Perforated Screens to Optimise Daylighting and Maintain Privacy in Girls' Schools in Hot Arid Areas:
The Case of Saudi Arabia

Investigating Parameters of Perforated Solar Screens

Welsh School of Architecture
Cardiff University

A thesis submitted in fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by **Ahmad G. Kotbi**

2019

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

ANNEX 1:
Specimen layout for Declaration/Statements page to be included in a thesis.

DECLARATION

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

Signed .... (candidate) Date ......03/May/2019............

STATEMENT 1

This thesis is being submitted in partial fulfillment of the requirements for the degree of ....PhD.......

Signed .... (candidate) Date ......03/May/2019............

STATEMENT 2

This thesis is the result of my own independent work/investigation, except where otherwise stated, and the thesis has not been edited by a third party beyond what is permitted by Cardiff University's Policy on the Use of Third Party Editors by Research Degree Students. Other sources are acknowledged by explicit references. The views expressed are my own.

Signed .... (candidate) Date ......03/May/2019............

STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available online in the University's Open Access repository and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .... (candidate) Date ......03/May/2019............

STATEMENT 4: PREVIOUSLY APPROVED BAR ON ACCESS

I hereby give consent for my thesis, if accepted, to be available online in the University's Open Access repository and for inter-library loans **after expiry of a bar on access previously approved by the Academic Standards & Quality Committee.**

Signed .... (candidate) Date ....

Perforated Screens to Optimise Daylighting and Maintain Privacy in Girls' Schools in Hot Arid Areas: The Case of Saudi Arabia

Investigating parameters of perforated solar screens

Abstract

This study investigates the special case of girls' schools in Saudi Arabia, where there are strict privacy requirements due to sociocultural and religious factors.

In the last few decades prototype buildings were introduced in this country to cover for the demand for school buildings in Saudi Arabia following the rapid economic growth since the discovery of oil. Prototypes were used for boys' and girls' schools without due consideration of the privacy requirements applicable to girls' schools. In the girls' schools most windows are blocked with dark opaque films or solid boards to maintain privacy. Such window treatments make electrical lighting a necessity at all times. Consequently, girls' schools have become one of the biggest energy consumers in the country when taking into consideration the number of schools and the peak time operational hours Moreover, the quality of life for the occupants of the buildings has been affected, as the lack of daylight is known to have negative effects on health, well-being and productivity.

This study will be examining the use of perforated solar screens on existing windows to resolve the problem, The aim of the research is to ascertain the configurations for the parameters of the proposed perforated solar screen, in order to provide acceptable daylight performance alongside maintaining privacy for occupants. The investigated parameters are: perforation rate, depth ratio, aspect ratio, cell size and tilting angle. Different values of each parameter are tested using lighting simulation and a qualitative study was designed and applied in order to investigate the privacy aspects. The results of these investigations have identified the recommended configuration for the parameters of perforated screens for each one of the main orientations: north, east, south and west, to achieve acceptable interior daylight conditions and provide privacy.

Dedication

I proudly dedicate my dissertation to my inspiration, my great-grandfather Abdulsattar Kotbi Aldahlawi (1869–1936) who was the author of more than 185 handwritten books. I also dedicate this work to my lovely wife Nada and gorgeous daughters, Amaya and Alana, and my future children. I also dedicate this work to my beloved mother and my dear father, and my siblings and their children.

Acknowledgement

Prima facie, all praises to God for giving me strength, well-being and the blessings I needed to complete this thesis. There are no words to describe my grateful thanks to King Salman and his Predecessor King Abdullah, as without their limitless support for education it would have been extremely difficult for me to accomplish this achievement.

I wish to express my sincere gratitude to my three supervisors; each one has played a vital role in my PhD. My earnest thanks to Dr Eleni Ampatzi for her continuous support of my PhD studies and her insightful comments and encouragement.

I would also like to extend a special thanks to Dr Julie Gwilliam, for the continuous support, valuable advice, and positive appreciation. Indeed, this work would not have been possible without her guidance, involvement and recommendations, especially during the maternity leave of my first supervisor until the submission date. Under her guidance I successfully overcame many difficulties and learnt a lot.

I am greatly indebted to Mr Huw Jenkins, for his motivation, zeal and immense knowledge in modelling, lighting measurements and using the sky dome facility. His advice and experience has been tremendously helpful throughout the research tenure. I would like also to thank the examiners of my thesis for their time and valuable feedback and comments.

Besides my supervisors, I would like to extend my gratitude to the staff members in WSA, especially the research officer Ms Katrina Lewis for her support and assistance especially whenever I asked for a letter for my sponsors. My sincere thanks also go to Mr Dan from the workshop and Mr Matthew from the FabLab for their help in creating my models; their help and advice, helped me to overcome many difficulties in creating my models. My thanks go also to the operations manager Mrs Kate Nash for her assistance in filling the risk assessment application. I also thank the financial support from WSA to attend conferences and Ms Susan Bowden for dealing with the financial matters.

I am also grateful for the financial and logistic support received through the Saudi Arabian Cultural Bureau and Ministry of Education. I am indebted to King Saud University for the scholarship and the research fund to undertake my PhD. My appreciation goes also to the deputy of building in the Ministry of Education for providing me with schools plans and allowing me access to school buildings especially Mr Fatani who organised all required meetings.

My gratitude goes to Dr John Mardaljevic, Dr Christoph Reinhart and Dr Alstan Jakubiec, world leaders in daylight simulation. I was so blessed and honoured to meet and know them during daylight conferences, forums and workshops. They continued to support me by emails whenever I have any enquiries. I would like also to thank Solemma LLC for providing Diva-for-Rhino software with a free education license.

It is my fortune to gratefully acknowledge the support of all my fellow PGR mates in WSA, especially, Saba, Anas, Amer, Dua'a, Sally, Mohammed, Hashem, Lama, Katerina, Amalia, Charlie, Clara, Chris, Diana, Hamida, Alissia, Carla, Tina, Noor, Irinie, Melina, Manos and Vasillis, for their motional support and all the days and nights we have worked together, as well as all the fun we had during our PhD candidature. I wish the best of luck to all of them in their endeavours!

Many thanks go to my brothers in foreignness, Manna, Mashhour, Loai, Homam, Emad, Ahmad, Amr and their families, who have provided both friendship and support for me as well as my family, and with whom we have shared laughter, frustration and companionship. They have been more than a family to me; our friendship will not be forgotten. A special graceful to my in-laws Dr Hatem, Dr Rana and their children Lamar, Malik and Lareen, their being in Cardiff during my first years made the life of my family and I much more easier due to their unlimited support by any means from the moment we arrived in Cardiff.

I would like to extend my sincerest thanks and appreciation to my lovely mother and dear father for all of the love, support, encouragement and prayers they have sent my way along this journey. Their unconditional love and support has meant the world to me and I would never be able to pay back the love, affection and sacrifice they provided to shape my life. I hope that I have made them proud. I am also grateful to all of my siblings; they have pushed me to succeed. In particular, I am grateful to my twin brother Dr Mohammed, We have shared the same womb, room, classroom, friends, until we graduated together. We have separated to continue our education, each at his own pace. He has finished his PhD before me and now it is time to rejoin him again to teach at the same school we have graduated from.

My heart-felt regards go to my dear wife, Nada for her continued and unfailing love, support and understanding during my pursuit of my PhD, that made the completion of my thesis possible. She was always around whenever I needed any kind of support; she helped me to keep things in perspective. I greatly value her contribution and recommendations in the optometry aspect of my research. I deeply appreciate her belief in me. I also appreciate my daughters, who have given me much happiness and filled my life with love. Each one is deeply loved in a unique way. Amaya, has grown up watching me studying and juggling between family and work, encouraging me to finish my book as she calls it. Alana, the little one, who always tries to do anything to make me smile and bring joy to my life. Words would never say how grateful I am to the three of them. I consider myself the luckiest person in the world to have such a lovely and caring family, standing beside me with their love and unconditional support.

