projections of future climate, derived by adding the climate change projections to an observed 1961 to 1990 baseline climate, meaning that all climate change projections are given relative to this period.

DAYSIM simulation – calculates the performance metrics considering the impact of local climate and generates a time series indoor annual illuminance profile at points of interest in a building. DAYSIM requires two steps to calculate the annual amount of daylight in a building. Daylight coefficients are calculated first considering the available daylight surrounding the building. After that, the daylight coefficients are combined with the specified climate data of building site. Based on generated illumination profile, DAYSIM derives several dynamic, climate-based daylight performance matrices, such as Daylight Autonomy (DA), Useful Daylight Index (UDI), Continuous Daylight Autonomy (DAcon) and Maximum Daylight Autonomy (DAmax). Figure A.4 shows the process of daylight simulation under DAYSIM. More details on the simulation algorithm used by DAYSIM can be found under Reinhart (2006).

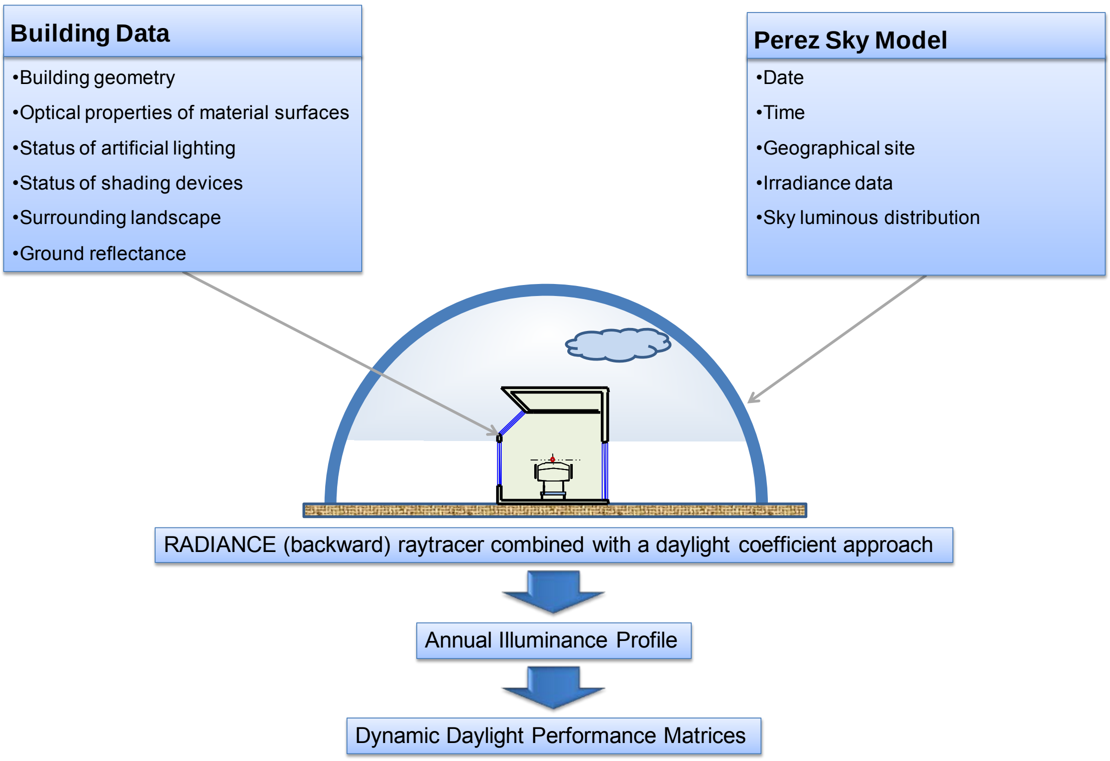

Figure A.4: The process of daylight simulation in DAYSIM (after, Reinhart, 2006).

DAYSIM uses **Perez all weather sky luminance model**. Perez sky model was developed in early nineties by Richard Perez et al. (1990; 1993). To investigate the performance of a building under all possible sky conditions that may occur in a year, DAYSIM first imports hourly direct and diffuse irradiances from a climate file and if required, a stochastic autocorrelation model is used to convert the time series down to five minute time series of direct and diffuse irradiances from one hour. Then, these irradiances are converted into illuminances and a series of sky luminous distributions of the celestial hemisphere. The sky luminous distribution for a given sky condition varies with date, time, site and direct and diffuse irradiance values, and influence the relative intensity of light back-scattered from the earth surface, the width of the circumsolar region, the relative intensity of the circumsolar region, the luminance gradient near the horizon, and darkening or brightening of the horizon. Figure A.5 shows the background steps of using Perez sky model in DAYSIM.

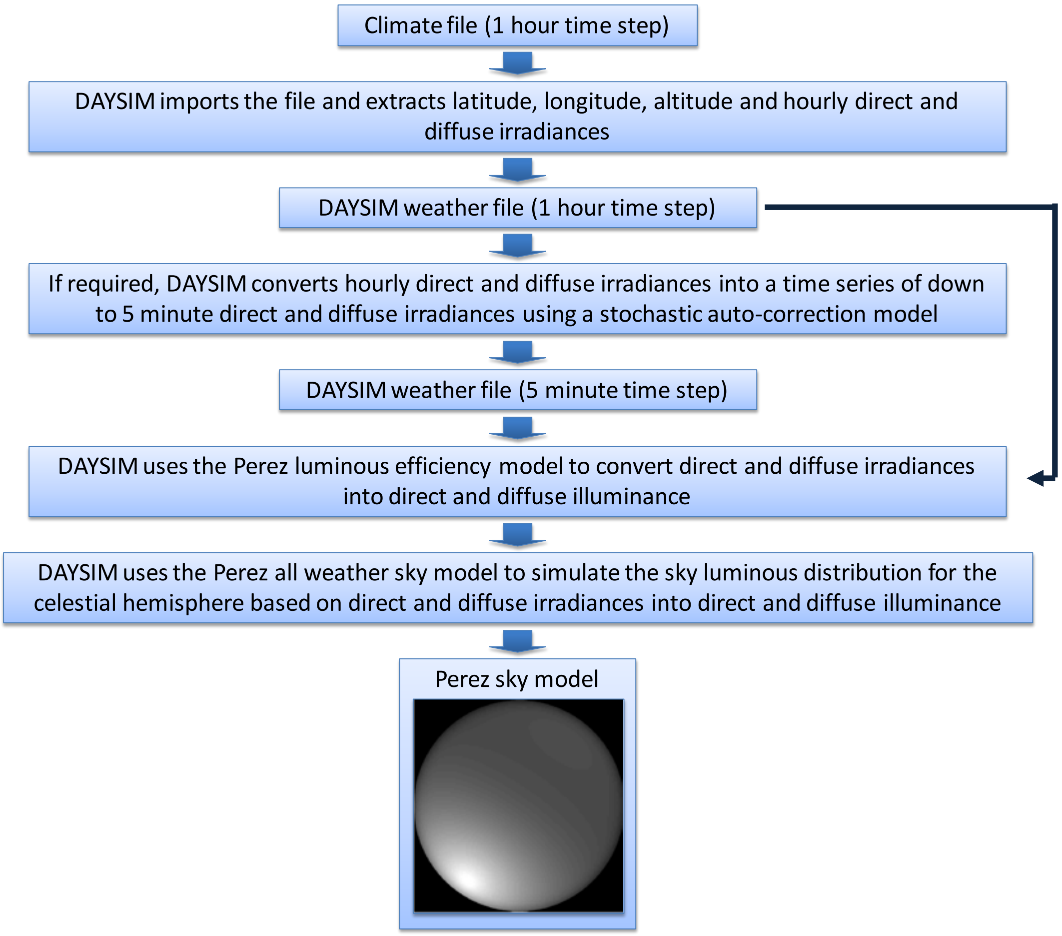

Figure A.5: The use of the Perez sky model in DAYSIM (after, Reinhart, 2006).

Design summer year (DSY) – consists of an actual one-year sequence of hourly data, selected from the 20-year data sets to represent a year with a hot summer. The selection is based on dry bulb temperatures during the period April–September.

Direct pretest density (dp*)* – is the number of samples per steradian that will be used to determine ahead of time whether or not it is worth following shadow rays through all the reflections and/or transmissions associated with a secondary source path. A value of zero means that the full secondary source path will always be tested for shadows if it is tested at all.

Direct sampling (ds) – assures accuracy in regions close to large area sources at a slight computational expense. A light source will be subdivided until the width of each sample area divided by the distance to the illuminated point is below this ratio. A value of zero turns source subdivision off, sending at most one shadow ray to each light source.

Ditect relays (dr) – is the number of relays for secondary sources. A value of zero means that secondary sources will be ignored. A value of one means that sources will be made into first generation secondary sources; a value of two means that first generation secondary sources will also be made into second generation secondary sources; and so on.

Future climate runs – is a projection of the response of the climate system with concentrations or emissions scenarios, based upon climate model simulations, and in UKCP09, weighted by observations. Values describe the climate system in absolute terms (e.g. without reference to the baseline climatology).

Limit reflection (lr) – is the maximum limit of reflections.

Limit weight (lw) – is the minimum limit of the weight of each ray. During ray-tracing, a record is kept of the final contribution a ray would have to the image. If it is less than the specified minimum, the ray is not traced.

Specular jitter (sj) – is the degree to which the highlights are sampled for rough specular materials. A value of one means that all highlights will be fully sampled using distributed ray tracing. A value of zero means that no jittering will take place, and all reflections will appear sharp even when they should be diffuse.

Specular threshold (st) – is the minimum fraction of reflection or transmission, under which no specular sampling is performed. A value of zero means that highlights will always be sampled by tracing reflected or transmitted rays. A value of one means that specular sampling is never been used. Highlights from light sources will always be correct, but reflections from other surfaces will be approximated using an ambient value. A sampling threshold between zero and one offers a compromise between image accuracy and rendering time.

Test reference year (TRY) – consists of hourly data for twelve typical months, selected from approximately 20-year data sets (typically 1983-2004), and smoothed to provide a composite, but continuous, 1-year sequence of data.

Appendix B: Example layout for a single-bed room and En-suite location

THIRD-PARTY CONTENT

Source: HBN 04‑01 (2008) In‑patient care, Health Building Note 04‑01: Adult in‑patient facilities, DH Estates and Facilities Division, Leeds.

THIRD-PARTY CONTENT

Source: HBN 04-01 (2008) In-patient care, Health Building Note 04-01: Adult in-patient facilities, DH Estates and Facilities Division, Leeds.

Appendix C : ADB Room Data Sheet B0303

ADB	**Room Data Sheet**	**B0303**

Project:	TUTORIAL	Sample project
Department:	HBN04	IN-PATIENT ACCOMMODATION: OPTIONS FOR CHOICE List of rooms
Room:	B0303	Single bedroom: Adult acute With clinical support. Relative overnight stay
Room Number:	**Revision Date:**	06/08/2007

Activities:	1) Patient may arrive on foot or in a wheelchair. 2) Patient may arrive on a trolley or in a bed. 3) Transfer patient to/from bed, stretcher trolley, or wheelchair. 4) Admission, with the intimate discussion of personal matters. 5) Patient to undress/dress in vicinity of bed, with/without assistance. 6) Patient to receive therapeutic and clinical attention from health team staff. 7) Patient to read, writes, listens to radio, views TV and use telephone. 8) Patient to take meals in bed or by the bed. 9) Patient to receive visitors. 10) Holding clothing and personal effects. 11) Preparing for clinical procedures. 12) Self dispensing medication or drugs. 13) Holding daily supply of linen and surgical goods/supplies. 14) Using monitoring/diagnostic equipment. 15) Using computer workstation(s). 16) Overnight stays by relatives.
Personnel:	1 x Patient 4 x Others
Planning Relationships:	Close to staff base. Close to ancillary rooms. Ward activity to be visible from room. En-suite sanitary facilities.

Space Data:	**Area (m²):**	19.00	**Height (mm):**	2,700

Notes: Space may required to accommodate use of hoist. Ceiling mounted hoist - project team option.
Storage of patient drug - see hospital policy.

Source: ADB (2009) Activity Data Base, The briefing, design & commissioning tool for both new‐build and refurbishment of healthcare buildings. [CD‐ROM]. Department of Health, NHS Estates.