Glossary of Abbreviations

DF	Daylight factor
DC	Daylight coefficient
CBDM	Climate Base Daylight Modelling
BRE	Building Research Establishment
IDMP	International Daylight Measurement Programme
DDPMs	Dynamic Daylight Performance Metrics
TAI	Total Annual Illuminance
SBI	Sunlight Beam Index
DA	Daylight Autonomy
DA_{con}	Continuous Daylight Autonomy
DA_{max}	Maximum Daylight Autonomy
sDA	Spatial Daylight Autonomy
ASE	Annual Sunlight Exposure
UDI	Useful Daylight Index
lx	Lux, measuring unit of Illuminance
fc	Foot-candles, US measuring unit of Illuminance
IES	Illuminance Engineering Society
IESNA	Illuminance Engineering Society of North America
CIBSE	Chartered Institution of Building Services Engineers
DIVA	Design Iterate Validate Adapt
E	Illuminance
L	Luminance
UV	Ultraviolet waves
MAR	Minimum Angle of Resolution

Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

1.1 Introduction

Providing visual privacy for occupants has become a rising issue in an increasingly crowded world, where traditional spacing between windows in buildings is often not possible. In some extreme cases, due to socio-cultural restrictions, the need for providing visual privacy tends to directly control the design of buildings and the way they operate and how their openings are treated. In order to investigate this area, the author looks at the specific case of girls' schools in Saudi Arabia, and in particular those schools that were not designed initially to be used as girls' schools for reasons discussed later in this chapter. Windows currently used in these schools are non-openable and covered with dark opaque materials. Many problems are associated with this act, especially the lack of indoor daylighting. Therefore, a better solution is needed for those windows.

There are numerous benefits from using natural light to provide illumination indoors in school buildings for students' health and well-being, both psychologically and physiologically, and in saving energy on lighting to reduce carbon emissions, the main contributing factor of global warming. Although using natural light has some negatives such as glare, low uniformity ratio and heat gain, these can be overcome however, by using appropriate sun-shading strategies designed according to the orientation and location of the building.

This thesis examines the use of perforated solar screens in girls' schools in Saudi Arabia to promote privacy and enhance indoor daylighting which could accordingly reduce energy consumed in artificial lighting.

1.2 Research context

It is important to look through the local context in order to have a better understanding of the problem. This section presents a background of the context of this research; it provides an overview of geographical characteristics of the local context of Saudi Arabia and the capital city of Riyadh. It also explains the economic and demographic development of the last 50 years leading to the current issues discussed here as relevant to this study. The section also introduces the education system and the socio-cultural background in Saudi Arabia that led to the privacy issue in girls' schools.

1.2.1 Location and climate of Saudi Arabia

Saudi Arabia is located in South-west Asia and occupies four fifths of the Arabian Peninsula with an area of 1,960,582km^2, making it the third largest country in Asia following China and India, and the second largest Arab country after Algeria. It is bounded on the north by Iraq and Jordan, on the north-east by Kuwait, on the east by the Arabian gulf, Qatar and the United Arab Emirates (UAE), on the south by Oman and Yemen, and on the west by the Red Sea and the Gulf of Aqaba, with a total estimated land boundary length of 4,431km and 2,640km coastline (Figure 1.1).

Figure 1.1: Map of Saudi Arabia (source: Nations Online Project 2018).

This widespread area contains a variety of topography although one third of the total area is sandy deserts. There are mountains as high as 2,740m in the south and western regions, and the central region is located on a large plateau with an elevation range between 1,520m in the west and 610m in the east (Worldmark Encyclopedia of Nations 2007). Although there are lots of wadis, there are no perennially flowing waters nor lakes except some small oases in deserts. This location makes its climate one of the hottest climates.

Koenigsberger (1973) has defined climate as “an integration in time of the physical state of the atmospheric environment, characteristic of a certain geographical location”. Climate is one of, if not, the most important factor influencing buildings and human behaviour (Fathy 1986). Peel et al. (2007) have categorised the world map into 29 different climate zones, and the climate of Saudi Arabia was categorised as a hot arid climate, since it is located between the tropic of Cancer and the equator, and therefore, the location is one of the most likely to receive direct solar radiation on Earth (Solar GIS 2013). Saudi Arabia is one of the hottest and most arid countries in the world, as it is located within the same desert belt as the Sahara (Facey 1997).

The country has a variation in geographical barriers such as mountains, plateaus, deserts, oases and valleys which divide the country into different climatic regions, each of which has its own climate, traditions and architectural heritage (Ministry of Culture and Information 2000). Talib (1984) and El-Sabbagh (1982) have explained that there are four local climatic regions in Saudi Arabia. The central region has a hot and arid climate. The coastal region in the east and west has a hot and humid climate. The upland region, with mountains as high as 1200–1800m, has a cold rainy climate, and the northern region has a hot dry climate. This research is focusing on school buildings in the city of Riyadh which is located in the central region.

The city of Riyadh is surrounded by deserts so generally it has a hot and arid climate and it lies on Latitude 24.7° north, Longitude 46.80° east and elevated 612m

above sea level (High Commission for the Development of Riyadh 2016). Summer temperatures could reach 42°C accompanied by harsh sandstorms (Abanomi and Jones 2005).

1.2.2 Development of Saudi Arabia and the city of Riyadh

Over the last 50 years, cities and towns in Saudi Arabia have been developed significantly due to the strong economic growth resulting from the discovery of its oil reserves. Establishing the oil industry has led to a vast economic growth that changed the country into a modern developing one (Mubarak 2004). As a result, a remarkable growth in urban development has been witnessed in most cities in general and specifically in Riyadh.

The rapid economic growth has been followed by a demographic growth, and the country has become one of the fastest growing countries in the world. According to the Food and Agriculture Organisation of the United Nations, in a database to compare the economic growth and the urbanisation between countries, the population of Saudi Arabia multiplied seven times in about 50 years from 4.2 million in 1961 to 32.2 million in 2016 (Food & Agriculture Organization 2017). The data includes the most recent survey conducted in Saudi Arabia by the Saudi Central Department of Statistics and Information (Figure 1.2). With a 2.7% expected annual growth, the population is expected to reach 37,610,985 inhabitants by 2025 (Aldossary 2015).

Being the capital of the country, Riyadh has grown more rapidly than any other region. In about 40 years, due to urbanisation and migration to big cities, Riyadh has transformed from a town in the 60s with 25,000 inhabitants to an international metropolis with ten times the population of 2.5 million inhabitants by the year 2000 (Al-Hemaidi 2001). The population was then doubled in one decade reaching 5.2 million inhabitants in 2010 (Al-Qahtany 2014). The United Nations estimates a growing annual rate of 2.95% in urban areas of Saudi Arabia, however, recent re-