ADB	**Room Environmental Data**	**B0303**

Project:	TUTORIAL	Sample project
Department:	HBN04	IN-PATIENT ACCOMMODATION: OPTIONS FOR CHOICE List of rooms
Room:	B0303	Single bedroom: Adult acute With clinical support. Relative overnight stay
Room Number:		**Revision Date:** 06/08/2007

AIR	Requirements	Notes
Winter Temperature (DegC):	21	
Summer Temperature (DegC):		
Mechanical Ventilation (Supply ac/hr):		
Mechanical Ventilation (Extract ac/hr):		
Pressure Relative to Adjoining Space:		
Filtration (%DSE and % Arrestance):	/	
Humidity (%RH):		

General Notes:

LIGHTING		
Service Illumination (Lux):	100	Floor. 200-400 Bed centre. 30-50 Bedhead. Areas for VDT's: See CIBSE Lighting Guide LG3 "The Visual Environment for Display Screen Use" Addendum 2001
Service Illumination Night (Lux):	5.0	Floor. 1-5 Bed centre. 0.1 Bedhead. Evening (lux): 50 Bed centre.
Local Illumination (Lux):	150.0	Bedhead
Colour Rendering Required:	Y	Not night & local
Standby Lighting Grade:		B: Lighting of the level and quality one third to one half that provided normal lighting. Day Bed centre: A: Lighting of the level and quality equal or nearly equal to that provided by normal lighting. For local examination & inspection.

General Notes:

NOISE		
Privacy Factor Required (dB):	80	Ref: HTM2045
Mechanical Services (NR):	30	
Intrusive Noise (NR Leq):	35	
***Acceptable Sound Level [L10dB(A)]:**		
***Speech Privacy Required:**	N	
***Quality Which Cannot Be Tolerated:**		
(* alternative format)		

General Notes:

SAFETY		
Hot Surface Max. Temp (DegC):	43	
Hot Water Max. Temp (DegC):		

General Notes:

FIRE		
Enclosure:		
Automatic Detection:		Smoke

Source: ADB (2009) Activity Data Base, The briefing, design & commissioning tool for both new‑build and refurbishment of healthcare buildings. [CD‑ROM]. Department of Health, NHS Estates.

Project:	TUTORIAL	Sample project
Department:	HBN04	IN-PATIENT ACCOMMODATION: OPTIONS FOR CHOICE List of rooms
Room:	B0303	Single bedroom: Adult acute With clinical support. Relative overnight stay

Room Number: **Revision Date:** 06/08/2007

Walls:	Surface Finish (HTM 56): 5 Moisture Resistance (HTM 56): N i.e. Normal humidity. Cleaning Routine (HTM 56): To manufacturers recommendations
Floor:	Surface Finish (HTM 61): 3 i.e. Hard, impervious, jointless, smooth Cleaning Routine (HTM 61): To manufacturers recommendations
Ceiling:	Surface Finish (HTM 60): 5 i.e. Imperforate Moisture Resistance (HTM 60): N i.e. Normal Humidity Cleaning Routine (HTM 60): To manufacturers recommendations
Doorsets:	(HTM 58) Two sets of doors: 1x 1500mm, one & a half leaf, half glazed, obscurable; bed access. 1x 1000mm,s ingle leaf, plain flush; wheelchair access
Windows:	(HTM 55) Clear, solar control, privacy control
Internal Glazing:	(HTM 57) Clear with privacy control
Hatch:	
Notes:	

Source: ADB (2009) Activity Data Base, The briefing, design & commissioning tool for both new‐build and refurbishment of healthcare buildings. [CD‐ROM]. Department of Health, NHS Estates.

ADB	Schedule of Components by Room	B0303

Project:	TUTORIAL	Sample project
Department:	HBN04	IN-PATIENT ACCOMMODATION: OPTIONS FOR CHOICE List of rooms
Room:	B0303	Single bedroom: Adult acute With clinical support. Relative overnight stay
Room Number:		**Revision Date:** 06/08/2007

Quantity			Code	Description	Alt. Code	Grp
New	Trans	Total				
1		1	BAS101	BASIN, medium, hospital pattern, vitreous china, no tap holes, no overflow, integral back outlet, 500W 400D. HTM64LBHM		1
1		1	BED022	BEDHEAD SERVICES UNIT - TRUNKING MOUNTED incorporating: Electrical panel - 6x Double socket outlet 1x Bedlight control switch; ON/DIM/OFF 1x Bedlight fuse unit Patient/Nurse call panel - 1x Reset switch/Indicator lamp 1x Socket for handset 1x Audio driver 1x Staff emergency switch 1x Handset parking bracket 1x Handset parking clip		1
1		1	BED040	BED HEAD BUFFER/DOCKING device, bed and wall protection, horizontal, wall mounted, (internal clearance 1000-1400)		1
1		1	CAL050	HANDSET patient's typical facilities: Nurse call button with reassurance Channel display Channel selection Volume control Bedlight control		1
1		1	LIG003	LUMINAIRE Reading, adjustable arm, 100watt, wall/trunking/rail mounted		1
1		1	MSC187	CABINET base, 400mm facing, with 2 shelves, 1 door hinged right, on plinth, o/a height 900, HTM71		1
1		1	MSW062	WORKTOP, for 400mm facing inserts cabinets, 1200W 700D nominal, HTM71		1
1		1	OUT005	SOCKET outlet switched 13amp single, wall mounted		1
2		2	OUT010	SOCKET outlet switched 13amp twin, wall mounted		1
1		1	OUT012	SOCKET outlet switched 13amp twin, trunking mounted		1
1		1	OUT121	SOCKET outlet computer data, wall/trunking mounted		1
1		1	OUT209	SOCKET outlet television aerial, single, trunking mounted		1
1		1	OUT217	SOCKET outlet telephone, trunking mounted		1
1		1	OUT452	OUTLET 4 kPa compressed air medical, trunking mounted		1
1		1	OUT471	OUTLET oxygen medical, trunking mounted		1
1		1	OUT476	OUTLET vacuum medical, trunking mounted		1
1		1	RAI130	RAIL, clinical equipment, wall mounted, 600mm		1
1		1	RAI136	RAIL, clinical equipment, wall mounted, 2100mm		1
1		1	STC003	BEDHEAD SERVICES TRUNKING SYSTEM for medical gases, electrical power, nurse call, 2400mm nominal		1

Source: ADB (2009) Activity Data Base, The briefing, design & commissioning tool for both new‑build and refurbishment of healthcare buildings. [CD‑ROM]. Department of Health, NHS Estates.