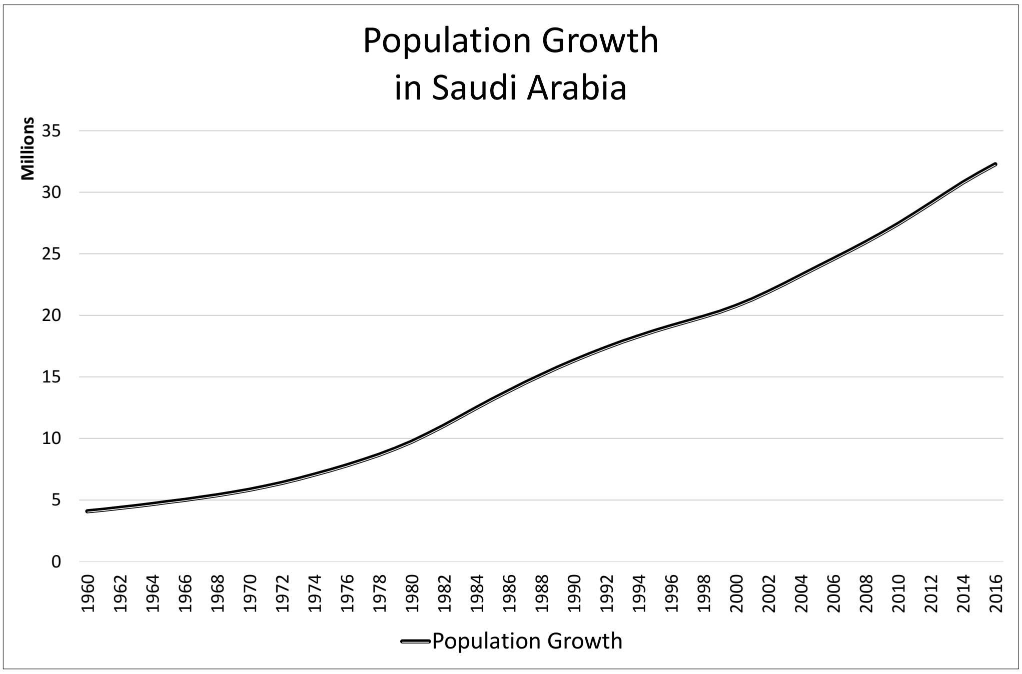
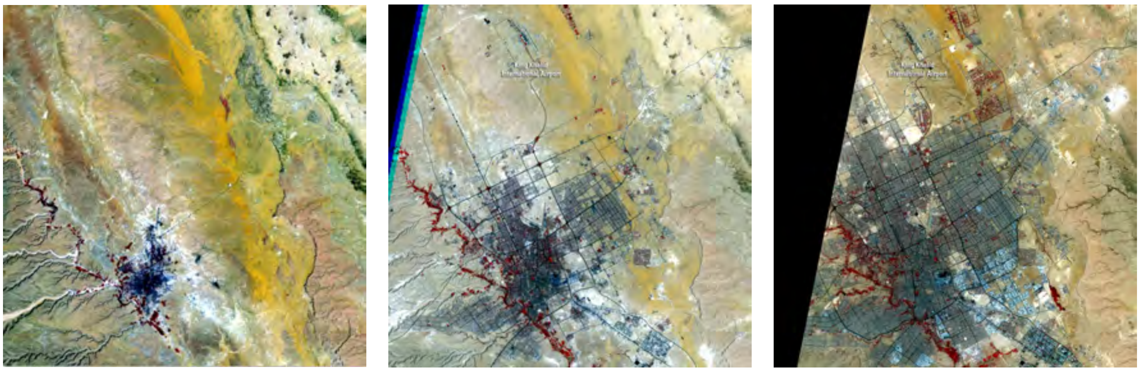


Figure 1.2: Population growth in Saudi Arabia (adapted from: World Bank 2017).

ports showed that Riyadh had a 4% annual growth between 2010 and 2016 reaching a population of 6,506,700 (High Commission for the Development of Riyadh 2016), which is equal to more than 20% of the total population of Saudi Arabia. The population of Riyadh is expected to reach 10 million by 2020 (Garba 2004). Parallel to the demographic growth, there was also a forced spatial growth, for accommodating the increasing number of inhabitants. The area of Riyadh has expanded more than a hundred times in about half a century. The recorded area of the city reached $765km^2$, $2435km^2$ and $2700km^2$ in 1996, 2008, 2011 respectively (Ibrahim 2010). Figure 1.3 shows satellite images for the urban growth of Riyadh from 1972 to 2016 (US Geological Survey 2016).

In order to organise and control the expanding demand for services, the Government of Saudi Arabia established the local and national governance in 1970, namely, the Ministry of Planning, that was in charge of national development planning, and the Ministry of Municipal and Rural Affairs, that was in charge of spatial planning at the national, regional and local levels in addition to the provision and management of infrastructure (Almotairi 1995). This growth has resulted in many changes in the social context and surrounding environment of the city; these changes have



(a) Riyadh 1972. (b) Riyadh 1990. (c) Riyadh 2016.

Figure 1.3: Satellite images showing development of Riyadh (source: US Geological Survey 2016).

been discussed extensively in the relevant literature (Chaaban 2008; Al-Fouzan 2012; Mubarak 2004).

As Riyadh is the biggest, most developed and most populated city with the highest annual growth rate, the city is chosen to be the focus of this research rather than any other city in Saudi Arabia.

The traditional architecture in Saudi Arabia has been developed over centuries to reflect and adapt to the local environment and its hot climate. There have been efforts to utilise wind circulation for cooling, using techniques such as, central courtyards, wind catchers and shading devices (Al-Oraier 2005). Some buildings embedded these techniques in seeking to provide acceptable levels of comfort in the indoor environment for inhabitants. The massive population growth forced the government to commission housing projects with foreign construction companies in order to meet the demand for housing, generating large-scale urban development. Over time, it appeared that the imported foreign designs and regulations were inadequate for meeting inhabitants' needs and local conditions (Al-Hathloul 1981), especially the issue of visual privacy in buildings. This growth impacted on the urban scale, and the resulting landscape became more crowded, affecting the traditional privacy spacing between windows in buildings. Moreover, this direct application of foreign architectural forms has resulted in a construction practice that does not respond to the key local factors and does not consider local materials and traditions.

1.2.3 Global warming in Saudi Arabia

The vast growth in Saudi Arabia created demands for infrastructure and new buildings of all types. Consequently, the energy demand and consumption has substantially risen, affecting the development of the country; some important industrial projects have been delayed and sometimes brownouts have occurred as a result of insufficient capacity of power supplies, particularly in the summer when the peak cooling demand occurs (Al-Twaijri 2002). Alongside the energy demand issues, there are also environmental problems due to the generation of pollutants by this massive energy consumption as the demand is largely met by gas. In the last 20 years, Carbon Dioxide (CO_2) emissions in Saudi Arabia have risen from 218 million tonnes to 464.4 million tonnes (World Bank 2017) (Figure 1.4).

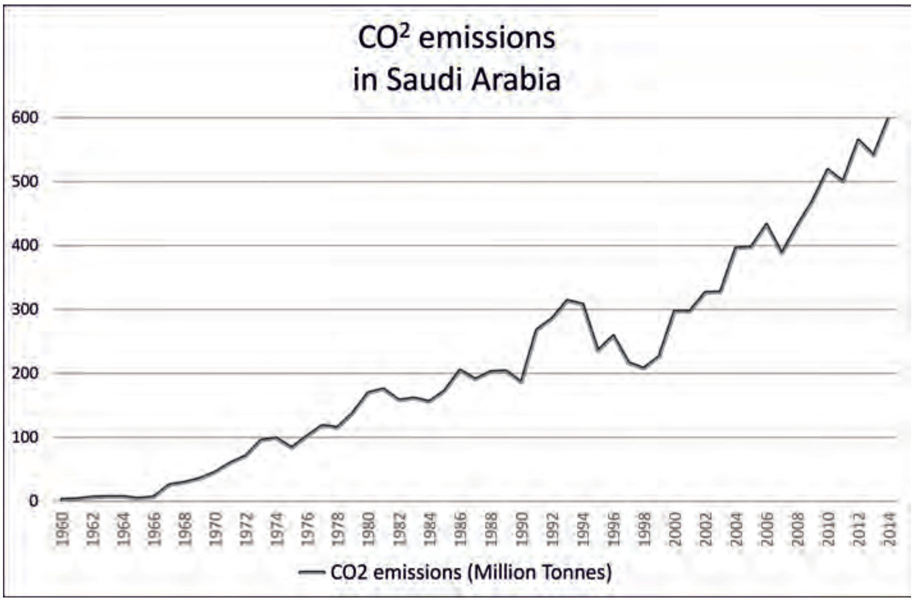


Figure 1.4: CO_2 emissions in KSA (adapted from: World Bank 2017).

A report in 2014 (British Petroleum 2014) stated that Saudi Arabia is the 12^{th} largest consumer of total primary energy in the world. Consequently, the country is now one of the highest CO_2 production countries per capita, and is now comparable to that of major industrial countries such as Australia and the US (World Bank 2017) (Figure 1.5).

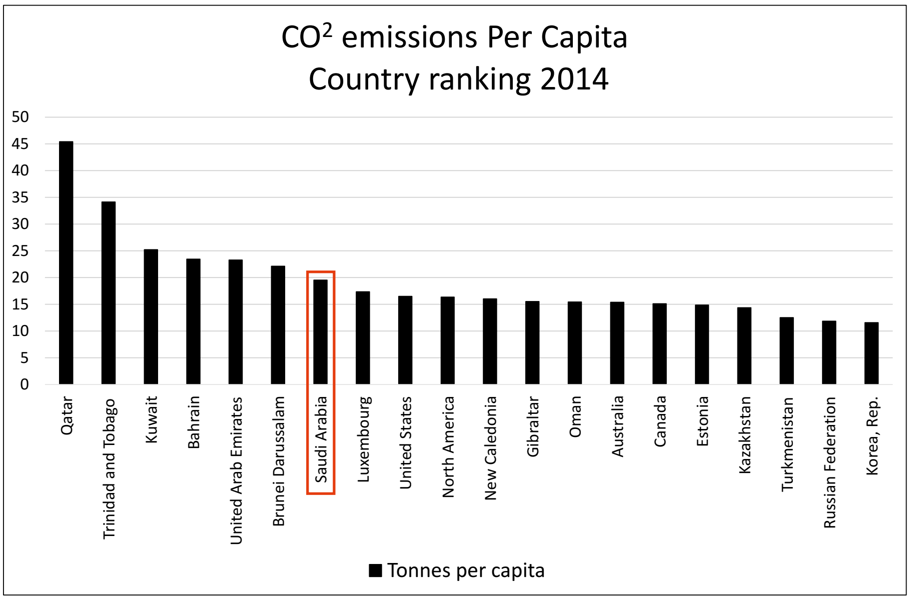


Figure 1.5: Country ranking for CO_2 emissions per capita (adapted from: World Bank 2017).

Generating electricity in Saudi Arabia is completely dependent on the unsustainable practice of fossil fuel burning (at the time of writing this thesis), which has a major environmental impact on air, climate, water and land (Alnatheer 2006; Taleb and Sharples 2011). The government of Saudi Arabia signed the Kyoto protocol in 2004 committing to minimise the environmental damage and reduce the rate of energy consumption (Taleb and Sharples 2011). However, the US Energy Information Administration (EIA) (2014) estimates an annual growth of at least 4.5% of energy demand in Saudi Arabia. In 2010, Saudi Arabia accounted for 4.5 hectares of ecological footprint per person (Susilawati and Al Surf 2011), that is almost double the universal average per person. The Saudi Ministry of Industry and Electricity has estimated that by 2023, at least 77,000GW will be needed in Saudi Arabia at a cost of $117 billion (Al-Oraier 2005).

According to the Intern-governmental Panel on Climate Change (IPCC) (2014), greenhouse gas emissions contribute most to global warming, and the building sector among all sectors, has the greatest potential for greenhouse gas reductions. Around two fifths of the consumed energy around the world is used to operate buildings (Hong et al. 2000; Roodman 1995). This is comparable to the 41.7% in the US and

44% in European Union (Energy Information Administration 2012). In contrast to these, the proportion of energy consumed by the building sector is higher in Saudi Arabia because the industrial sector is much smaller than in the US and Europe.

In previously published reports (Ministry of Industry and Electricity 1993, 2002), the building sector is found to be responsible for 65% of the total energy consumption (Al-Sanea et al. 2012). Thus, in such a big capital city like Riyadh, this number is as high as 88% according to the Saudi Consolidated Electrical Company (2001), the only provider of electricity in Saudi Arabia. This large consumption of electrical energy by buildings in Saudi Arabia presents a major potential for reducing energy consumption (Fasiuddin and Budaiwi 2011). Therefore, architects, engineers and designers have a significant role to play in controlling energy consumption and its corresponding impact on global warming by improving the design of buildings and the integration of services to lower the energy consumption of buildings.

Desert areas such as Saudi Arabia have a great potential for providing a successful sustainable environment in buildings, because they are endowed with an abundance of clear skies and excellent luminous settings (Sabry et al. 2010). Previous studies have shown that retrofitting a residential building with due consideration to the local climate in Saudi Arabia can reduce the electrical consumption effectively (Al-Mofeez 2007; Numan et al. 2000). Other studies also indicated that by doing so in Saudi Arabia, a payback time for the cost of a power plant could be as short as seven years (Al-Khoutani 2001; Al-Ragom 2003), this payback time refers to the save in budget since the government pays electricity bills for public buildings including schools. Retrofitting old buildings has also a potential to bring economical benefits at national level (Al-Khoutani 2001) as retrofitting old buildings could save capital investment on a new power generating plant and increase efficiency in plant operation. The above findings are based on studies considering all building types. It is anticipated that the potential will be at least similar, if not higher, for school buildings, as discussed below and due to the fact that schools operate at peak hours with regard to electricity usage.

1.2.4 Schools in Saudi Arabia

After discussing the development of Saudi Arabia and Riyadh particularly in Section 1.2.2, it is apparent that the education sector has also expanded rapidly in a short period of time. As a matter of fact, the education sector faced the most sudden changes, given also that the education in Saudi Arabia has become compulsory only in the late 60s (Al-Soliman 1994), in fact the first ever high school for girls in Saudi Arabia opened in 1963 (Al-Hokail 1992). According to the Ministry of Education in Saudi Arabia, the number of enrolled students in schools multiplied ten times from 300,000 in 1965 to more than 3 million students in less than 40 years (Ministry of Education 2004). Numerous school building projects were needed across all levels to accommodate this large number of students, which tripled the number of school buildings in less than 35 years from 3,283 in 1970 to 30,414 (Abanomi and Jones 2005). As a fast solution during that time, many buildings were rented and re-purposed to be used as schools. These buildings were originally designed and built for other uses, mostly residential and commercial (Al-Soliman 1995). Due to this emerging need to build as many schools as possible in the shortest period, prototype school buildings were also introduced. The key factors driving the design of these prototype buildings were low cost and fast construction; therefore, schools were designed with little effort made towards the utilisation of the natural resources to improve indoor conditions (Abanomi and Jones 2005). In the 70s and 80s five prototype design variations were used around the country, according to the size requirement for the new school (Al-Soliman 1995). These prototypes were used across the country without considering the local climate of each region (Khafaji 1987; Al-Soliman 1981, 1994).

The latest report of the General Authority of Statistics in Saudi Arabia (2017) about numbers of pupils and schools in Riyadh, is summarised in Table 1.1 and 1.2 respectively. The last column of the table (highlighted) presents the data covering the number of female students in public schools which is related to this research.

In Riyadh, almost all schools rely on mechanical equipment to cool down spaces in summer and provide heating in winter, and rely on artificial light to illuminate interior spaces (Abanomi and Jones 2005; Al-Hemmiddi 2002). Consequently, these schools have become major energy consumers, considering the high number of schools (2,692) as can be seen in Table 1.2 and the fact that they operate during peak hours (Al-Soliman 1981).

Table 1.1: Numbers of students in Riyadh (Source: General Authority of Statistics 2017).

	Boys		**Girls**	
	Private	Public	Private	**Public**
Elementary pupils	58,203	169,448	45,495	**185,809**
Middle pupils	25,142	84,429	15,225	**92,757**
Secondary pupils	39,327	38,844	21,970	**59,647**
Total	122,672	292,721	82,690	**338,213**
Grand total	836,296			

Table 1.2: Numbers of schools in Riyadh (Source: General Authority of Statistics 2017).