Project:	TUTORIAL	Sample project
Department:	HBN04	IN-PATIENT ACCOMMODATION: OPTIONS FOR CHOICE List of rooms
Room:	B0303	Single bedroom: Adult acute With clinical support. Relative overnight stay
Room Number:		**Revision Date:** 06/08/2007

Quantity			Code	Description	Alt. Code	Grp
New	Trans	Total				
1		1	TAP892	TAP bib, 2x8mm thermostatic mixer, automatic action, sensor operated non-touch. HTM64TBH6		1
1		1	WAS107	TRAP, bottle, 1.1/4 in, plastic resealing. HTM64TRR1/P		1
1		1	BRA004	BRACKET, holder, suction unit, trunking mounted		2
1		1	CAB065	CABINET, drugs, self dispensing medication, lockable, wall mounted, 315H 210W 155D		2
1		1	DIS011	DISPENSER, barrier cream, disposable single cartridge, wall mounted		2
1		1	DIS013	DISPENSER, paper towel, wall mounted		2
1		1	DIS026	DISPENSER, Medical hand sanitizer, lever action, wall mounted		2
1		1	DIS030	DISPENSER, soap, disposable single cartridge, lever action, wall mounted		2
1		1	HOO019	HOOK, single, small, wall mounted		2
1		1	BED013	BED Kings Fund, variable height, two-way tilt, adjustable backrest, bedstripper, on castors		3
1		1	CHA007	CHAIR, easy, with open arms, high back, upholstered		3
1		1	COM032	COMPUTER VDT MONITOR		3
1		1	COM033	COMPUTER KEYBOARD		3
1		1	HOL006	HOLDER, sack, with lid foot operated, medium, freestanding, 875H 430W 385D		3
1		1	LOC002	LOCKER, bedside, 3 compartment, towel rail at rear, on castors, 902H 485W 485D		3
1		1	MAT004	MATTRESS, Kings Fund bed, standard backrest, 1955L 865W 125D		3
1		1	MST005	TROLLEY, small, half size, with 5 sets of runners, 400mm facing, 850H 445W 350D nominal, HTM71		3
1		1	SET001	SETTEE/BED, convertible, with arms		3
1		1	TAB073	TABLE, overbed, cantilevered		3
1		1	WAR003	WARDROBE, 1800H 600W 600D		3

Source: ADB (2009) Activity Data Base, The briefing, design & commissioning tool for both new‑build and refurbishment of healthcare buildings. [CD‑ROM]. Department of Health, NHS Estates.

Appendix D : Compilation of Simulation Analysis

Window	Location	Orientation	Window Width	Angle of Sky window	Depth of sun Shade	Depth of overhang	internal light shelf	Material of Light shelf	Material of Sky Window (visual transmitence)	Blind Control	DA(%)	DF>2%(%)	DA $_{max}$ above 5% (%)	UDI $_{<100}$ (%)	UDI$_{100-2000}$ (%)	UDI $_{>2000}$ (%)	Electric Lighting Use (kWh/unit area)	Annual lighting Energy Use (kWh)
Viewing Window	1st Floor	North	1800	-	-	-	-	-	90%	-	49	13	5	41	59	0	31.9	478.1
	1st Floor	West	1800	-	-	-	-	-	90%	-	50	14	11	40	58	2	31.7	475.2
	1st Floor	East	1800	-	-	-	-	-	90%	-	54	13	13	37	62	1	30.8	461.4
	1st Floor	South	1800	-	-	-	-	-	90%	-	53	14	13	37	61	1	31.8	477
	1st Floor	North	4500	-	-	-	-	-	90%	-	57	56	14	34	66	0	31.3	469
	1st Floor	West	4500	-	-	-	-	-	90%	-	60	56	40	32	66	3	30.5	457.4
	1st Floor	East	4500	-	-	-	-	-	90%	-	57	55	40	34	60	6	31.2	467.8
	1st Floor	South	4500	-	-	-	-	-	90%	-	60	57	41	32	64	5	31.2	467.5
Viewing window + High Window	1st Floor	North	1800	0	-	-	-	-	90%	-	65	41	11	27	73	0	30.5	458.1
	1st Floor	West	1800	0	-	-	-	-	90%	-	65	41	25	28	59	13	30.5	456.9
	1st Floor	East	1800	0	-	-	-	-	90%	-	68	41	37	26	63	11	29.8	447.5
	1st Floor	South	1800	0	-	-	-	-	90%	-	67	41	33	27	52	21	30.6	458.3
	1st Floor	South	1800	0	750	-	750	-	90%	-	59	37	27	31	58	11	31.2	468.6
Viewing window + Sky window	1st Floor	North	1800	45	-	-	-	-	90%	-	69	51	11	25	74	0	30.3	454.9
	1st Floor	West	1800	45	-	-	-	-	90%	-	69	54	30	25	58	17	30.4	455.5
	1st Floor	East	1800	45	-	-	-	-	90%	-	71	54	49	24	60	16	29.7	445.7
	1st Floor	South	1800	45	-	-	-	-	90%	-	70	54	43	25	48	27	30.5	457.1
	1st Floor	South	1800	30	-	-	-	-	90%	-	64	51	40	25	50	25	30.9	463.1
	1st Floor	South	1800	45	-	-	-	-	90%	-	70	54	43	25	48	27	30.5	457.1
	1st Floor	South	1800	60	-	-	-		90%	-	71	59	52	25	47	28	30.3	455.2
	1st Floor	East	1800	45	825	-	-	-	90%	-	70	52	43	25	61	14	30.9	463.4
	1st Floor	West	1800	45	825	-	-	-	90%	-	68	49	30	26	58	16	30.6	458.7
	1st Floor	South	1800	45	825	-	-	-	90%	-	70	51	38	25	50	26	30.2	453
	1st Floor	west	1800	45	825	-	-	-	90%	-	68	49	30	26	58	16	30.6	458.7
	1st Floor	west	1800	45	825	100	-	-	90%	-	67	49	30	26	59	15	30.6	458.3
	1st Floor	west	1800	45	825	200	-	-	90%	-	66	46	29	27	59	14	30.7	460.1
	1st Floor	west	1800	45	825	225	-	-	90%	-	65	46	27	27	59	13	30.5	457.9
	1st Floor	west	1800	45	825	250	-	-	90%	-	65	46	25	28	59	13	30.8	462.5
	1st Floor	west	1800	45	825	275	-	-	90%	-	65	46	25	28	59	13	30.6	459.5
	1st Floor	west	1800	45	825	300	-	-	90%	-	65	46	25	28	59	13	30.9	463
	1st Floor	south	1800	45	825	200	-	-	90%	-	68	46	38	26	51	23	30.7	460.8
	1st Floor	South	1800	45	825	200	300	DF	90%	-	68	44	38	26	51	23	30.7	460.2
	1st Floor	South	1800	45	825	200	650	DF	90%	-	65	43	33	28	54	18	30.6	458.5
	1st Floor	South	1800	45	825	200	750	DF	90%	-	63	43	32	29	56	15	31	465.4
	1st Floor	South	1800	45	825	200	775	DF	90%	-	63	43	32	29	56	14	30.9	463.9
	1st Floor	South	1800	45	825	200	800	DF	90%	-	62	41	32	30	57	13	31.2	467.8
	1st Floor	South	1800	45	825	200	800	SP	90%	-	62	43	33	30	57	14	31.2	467.9
	1st Floor	South	1800	45	825	200	1000	DF	90%	-	55	37	25	35	62	3	31.7	475.7
	1st Floor	South	1800	45	825	200	-	-	30%	-	58	24	22	33	59	8	31.5	471.9
	1st Floor	South	1800	45	825	200	-	-	50%	-	63	35	32	29	58	13	31.2	467.3
	1st Floor	South	1800	45	825	200	-	-	70%	-	66	44	37	27	53	20	30.8	462.2
	1st Floor	South	1800	45	825	200	-	-	90%	-	68	46	38	26	51	23	30.7	460.8
	1st Floor	South	1800	45	-	-	1000	DF	90%	-	58	37	32	33	61	5	31.2	468.4
	1st Floor	South	1800	45	-	-	650	DF	90%	-	66	43	37	28	53	20	30.7	460.9
	1st Floor	South	1800	45	-	-	600	DF	90%	-	66	43	37	27	52	21	30.6	459.6
	1st Floor	South	1800	45	-	-	550	DF	90%	-	67	44	37	26	52	22	31.2	468.4
	1st Floor	South	1800	45	-	-	500	DF	90%	-	68	46	38	26	51	22	30.6	459.7
	1st Floor	South	1800	45	-	-	300	DF	90%	-	69	51	38	25	49	26	30.6	459.4
	1st Floor	South	1800	45	-	-	250	DF	90%	-	69	49	38	25	49	26	30.6	459.5
	1st Floor	South	1800	45	-	-	225	DF	90%	-	70	49	40	25	49	26	30.6	459.3
	1st Floor	South	1800	45	-	-	200	DF	90%	-	70	51	40	25	49	26	30.7	460.4
	1st Floor	South	1800	45	-	-	None	DF	90%	-	70	54	43	25	48	27	29.7	445.5
	1st Floor	South	1800	45	-	-	1000	DF	90%	-	58	37	32	33	61	5	31.2	468.4
	1st Floor	South	1800	45	-	-	1000	SP	90%	-	59	41	33	32	58	10	31.1	467.1
	1st Floor	South	1800	45	-	-	600	DF	90%	-	66	43	37	27	52	21	30.6	459.6
	1st Floor	South	1800	45	-	-	600	SP	90%	-	67	46	37	26	52	22	30.7	460.5
	1st Floor	South	1800	45	-	-	300	DF	90%	-	69	51	38	25	49	26	30.6	459.4
	1st Floor	South	1800	45	-	-	300	SP	90%	-	69	48	38	25	49	26	30.6	459.5
	1st Floor	South	1800	45	-	900	600	SP	90%	-	57	17	13	34	63	3	31.4	470.7
	1st Floor	South	1800	45	-	600	600	SP	90%	-	59	30	24	33	63	5	31.3	468.9
	1st Floor	South	1800	45	-	300	600	SP	90%	-	64	43	33	29	55	16	30.8	461.9
	1st Floor	South	1800	45	-	275	600	SP	90%	-	64	41	33	29	55	17	30.5	458.2
	1st Floor	South	1800	45	-	250	600	SP	90%	-	64	43	33	28	54	18	30.5	458.2
	1st Floor	South	1800	45	-	225	600	SP	90%	-	65	43	35	28	54	18	30.6	459.6