	Boys		**Girls**	
	Private	Public	Private	**Public**
Elementary schools	163	513	232	**456**
Middle schools	150	267	146	**276**
Secondary schools	109	112	105	**163**
Total	422	892	483	**895**
Grand total	2,692			

Public education is free in Saudi Arabia (at the time of writing this thesis), and therefore the cost of constructing and running schools falls on the government funds for education. As the main income to the country is oil productions and revenues from oil is not stable, sometimes the education budget is frozen or reduced because of low oil prices (Shash 2005). In fact the oil price has recently dropped and the government started to struggle and reduce the budget in all sectors. Therefore, it is important to reduce the running cost for school buildings in order to enhance resilience and limit reliance on the unstable revenue from oil.

1.2.5 Privacy for women in Saudi Arabia

In a conservative society like that of Saudi Arabia, there are some religious and cultural barriers that affect everyday life. According to Struyk (2005), part of the problem faced by Riyadh and many other cities in the Middle East and North Africa is the struggle between the modern, globalised city and the traditional Muslim ideals of the community. Most relevant to this research is the level of privacy required for women, as females must remain covered in the attendance of unrelated men (Mahfouz and Serageldin 1990). They have to wear a black robe called Abaya and a veil on the head to be covered. The requirement for women wearing Abaya and veil in public spaces is regulated in Saudi Arabia by the Islamic law. The restriction applies also to non-Muslim women present in the country. In addition to being a requirement, the notion of privacy is also embedded in the religious belief for most Saudi women; some women continue to wear Abaya when travelling in other countries although they are not obligated to.

According to Susilawati and Al Surf (2011), privacy is a challenging factor for Riyadh's residents today, and the reason for that is the lack of proper building codes that may help regulate the need for privacy. This need for privacy has resulted in a gender restriction in some buildings such as schools, banks and some government buildings in order to allow female employees and students to work or study without wearing a veil inside their working environment, whether it is a whole building or just a section in a building. In order to provide visual privacy, windows of such buildings should not provide any visual connection from outside to the inside. The most common features used for this purpose are frosted glass, blackout films or curtains. This prohibition imposed by socio-religious restrictions is the reason why the education sector is gender separated in Saudi Arabia (Al-Mayoof 2003).

This separation adds more challenges to the resources and budget for education, as it means that every district needs at least two schools, one for boys and one for girls. Consequently, each school has to cover a larger catchment area for students than any other ordinary school resulting in longer distances between students and their school and longer transportation trips. This high level of privacy is the main reason for gender separation in the education system in Saudi Arabia. Hence, the level of privacy required in girls' schools is extremely high. Girls' schools have female only teachers and employees, and no men are allowed inside including male parents. The only exception is for emergency cases when fire fighters or paramedics need access. None of the school occupants should be identifiable from outside through openings.

1.3 Definition of the problem

The previous section discussed the rapid growth in the education sector since primary education became compulsory in this region in the 1960s. To meet this need, the government used prototype buildings and these prototype schools were not different in design for either gender so were introduced without any consideration to the privacy issue. The issue would have been solved if schools were designed to be used for girls in first place, as is the case with many private girls' schools that were designed with courtyard solutions for privacy and access to daylight. Instead administration of public schools tried to solve the problem by covering windows with black opaque films or boards. Photos of the current situation in public schools where the issue is experienced were presented by Abanomi (2005) (Figure 1.6). He discussed that this approach does not only affect the well-being of students and energy demand for artificial lighting, it also increases the yearly maintenance cost and time as these covers must be removed from every single school during the annual maintenance process every summer (Figure 1.7).

However, this research is concerned with retrofitting of the existing buildings in urban areas with little, if any, leeway in design modification. In 2017 there were about 900 public girls' schools in Riyadh as presented in Table 1.2. Solving this problem would affect a large number of schools and pupils in Riyadh; any method

(a) An example of a way to cover windows.

(b) Near the end of a school year, the black film is ruined because of the heat from the sun and needs to be replaced.

Figure 1.6: Examples of using dark opaque films to cover windows to maintain privacy (source: Abanomi 2005).

identified may have the potential to be transferable to other locations within this broader region, given the similarities in building typologies, climatic characteristics and privacy requirements.

Figure 1.7: Removing the black films during annual maintenance every summer (source: Abanomi 2005).

1.3.1 Possible solutions

Since the problem concerns retrofitting of existing buildings and not new-build schools, any solution applicable to early design stages or major retrofits that would modify the building's footprint on site are ignored. This would include solutions such as internal courtyards (DeKay and Brown 2013). The author reviewed previously suggested possible solutions, that appear to have the potential to solve this particular problem for girls' schools in Riyadh. More specifically, the following possible solutions to be applied on windows in order to solve the problem can be listed as follows:

- Covering windows completely, the solution currently applied (Figure 1.6a), and discussed by Abanomi (2005).
- Low-e tinted films on windows (Schaefer et al. 1997).
- Frosted glass (3M-Glass-Finishes 2017).
- Perforated solar screens (Mashrabiyas) (Fathy 1986; Sherif et al. 2010b).

The advantages and disadvantages of these options are summarised in Table 1.3. It is evident that the first three options: covering windows completely; using UV dark window films; and using sand-blasted glass, have disadvantages over some of the requirements present in the particular design problem stated here that render them unsuitable for application. However, using perforated solar screens has more advantages than all other options and yet its disadvantages may be overcome through design optimisation. This solution is a vernacular principle revisited in this research to assess whether it can satisfy contemporary living requirements and standards, and is discussed more in Chapter 2. This research is looking into investigating its parameters to create proper understanding of how each parameter affects its performance in providing indoor daylight and maintaining visual privacy for occupants.

Table 1.3: Comparing possible solutions.

	Advantages	**Disadvantages**
Covering windows completely	•Provides privacy.	•Blocks view to outside. •Blocks daylight completely.
Low-e dark films	•Reduce UV. •Provides view to outside.	•Privacy can be breached when internal illuminance is higher than outside.
Sand-blasted glass	•Provides privacy. •Allows daylight in.	•Blocks view to outside.
Perforated solar screens	•Provides view to outside. •Provides privacy. •Allows daylight to admit. •Blocks direct sunlight. •Succeeded to solve similar problems vernicularly.	•Some configuration can reduce interior daylight. •Ability to provide privacy has not been investigated yet.

1.3.2 The research gap

After reviewing previous work in investigating parameters of Mashrabiya and their impacts on daylight performance in hot arid areas, later discussed extensively in the literature review in Chapter 2, it is found that most work has been done for residential living rooms and to the knowledge of the author, very little has been done for classrooms. Moreover, no qualitative study has been conducted to investigate how different configurations of perforated solar screen parameters affect the aspect of maintaining visual privacy of occupants. This research builds on these findings.

1.4 Research aim and objectives

Although the research is directed to solve an existing issue in girls' schools in Saudi Arabia, the overall aim of this research is to develop a design guide for identifying configurations of perforated solar screens that is able to maintain privacy and provide acceptable levels of indoor daylighting for a building in a specific location with openings at any known orientation. The aim is driven by the desire to improve daylighting levels in Girls' Schools in Saudi Arabia to reduce energy demand for artificial lighting and to improve access to daylight which would improve pupils' productivity and well-being, whilst maintaining the privacy levels expected from the socio-cultural and religious norms in the region.

The objectives of this research are as follows:

1. To establish whether the use of perforated solar screens is a successful design solution for achieving acceptable interior daylight levels.
2. To establish whether using perforated solar screens is able to maintain privacy for occupants.
3. To examine the parameters of perforated solar screens and evaluate how they affect both the daylight performance and the visual privacy for occupants.
4. To recommend values for each parameter of perforated screens that would satisfy the requirements for visual privacy and achieve an acceptable level of daylight at the same time in classrooms in Saudi Arabia. It is however,

intended that the results can be generalised to recommend these values for any location and for any set of variables including the occupancy time of the space.