Window	Location	Orientation	Window Width	Angle of Sky window	Depth of sun Shade	Depth of overhang	internal light shelf	Material of Light shelf	Material of Sky Window (visual transmitence)	Blind Control	DA(%)	DF>2%(%)	DA $_{max}$ above 5% (%)	UDI $_{<100}$ (%)	UDI$_{100\text{-}2000}$ (%)	UDI $_{>2000}$ (%)	Electric Lighting Use (kWh/unit area)	Annual lighting Energy Use (kWh)
Viewing window + Sky window	1st Floor	South	1800	45	850	300	600	SP	90%	-	62	40	32	30	57	13	30.9	463.3
	1st Floor	South	1800	45	825	300	600	SP	90%	-	62	41	32	30	57	13	30.9	463.3
	1st Floor	South	1800	45	850	275	600	SP	90%	-	62	43	33	29	57	13	30.9	463.5
	1st Floor	South	1800	45	825	275	600	SP	90%	-	63	43	32	29	57	14	30.9	463.4
	1st Floor	South	1800	45	850	250	600	SP	90%	-	63	43	32	29	56	15	30.6	461.1
	1st Floor	South	1800	45	825	250	600	SP	90%	-	63	43	32	29	56	15	30.7	460.9
	1st Floor	South	1800	45	850	225	600	SP	90%	-	63	43	33	29	56	15	30.8	462
	1st Floor	South	1800	45	825	225	600	SP	90%	-	63	43	33	29	56	15	30.8	462
	1st Floor	South	1800	45	750	None	None	DF	90%	-	70	54	43	25	48	27	30.9	462.9
	1st Floor	South	1800	45	750	None	750	DF	90%	-	65	43	38	28	51	21	31	465.6
	1st Floor	South	1800	45	750	None	750	SP	90%	-	66	49	38	27	52	21	30.8	462.6
	1st Floor	East	1800	45	750	None	750	DF	90%	-	66	46	40	27	62	11	30.1	451.9
	1st Floor	South	1800	45	850	None	225	SP	90%	-	68	48	38	26	51	23	30.6	458.3
	1st Floor	South	1800	45	750	None	225	SP	90%	-	68	48	38	26	51	23	30.6	458.3
	1st Floor	South	1800	45	650	None	225	SP	90%	-	69	48	38	26	50	24	30.6	458.6
	1st Floor	South	1800	45	550	None	225	SP	90%	-	69	49	38	25	49	25	30.6	458.9
	1st Floor	South	1800	45	450	None	225	SP	90%	-	69	49	38	25	49	25	30.6	459.1
	1st Floor	South	1800	45	None	None	225	SP	90%	-	70	49	40	25	49	26	30.6	459.3
	5th Floor	South	1800	45	825	275	600	SP	90%	-	62	43	33	30	57	13	31.2	468.3
	5th Floor	South	1800	45	825	250	600	SP	90%	-	63	43	33	29	57	14	30.9	463.3
	5th Floor	South	1800	45	825	225	600	SP	90%	-	63	43	33	29	56	15	30.8	461.5
	5th Floor	South	1800	45	825	200	600	SP	90%	-	63	43	33	29	57	14	30.9	463.3
	1st Floor	South	1800	45	825	275	600	SP	90%	-	63	43	32	29	57	14	30.9	463.4
	1st Floor	East	1800	45	825	275	600	SP	90%	-	63	41	32	29	64	7	30.3	455
	1st Floor	East	1800	45	825	275	-	-	90%	-	68	46	33	26	62	12	30.1	451.3
	1st Floor	west	1800	45	825	275	-	-	90%	-	65	46	25	28	59	13	30.6	459.5
	1st Floor	North	1800	45	-	275	-	-	90%	-	66	46	11	26	74	0	30.3	454.1
	1st Floor	South	1800	45	825	200	775	DF	90%	Active	43	63	30	29	59	11	31.1	465.9
	1st Floor	South	1800	45	825	200	775	DF	90%	Passive	43	36	0	50	50	0	31.1	465.9
	1st Floor	West	1800	45	825	200	-	-	90%	Active	46	66	14	27	64	9	30.6	465.3
	1st Floor	West	1800	45	825	200	-	-	90%	Passive	46	38	0	46	54	0	30.6	465.3
	1st Floor	East	1800	45	825	-	-	-	90%	Active	52	70	37	25	62	13	30.6	465.3
	1st Floor	East	1800	45	825	-	-	-	90%	Passive	52	44	0	42	58	0	30.6	465.3
	1st Floor	south	1800	45	825	275	600	SP	90%	Active	43	63	30	29	59	12	30.8	462.5
	1st Floor	south	1800	45	825	275	600	SP	90%	Pasive	43	37	0	49	51	0	30.8	462.5
	1st Floor	East	1800	45	825	275	-	-	90%	Active	46	68	35	26	64	10	29.9	448.7
	1st Floor	East	1800	45	825	275	-	-	90%	Pasive	46	39	0	44	56	0	29.9	448.7
	1st Floor	East	1800	45	(45^{0})	275	-	-	90%	Active	40	65	27	28	67	5	30.3	455.2
	1st Floor	East	1800	45	(45^{0})	275	-	-	90%	Pasive	40	31	0	50	50	0	30.3	455.2
	1st Floor	West	1800	45	(45^{0})	275	-	-	90%	Active	40	62	8	30	65	5	31	465.3
	1st Floor	West	1800	45	(45^{0})	275	-	-	90%	Pasive	40	29	0	53	47	0	31	465.3
	1st Floor	West	1800	45	825	275	-	-	90%	Active	46	65	14	28	64	8	30.5	456.9
	1st Floor	West	1800	45	825	275	-	-	90%	Pasive	46	37	0	47	53	0	30.5	456.9
	1st Floor	north	1800	45	-	275	-	-	90%	Active	46	66	11	26	74	0	30.3	454.1
	1st Floor	north	1800	45	-	275	-	-	90%	Pasive	46	37	0	47	53	0	30.3	454.1
	1st Floor	South	1800	45	825	275	-	-	30%	-	59	24	22	32	60	8	31.3	468.9
	1st Floor	South	1800	45	825	275	-	-	50%	-	63	33	30	30	58	13	30.9	463.1
	1st Floor	South	1800	45	825	275	-	-	70%	-	66	40	35	28	53	19	30.7	460.9
	1st Floor	North	1800	45	-	-	-	-	90%	Active	52	69	11	25	74	0	30.5	457.5
	1st Floor	North	1800	45	-	-	-	-	90%	Passive	52	42	0	44	56	0	30.5	457.5
	1st Floor	South	4500	45	825	200	775	DF	90%	Active	69	98	97	25	54	21	30.4	455.6
	1st Floor	South	4500	45	825	200	775	DF	90%	Passive	48	98	0	42	58	0	30.4	455.6
	1st Floor	South	3125	45	825	200	775	DF	90%	Active	68	87	78	25	55	20	30.6	459.2
	1st Floor	South	3125	45	825	200	775	DF	90%	Passive	47	87	0	43	57	0	30.6	459.2
	1st Floor	South	1800	45	825	200	775	DF	90%	Active	66	43	35	28	57	15	30.6	458.9
	1st Floor	South	1800	45	825	200	775	DF	90%	Passive	41	43	0	46	54	0	30.6	458.9
	1st Floor	South	4450	45	825	200	775	DF	90%	-	69	98	97	25	50	25	30.5	457.7
	1st Floor	South	3125	45	825	200	775	DF	90%	-	67	87	79	26	51	23	30.5	458.1
	1st Floor	South	1800	45	825	200	775	DF	90%	-	66	43	37	28	53	19	30.6	458.9
	1st Floor	South	4450	45	-	-	-	-	90%	-	74	98	98	24	38	39	29.8	447