1.5 Research hypothesis

The basis of this PhD is the supposition that perforated screens are able to solve the problem of resolving privacy and daylighting concerns in girls' schools in Saudi Arabia, and that there are different recommended configurations for each cardinal direction.

1.6 Research outline

This thesis is divided into five chapters, each of which deals with a specific part of the research. The following key points give an overview of the contents of these chapters:

Chapter One: Introduction

This chapter introduces the research and presents the Saudi Arabian context, with focus on the capital city of Riyadh, its climate, crowded urban context and the issue of privacy for women in general and in girls' school buildings in particular. It also introduces and describes the issue of privacy in Saudi Arabia. The chapter also highlights the objectives of this research and the contribution of the thesis to the body of knowledge. It defines the problem and states the research question. It also gives a brief overview of the research outline including the structure of the thesis.

Chapter Two: Literature review

This chapter starts with a review of privacy trying to identify ways of assessing privacy in buildings. The chapter then provides an overview of the theory of daylight in buildings with a focus on the physiological and psychological implications on occupants and the energy consumption of buildings. The chapter also introduces the origin and history of Mashrabiya, a type of perforated solar screen that is typical in the research context. It also describes the design parameters of this type of solar screen providing also a review of previous work regarding those parameters. The chapter also reviews the literature in the area of measuring and predicting daylight performance inside buildings, methods and simulation tools in order to inform the choice of an appropriate methodology for conducting this research.

Chapter Three: Methodology

This chapter presents the literature review outcomes and the options regarding available research methods; it analyses them and concludes that the selected method is the most appropriate to achieve the research aims and objectives. The chapter then introduces the workflow of the thesis that explains the necessary preparations before starting the experiments in this research. The workflow also explains the phases of the research and how the experiments are spread in these phases. The chapter ends with explaining the research methods used to evaluate interior daylight and privacy, and how the results of these experiments will be presented.

Chapter Four: Research

This chapter presents the final results of all experiments in each of the four phases of the research. The discussion revisits the research hypothesis and research aims, and answers the research question drawing from the research outcomes of both the daylight performance and privacy assessments. The chapter ends with recommendations for the configurations of parameter values to achieve that.

Chapter Five: Concluding discussion

This chapter presents the concluding discussion to this work in response to the research aim, objectives and hypothesis. Moreover, the chapter gives general recommendations and suggestions for future research work in the same field.

Reference list and Appendices

At the end of the thesis, a reference list is presented followed by appendices. The appendices include:

1. Two papers published during the PhD study presenting the findings of the work with relevance to the effect of perforated solar screens on interior daylight levels.
2. Risk assessment form.
3. Research ethics application that was approved by the School's Research committee.
4. Prevent duty form prepared in compliance with guidelines.
5. The questionnaire used in this research.
6. Permission to use KAY pictures in this research.
7. Licensed images displayed in this research.
8. Method of presenting results of light simulation.

CHAPTER 2

Literature Review

2.1 Introduction

This chapter reviews the current literature in the relevant subject areas. It starts with the subject of privacy and moves on to review relevant past work on the subject of daylight. It considers several aspects of daylight, in general and in buildings, and how it affects human health and productivity as well as the energy consumption of buildings; it discusses specifically the importance of providing daylighting inside school buildings with the use of appropriate shading devices. The chapter also introduces and describes Mashrabiya as a possible solution with an overview of its function and parameters and discusses previous work in literature that have studied its parameters and their effect on interior daylight. In order to inform the choice of the appropriate methods in this research, the chapter reviews the relevant literature in the area of measuring interior daylight, methods and simulation tools used by others to evaluate indoor daylighting. At the end of the chapter, the analysis moves on to a discussion on previous research that has studied indoor daylighting in hot areas and how different cases were assessed and compared.

2.2 Visual privacy in buildings

2.2.1 Definition of privacy

The term privacy dates back to the fifteenth century (*Encyclopedia Britannica* 2015). The Britannica Encyclopaedia has two definitions of privacy: it is the quality or state of being apart from company or observation. As an act, privacy provides freedom from unauthorised intrusion. A second definition states that privacy denotes a place of seclusion (ibid.). A similar definition can also be seen in the Webster's Online Dictionary: privacy is the quality of being secluded from the presence or view of others or the condition of being concealed or hidden (*Merriam Webster* 2018). The definition of privacy can also be seen in relative literature, privacy literally means where it is necessary to protect and defend (Ghayeghchi 2015). Privacy can be seen as a range of beliefs, practices, behaviours, characteristics, features and ownership of each person, and people are not willing to relinquish their privacy and guard against the entrance and supervision of others (Naghibi 2010). Privacy is about the ability of individuals or groups to control their visual, auditory and olfactory interaction with others (Lang 1987). A definition of privacy from sociologist's point of view is a boundary between person, environment and outsiders, where they can declare their boundaries are restricted, and the outsiders will not intrude (Fahey 1995).

According to Westin and Ruebhausen (1967) Privacy is the claim of individuals, groups, or institutions to determine for themselves when, how, and to what extent information about them is communicated to others. Viewed in terms of the relation of the individual to social participation, privacy is the voluntary and temporary withdrawal of a person from the general society through physical or psychological means, either in a state of solitude or small-group intimacy or, when among larger groups, in a condition of anonymity or reserve. The individual's desire for privacy is never absolute, since participation in society is an equally powerful desire. Thus, each individual is continually engaged in a personal adjustment process in which he balances the desire for privacy with the desire for disclosure and communication of himself to others, in light of the environmental conditions and social norms set by the society in which he lives.

The theory of privacy regulation refers to the closeness of a person who is isolated from others and vice versa to the openness of a person who attempts to be more easy to access (Altman et al. 1981; Newell 1995). Therefore, creating a boundary control can control the closeness or openness in terms of accessibility to others to comply with the privacy regulations (Altman and Chemers 1980).

The concept of privacy invokes the possibility of controlling, in different degrees, interactions among people and/or with external or internal spaces (Reis and Lay 2004), and so the interruption or reduction of information flow, as already revealed by some researchers (Kupritz 2000; Rapoport 1980). According to Newell (1995), there is no agreement on what privacy actually is. It was also suggested by several authors that definitions of privacy changed as a function of the development of the individual and the specific environmental context (Margulis 2003a; Pastalan 1970; Westin and Ruebhausen 1967). Thus, it has been assumed in the investigation of privacy by all disciplines that people have to avoid contact and keep a distance from others at specific times or occasions (Altman and Chemers 1980; Altman et al. 1981).

Altman (1975) presents privacy as a collection of six points:

1. Privacy is an interpersonal boundary-control process, which paces and regulates interaction with others. Privacy regulation by persons and groups is somewhat like the shifting permeability of a cell membrane.
2. Two important aspects of privacy are desired privacy and achieved privacy. Desired privacy is a subjective statement of an ideal level of interaction with others, how much or how little contact is desired at some moment in time.
3. Privacy is a dialectic process, which involves both a restriction of interaction and a seeking of interaction.
4. Privacy is an optimising process. In other words, there is an optimal degree of desired access of the self to others at any moment in time.
5. Privacy is an input and output process; people and groups attempt to regulate contacts coming from others and output they make to others.
6. Privacy can involve different types of social units: individuals, families, mixed or homogeneous sex groups, and so on.

There are some social behaviour studies related to the built environment. The studies focus on the concept of privacy related to the cultural, behavioural, built environment, privacy in the dwelling and other privacy realms (Altman and Chemers 1980; Altman et al. 1981). The interest of privacy has been discussed in different disciplines, namely by, psychologists, sociologists and architects (Razali and Talib 2013). According to Altman and Chemers (1980), privacy is a selectively controlled access to oneself. It is part of the privacy regulation that had emphasised closeness and openness which may lead to human behaviour development and moral growth (Newell 1995). There are five parameters of privacy: accessibility, visibility, proximity, vocals and olfactory (Georgiou 2006).

It appears that privacy includes many types and what is relative to this study is the visual privacy in buildings; Reis and Lay (2004) define visual privacy as what is visualised from a single point of view in a particular space depending on the viewing angle and distance. They define internal visual privacy regulation as controlling the extent of visual integration; that is to block or allow visual connections. Shach-Pinsly et al. (2011) define visual privacy as an optimisation process of controlling the level of visual exposure and visual openness. This definition is close to the one presented by Altman (1977) which described visual privacy regulation as an open-close system to attain the optimum amount of privacy required specific to each individual's needs. Visual privacy in buildings can be defined as the ability to conduct activity in a building without being observed and without fear of being observed by those outside the building (Al-Kodmany 1999). Although previous studies defined visual privacy differently depending on the focus and issues of the studies, most studies relate back to the same point which is the visual permeability of a space or building (Hakim 2013; Mortada 2003; Reis and Lay 2004; Shach-Pinsly et al. 2011).

Most researchers tend to define characteristics of visual privacy from the built environment's point of view. They use terms such as "visual corridors" (Hakim 2013), "visual integration" and "control of visual connections" (Shach-Pinsly et al. 2011). The terms are mostly in reference to the visual line of sight created by the built environment and is dependent of the direction of looking (inside to outside or outside to inside), or the morale behind it (Manaf et al. 2018).

Shach-Pinsly et al. (2011) have divided visual privacy in buildings into two characteristics: Visual Exposure and Visual Openness. Visual exposure refers to privacy aspects in the built environment and they defined it as the visual penetration into one's privacy as a result of being viewed from the external spaces of other buildings' façades or from public spaces at street level around the building. Archea (1977) has defined visual exposure as: the probability that one's behaviour can be monitored by sight from one's surroundings. Conversely, the Visual openness refers to the view of building occupants to outside. Some other researchers used the term "Visual Access" rather than visual openness to describe the view from inside to outside (Mortada 2003; Rahim 2015). Visual access allows one to look out and to monitor immediate spatial surroundings by sight (Rahim 2015).

Internal visual privacy has implications in the consideration of what is visualised from certain spaces and in the possibility of controlling visual integration, that is, of blocking or not visual connections. Therefore, visual privacy inside buildings is affected, besides visual connections from certain observation points, by movement possibilities and control through the existing functional or physical connections (Reis and Lay 2004). To the designer, questions of privacy are involved in decisions about visual separation between the different sections and elements within the building, between the building and the street, and between the building and other buildings (Altman 1977; Marshal 1970).

2.2.2 Privacy and cultures

Privacy is a universal concept, although the means used to regulate it may vary according to different social systems (Kupritz 2000). Altman (1975) has observed that although privacy is "a universalprocess which involves unique regulatory mechanisms", it differs among cultures in terms of the 'behavioural mechanisms used to regulate desired levels of privacy'. Moreover, similar environments can have very different effects on different groups of people, depending on their specific characteristics, many of which are cultural or influenced by culture (Rapoport 2005).

One of the issues greatly affecting visual openness and visual exposure is cultural difference. Various cultures regard visual exposure and visual openness differently (Shach-Pinsly et al. 2011). The differences between cultures can be seen in privacy need, the use of space and how privacy is regulated. These result in different house and building forms around the world (Rapoport 2005), because the conception of privacy is culturally specific (Altman 1977; Fahey 1995; Newell 1995).

Cultural differences in attitudes towards privacy were documented in the anthropological literature (Gregor 1974; Moore 2018) and discussed by Altman (1977). The consensus was that cultural differences existed in styles of privacy, or mechanisms for obtaining privacy, but for different purposes. Nearly every culture has sought some type of privacy (Newell 1995). Religious and sexual behaviours were most frequently found to incorporate privacy across cultures. Nearly all societies, primitive as well as modern, have sought privacy for sexual relations (Hixson 1987). The level of satisfaction regarding visual exposure is subjective and varies between groups of people, based on age, personality, time in life, gender, the attitude of the self, location, relationships with neighbours and the way privacy is obtained (Newell 1995).

According to Kupritz (2000), the need for privacy can be related to the need for safety, which is the second in the hierarchy of human needs after the physiologic needs. Abu-Lughod (1993) argues that the main object of urban design in the traditional city is to protect visual privacy. Confidentiality is one of the basic principles that governs the universe and its phenomena that its impacts on the physical structure of the traditional architecture of the space are not deniable (Ghayeghchi 2015).

The importance of privacy can be seen in many cultures and backgrounds, for example in social housing studies in the US (Francescato 1979), and in the UK (Darke 1982). The government of New South Wales in Australia have a development control plan to regulate the Local Environment Plan (Marrickville 2011). In this document, the visual privacy is taken into consideration and measures must be applied if the visual privacy of adjacent residential properties is likely to be significantly affected from windows. These recommended measures include: fixed screens of a reasonable density (minimum 75% block out) to a minimum height of 1.6m from finished floor level must be fitted to windows in a position suitable to alleviate loss of privacy; screen planting or planter boxes in appropriate positions may supplement the above provision in maintaining privacy of adjoining premises.

Shach-Pinsly et al. (2011) argued that visual exposure is a major aspect influencing the quality of the human environment. They presented that the lack of visual privacy can influence the economic attractiveness of the high density urban environments, thus, apartments in crowded dense urban developments have less real estate value because of their visual exposure. The satisfaction of buildings' occupants with their urban development will grow if the buildings offer low levels of visual exposure (more visual privacy) and simultaneously high levels of visual openness (Feitelson 1992; Al-Kodmany 2000; Oh and Lee 2002).

These studies proved that visual privacy is also important in the Western world, not only in the Arabian and Islamic world. Visual privacy is an intriguing subject, and if this is true in the West, it is especially true in the Arab and Islamic world (Tomah 2011). Privacy is a socio-cultural need present in the culture of communities in the Arab and Islamic regions (Fathy 1986). Tomah (2011) argued that one needs only to visit any Middle Eastern country for a day to realise the place of importance given to visual privacy, because Arabs have high expectations with regard to visual privacy. These high expectations certainly extend to visual privacy as it relates to architectural design. The translation of privacy into the built environment varies between the cultures that embraced Islam partly due to the strong influence of the culture of origin (ibid.). Privacy in Muslim society is more towards gender segregation and separation between the privacy life and public intercourse (Gregor 1974).

Visual privacy is pertinent in Islam. The Holy Quran stated very clearly that one's privacy is one's own right and no one should intervene in it without one's permission. The architectural, social, and psychological dimensions of privacy are fundamental to the daily life of Muslims (Rahim 2015). Visual privacy influences design attributes of houses such as the specifics of doors, windows and openings, organisation of spaces and positioning of houses in relation to other houses and physical elements such as partitions, walls, blinds, louvres and landscape elements. Provision for visual privacy has always been an important aspect and consideration in the houses of Muslims (ibid.). Islam placed the highest importance on visual privacy due to its direct impact on physical elements of the traditional Islamic city (Hakim 2013). In order to follow with the law of God and securing houses, in terms of privacy and the veil, the houses were built so that no strangers would be able to see inside the houses (Ghayeghchi 2015). From an Islamic point of view, a dwelling is defined as a safe shelter and private sanctuary, the best place to enjoy tranquillity, and a refuge from the outside world (Manaf et al. 2018; Omer 2010a). Mortada (2003) and Abdul-Rahim (2008) mentioned that every Muslim family should take into consideration the dwelling's function and design emphasis on segregation of gender, seclusion of females and visual privacy from outside.