Appendix E: Comparison between Standard and Daylit Buildings

THIRD-PARTY CONTENT

Source: Ternoey, S.E. (1999) Daylight Every Building. LightForms LLC, Daylighting Collaborative/Energy Center of Wisconsin Santa Barbara, CA. http://www.daylighting.org/pubs/daylight_every.pdf, accessed on 17 January 2011.

Appendix F: Hospital In-patient Room images with windows

THIRD-PARTY CONTENT

Figure F.1: Leeds Nuffield Hospital, UK, 2002; Carey Jones Architects.

THIRD-PARTY CONTENT

Figure F.2: Kidderminster, UK, 2003; MAAP Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.3: Charmes, France, 2003; Group 6/ BDP Architects.

THIRD-PARTY CONTENT

Figure F.4: Digne and Montceau, France, 2003; Group 6/ BDP Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.5: Digne and Montceau, France, 2003; Group 6/ BDP Architects.

THIRD-PARTY CONTENT

Figure F.6: Kidderminster Treatment Centre, 2003; MAAP Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.7: Clarian Methodist Hospital, Indianapolis, US; BSA Design Architects.

THIRD-PARTY CONTENT

Figure F.8: Clarian Methodist Hospital, Indianapolis, US; BSA Design Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.9: Northwestern Memorial Hospital, Chicago, Illinois, US; Hellmuth, Obata + Kassabaum, P.C. Architects.

THIRD-PARTY CONTENT

Figure F.10: Health Central Ocoee, Florida, US; HKS Inc.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.11: Riverview Regional Medical Center, The Women’s Pavilion Gadsden, Alabama, US; Helman Hurley Charvat Peacock Architects Inc.

THIRD-PARTY CONTENT

Figure F.12: PineLake Medical Center, Mayfield, Kentucky, US.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.13: Greater Baltimore Medical Center, Maryland, US, 1991; RTKL Architects.

THIRD-PARTY CONTENT

Figure F.14: Methodist Health Center, Sugarland, TX, US.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.15: Mary Birch Hospital for Women, San Diego, CA, 1994, HKS Architects.

THIRD-PARTY CONTENT

Figure F.16: Health Park Florida, Lee Memorial Hospital, Fort Meyers, FL, US, 1994, HKS Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.17: Methodist Health Center, Sugarland, TX, US.

THIRD-PARTY CONTENT

Figure F.18: Celebration Health, Celebration, FL, US.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.19: IHC McKay Dee Medical Center, Ogden, UT, US.

THIRD-PARTY CONTENT

Figure F.20: Children’s Hospital, Omaha, NE, US, 2000; HDR Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.21: Oklahoma Heart Hospital,Oklahoma City, OK, US, 2002; Watkins Hamilton Ross Architects.

THIRD-PARTY CONTENT

Figure F.22: La Rabida Children's Hospital- Inpatient Addition, Chicago, Illinois, US, 2002; VOA Associates Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.23: Sacred Heart Hospital, US, 2002; VOA GSP Architects.

THIRD-PARTY CONTENT

Figure F.24: Vail Valley Medical Center, Ambulatory Surgery Center & Women & Children Center, Vail, CO, US, 2003; HLM Design.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.25: Florida Hospital, Flagler, Palm Coast, FL, US, 2002; Gresham, Smith & Partnership & The Robins & Morton Group.

THIRD-PARTY CONTENT

Figure F.26: Hazelton General Hospital OB Unit, Hazelton, PA, US, 2002; Highland Associates, Architects.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.27: Northwestern Memorial Hospital, Chicago, Illinois, US; Hellmuth, Obata + Kassabaum, P.C. Architects.

THIRD-PARTY CONTENT

Figure F.28: Charles Canu Hospice, Centre Hospitalier, Vire France EU 1994; Y. Brunel.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.29: Poole Hospital, UK.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.30: Inha University Hospital, Inchon, Korea.

THIRD-PARTY CONTENT

Figure F.31: St. Joseph Regional Health Centre, Bryan, Texas, U.S.A.

Source: Choi, J., (2005). Study of the Relationship between Indoor Daylight Environments and Patient Average Length of Stay (ALoS) in Healthcare Facilities. Thesis (Master). Department of Architecture, Texas A&M University. College Station, TX.

THIRD-PARTY CONTENT

Figure F.32: PineLake Medical Center, Mayfield, Kentucky, US.

THIRD-PARTY CONTENT

Figure F.33: The Wellness Room, US.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.34: Single bedroom, US.

THIRD-PARTY CONTENT

Figure F.35: Single bedroom; HKS Architect.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

THIRD-PARTY CONTENT

Figure F.38: The Universal ICU, Desert Samaritan Medical Center, Mesa, Arizona, US, 2002; Orcutt/Winslow Partnership Architects.

THIRD-PARTY CONTENT

Figure F.39: LDRP Room, Before Delivery, Swedish Hospital, Seattle, WA, US. LDRP Room, Ready for Delivery, Swedish Hospital, Seattle, WA, US.

Source: Phiri, M. (2004) NHS Research Project: One Patient One Room – Theory and Practice: An evaluation of The Leeds Nuffield Hospital, January 2004, School of Architecture, University of Sheffield, UK

Appendix G: Publications during this PhD course

Journal Publications – Recognized and Refereed

- **Joarder, M.A.R** and Price, A.D.F. (2012). “Impact of Daylight Illumination on Reducing Patient Length of stay (LoS) in Hospitals after CABG Surgery". *Lighting Research & Technology.* [in press].
- **Joarder, M.A.R** and Price, A.D.F., (2012). “Impact of Climate Change on the Constructed Luminous Environment: An Evaluation for the Hospital In-patient Rooms Located in London”. The *International journal of the Constructed Environment.* [in press].
- **Joarder, M.A.R,** Price, A.D.F. and Mourshed M.M. (2010). “Access to Daylight and Outdoor Views: A comparative study for therapeutic daylighting design”. *World Health Design,* **3 (1)**: pp. 62-69.
- **Joarder, M.A.R** (2009). “A Survey on Daylighting Potentiality in the Offices of Dhaka Bangladesh*”. Global Built Environment Review (GBER),* **7(1)**: pp 5-22.

Conference Contributions – Refereed

- **Joarder, M.A.R.** and Price, A.D.F. (2012). “Therapeutic Daylight for Hospital Patients: A Search for the Benchmarks”. *European Conference on Design for Health*, July, Sheffield, UK. [in press].
- **Joarder, M.A.R** and Price, A.D.F., (2012). “Daylight Simulation in Architectural Practice: Shading Design for Hospitals in London”. *International Seminar on Architecture: Education, Practice and Research*, 02 - 04 February, Dhaka, Bangladesh, [in press].
- **Joarder, M.A.R,** Price, A.D.F. and Mourshed M.M. (2009). “The Changing Perspective of Daylight Design to Face the Challenge of Climate Change”. *3rd CIB International Conference on Smart and Sustainable Built Environments*, 15-19 June (SASBE, 2009), Delft, The Netherlands, (CD).
- **Joarder, M.A.R,** Ahmed, Z.N., Price, A.D.F., and Mourshed M.M. (2009). “Daylight Simulation for Sustainable Urban Office Building Design in Dhaka, Bangladesh: Decision-making for Internal Blind Configurations”. *2nd International Conference on Whole Life Urban Sustainability and its Assessment*, 22-24 April (SUE-MoT 2009), Loughborough, UK, pp. 218-41.
- **Joarder, M.A.R,** Ahmed, Z.N., Price, A.D.F. and Mourshed M.M. (2009). “A Simulation Assessment of the Height of Light Shelves to Enhance Daylighting Quality in Tropical Office Buildings under Overcast Sky Conditions in Dhaka, Bangladesh”. *11th International Building Performance Simulation Association Conference and Exhibition*, 27-30 July (IBPSA, 2009), Glasgow, UK, pp. 1706-13.
- **Joarder, M.A.R,** Price, A.D.F., and Mourshed M.M. (2009). “A Systematic Study of the Therapeutic Impact of Daylight Associated with Clinical Recovery”. HaCIRIC PhD workshop, *2nd Annual International Conference of the Health and Care Infrastructure Research and Innovation Centre, Improving healthcare infrastructures through innovation*, 1-3 April (HaCIRIC, 2009), Brighton, UK, pp. 25-31.

Conference Contributions – Others

- **Joarder, M.A.R** and Price, A.D.F., (2011). “Impact of Climate Change on the Constructed Luminous Environment: An Evaluation for the Hospitals in London”. *Second International Conference on the Constructed Environment, 29-30 October 2011, University Center, Chicago, USA*.
- **Joarder, M.A.R.** and Price, A.D.F. (2011). “Therapeutic Daylight for Hospital Patients: A Search for the Benchmarks”. *European Conference on Design for Health*, 13-15 July, Sheffield, UK, pp 58-60.
- **Joarder, M.A.R.,** Price, A.D.F. and Mourshed, M.M. (2009). “Impact of Daylight on Open Heart Surgery Patients: An Evidence Based Study necessary for Therapeutic Daylighting Design”. *6th World Congress on Design and Health*, June 24-28, Singapore.

Posters

- **Joarder, M.A.R** (2011). “Daylit Hospitals to Accelerate Clinical Recovery”. *Health and Life Sciences Research Student Conference*, Loughborough University, 14 March, Loughborough, UK.

- **Joarder, M.A.R** (2010). “Use of Daylight to Accelerate Clinical Recovery”. *Poster Competition for PGRs*, Loughborough University, 7 May, Loughborough, UK.

- **Joarder, M.A.R,** Price, A.D.F. and Mourshed M.M. (2009). “Implementation of Therapeutic Daylight on Hospital Design to Accelerate Clinical Recovery: A Search for Knowledge Gap and Development of an Evidence Based Methodology”. ACHSE *National Congress*, 4-7 August, Gold Coast, Australia.

- **Joarder, M.A.R** (2009). “Innovative Healthcare Design with Daylighting to Support Clinical Recovery”. *Engineering and Physical Sciences Research Council (EPSRC) Panel Review*, 23 September, University of Reading, Reading, UK.

- **Joarder, M.A.R,** Ahmed, Z.N., Price, A.D.F. and Mourshed M.M. (2009). “A Simulation Study of the Effectiveness of Light Shelves to Enhance Daylighting Quality in Tropical Offices, Dhaka”. *IBPSA Conference*, 27- 30 July, Glasgow, UK.

- **Joarder, M.A.R,** Price, A.D.F. and Mourshed M.M. (2009). “UVR Protection from Sun inside the Buildings: New Perspective of Daylight Design to Face the Challenge of Climate Change”. *SASBE Conference*, June15-19, Delft, The Netherlands.

The outcome of this PhD was presented in the following conferences/ seminars/ workshops

- **Joarder, M.A.R,** (2012). “Daylight Simulation in Architectural Practice: Shading Design for Hospitals in London”. *International Seminar on Architecture: Education, Practice and Research*, 03 February, Dhaka, Bangladesh.

- **Joarder, M.A.R**, (2011). “Impact of Climate Change on the Constructed Luminous Environment: An Evaluation for the Hospitals in London”. [virtual presentation] *Second International Conference on the Constructed Environment, 29-30 October 2011, University Center, Chicago, USA.* Available at: http://www.youtube.com/watch?v=0tggKbJvyqk [Accessed 1 December 2011].

- Shikder, S. and **Joarder, M.A.R**, (2011). "Improving the Therapeutic Performance of Healthcare Spaces: Modelling, Simulation and Visualisation (MSV) of Aesthetics and Lighting". Final Project Reviews, Health and Care Infrastructure Research and Innovation Centre (HaCIRIC), Imperial College, 20 October, London.

- **Joarder, M.A.R.** (2011). "Therapeutic Daylight for Hospital Patients: A Search for the Benchmarks". *European Conference on Design for Health*, 14 July, Sheffield, UK.

- **Joarder, M.A.R** (2011). "Daylit Hospitals to Accelerate Clinical Recovery". *Health and Life Sciences Research Student Conference*, Loughborough University, 14 March, Loughborough, UK.

- Shikder, S. and **Joarder, M.A.R**, (2010). "Therapeutic lighting design for the elderly“. *HaCIRIC workshop*, Department of Civil and Building Engineering, 21 October, Loughborough University, UK.

- **Joarder, M.A.R.** (2009). "Impact of Daylight on Open Heart Surgery Patients: An Evidence Based Study Necessary for Therapeutic Daylighting Design". *6th World Congress on Design and Health*, 25 June (WCDH, 2009), Singapore.

- **Joarder, M.A.R.** (2009). "The Changing Perspective of Daylight Design to Face the Challenge of Climate Change". *3rd CIB International Conference on Smart and Sustainable Built Environments*, June 16 (SASBE, 2009) Delft, The Netherlands.

- **Joarder, M.A.R.** (2009). "Daylight Simulation for Sustainable Urban Office Building Design in Dhaka, Bangladesh: Decision-making for Internal Blind Configurations". *Second International Conference on Whole Life Urban Sustainability and its Assessment*, 23 April (SUE-MoT 2009), Loughborough, UK.

- **Joarder, M.A.R.** (2009). "Direct and Indirect Impacts of Daylight on Hospital Patients and an Evidence Based Research Necessary for Sustainable Daylit Hospital Design". *PhD Workshop, Second International Conference on Whole Life Urban Sustainability and its Assessment*, 22 April (SUE-MoT 2009), Loughborough, UK.

- **Joarder, M.A.R.** (2009). "A Systematic Study of the Effect of Daylight on Hospital Patients and an Evidence Based Research Output". *HaCIRIC PhD workshop, 2nd Annual International Conference of the Health and Care Infrastructure Research and Innovation Centre, Improving healthcare infrastructures through innovation*, 1 April, Brighton, UK.

- **Joarder, M.A.R.** (2009). "Implementation of Therapeutic Daylight on Architectural Design of Hospital Buildings to Accelerate Clinical Recovery". *Second Doctoral Seminar, Department of Civil and Building Engineering*, 24 February, Loughborough University, UK.

- **Joarder, M.A.R.** (2008). "A Study of Daylit Hospital Building to Support Clinical Recovery". *HaCIRIC Phd Research Seminar 1,* Department of Civil and Building Engineering, 7 July, Loughborough University, UK.