Bemanian et al. (2015) studied the privacy in the built environment in Iran, one of the biggest Islamic countries; they stated that the role of privacy in life according to the teachings and commands of Islam and cultural affiliations of the people in Iran, is no secret to anyone. Tomah (2011) interviewed 276 families in Jordan in an attempt to investigate visual privacy in buildings. Respondents in different neighbourhoods expressed a strong desire for a higher level of visual privacy. They want visual protection in place to guard against any perceived invasion of privacy, both from within the building and from outside. Rahim (2015) has interviewed 381 people to find the influence of culture and religion on the conception of visual privacy. His findings indicate that the majority of the respondents (89.6%) feel that the control of visual exposure is important. There is no significant difference for perception on control of visual exposure at p = 0.05 between genders, education, age and family income.

The concept of privacy in Islam involves the segregation between males and females. Islam only allows free social interaction between females and males known as Mahram referring to close family members (fathers, brothers, sons, uncles or nephews) (Mortada 2003). Islam also suggests ways in dressing to cover the body and hair of women that need to be concealed (Abdul-Rahim 2008) and in behaviour and relationships between male and female (Mortada 2003; Rahim 2015). The layout plan and design of houses should follow the Islamic principles of visual and audio privacy to prevent unethical acts (Abdul-Rahim 2008; Mortada 2003).

Privacy as a key principle in Islamic architecture has different aspects. The purpose of the privacy is creating borders not inducing separation. Privacy creates an aura preventing the invasion of others and connects two sides without blending. Privacy does not apply only to social relations, but it can be found in regulating the spaces, dividing urban spaces and buildings (Ghayeghchi 2015).

In Saudi society, as one of the Muslim societies, dwelling privacy is defined by explicit Islamic teachings. These rules have existed for many centuries and their influence is clearly visible in traditional architecture in Saudi Arabia (Bahammam 1998). The need of privacy for women is extreme in Saudi Arabia (Al-Mansuree 1997). Ben-Saleh (1998) has investigated the traditional architecture in Saudi Arabia and how the Islamic and customary laws had an impact on urban form development. He found that the key organising concept of urban development was the respect for privacy and rights of spaces which condition the relationships between the various participants.

The contemporary architecture in Saudi Arabia neither maintains the required level of privacy for the society (Bahammam 1987) nor provides a climatic enjoyable space in the harsh weather of the region (Bahammam 1998).

2.2.3 Levels of privacy

Altman (1975) distinguished three cases:

1. Achieved = desired: optimum state of privacy exists, resulting in psychological comfort.
2. Achieved < Desired: a person has more interaction than s/he wants and intended to achieve
3. Achieved > desired: results in a sense of loneliness and isolation.

Al-Kodmany (1999) has defined the desired and achieved privacy levels as follows: Desired privacy is the extent to which an occupant wants visual privacy inside a building from outsiders (neighbours and passers-by), whereas, achieved privacy is the extent to which the traditional building meets women's desire for visual privacy from outsiders. He then interviewed 200 women in Syria (which has similar traditions to Saudi Arabia) to identify the desired level of privacy and the reasons for this level of privacy; he concluded that the reasons are cultural, religious, psychological and personal. He asked them whether they prefer to occupy a building with many windows and little privacy or an identical building with less windows and more privacy. More than 85% preferred a building with more privacy.

2.2.4 Traditional strategies to maintain privacy

Many researchers discussed the effect of the visual privacy issue on the traditional architecture in the Middle East, and many strategies that aim to maintain privacy can be learned from traditional architecture. The attitude toward privacy is a major factor that has influenced the design and shape of the traditional house in Saudi Arabia (Bahammam 1998). The need to provide visual privacy to the individual family and community at large resulted in careful location of buildings in relation to one another and the placement of windows (Hakim 2013). The traditional architecture can provide valuable lessons (related to privacy and other issues) to planners and designers of contemporary environments regarding the impact of Islamic law and customary laws on urban form development (Ben-Saleh 1998). The layout and orientation of residential units and site plans, along with the architectural treatment of exterior elevations, all contribute to the achieved level of visual privacy (Al-Kodmany 1999). Mortada (2003) and Rahim (2015) explained that the visual privacy involves site location and layout plan.

In a study conducted by Abbasoglu and Dagli (2009), they concluded that early age designers were more successful in creating visual privacy in their designs and this is connected to designers understanding the meaning of the visual privacy. Visual privacy also influenced architectural design strategies such as the louvre windows, screened panels or Mashrabiyas, roof terrace, high windows, recessed windows and entrance (Rahim 2015). According to Ben-Saleh (1998), the Private open space in the form of a residence backyard or roof terrace in the traditional architecture in Saudi Arabia emerged to fulfil the religious demand for privacy, especially for female members of the household. Archea (1984) stated that, in bounded settings, the location of edges (corners) and surfaces (walls), their spatial arrangement, and their properties (opacity) affect the distribution of visual information about the occupants inside. This information creates psychological opportunities for privacy, social interaction, creating the desired impressions (Margulis 2003b).

According to El-Shorbagy (2010) the courtyard is the most essential element, which represented the core of all Islamic-Arab houses. The concept of the courtyard is commonly used in traditional architecture, both rural and urban, of the hot arid regions from Iran in the East to the shores of the Atlantic in the West. Muslims adopted the concept of the courtyard because it suited their religious and social needs, especially the degree of privacy needed. The arrangements of the courtyard also provided a satisfactory solution to their specific environmental problems. The number of courtyards varies, as does the size of each courtyard, according to the available space and resources (Danby 1993). Using courtyards in traditional architecture was intended to provide the maximum privacy desired by the society

(Bahammam 1998). Al-Kodmany (1999) suggests that an inwardly oriented built environment is a good method to maintain privacy as well as using courtyards.

Strategies related to windows were also mentioned by researchers as a way to maintain visual privacy in buildings. Some researchers emphasised three elements of design that can control the visual privacy of the dwelling, including the height of windows and screens (Mortada 2003; Omer 2010b; Rahim 2015). Day (2000) argued that the height and location of façade openings in relation to those in adjacent buildings are critical to visual exposure. Mortada (2003) and Rahim (2015) suggest that in order to maintain internal visual privacy through openings, windows must be built above the eye level for the upper and lower floor of dwellings. As many as 89.5% of the 381 participants interviewed by Rahim (ibid.) identified that curtains, screens and blinds are the most important regulating mechanisms for visual privacy. In a similar study conducted by Tomah (2011), most respondents (of 276 families) indicated that they prefer to use traditional architectural elements, such as the Mashrabiya, in order to insure visual privacy. Mashrabiya used to be installed to ensure a one-way view, whereby occupants, especially women, could see outside but passers-by, especially men, could not see inside (Abu-Lughod 1993; Al-Kodmany 2000).

It appears that most strategies learned from the traditional built environment in the Middle East to provide visual privacy in buildings must be applied during the design process, such as using courtyards and inwardly oriented buildings. It was mentioned in Chapter 1 that schools in Saudi Arabia were built using prototypes without any distinguishing between those for boys and girls. In an ideal design scenario they should have been designed differently to consider the privacy issue in earlier design stages by using one of the strategies discussed here. Unfortunately that did not happened. As a result, windows in girls' schools are currently covered with black opaque films or coloured solid boards in order to maintain privacy. This act would surely diminish visual exposure but it would simultaneously diminish visual access. This is in addition to other issues related to the lack of indoor daylight.

This study is considering retrofitting existing buildings, and there are about 900 girls' schools in Riyadh only (Table 1.2) (General Authority of Statistics 2017) that have the same problem, and many more around Saudi Arabia.

Therefore, the literature review is directed toward strategies related to openings. The possible solutions to solve the problem of privacy that can be applied to windows include: covering windows completely, which is discussed by Abanomi (2005); low-e dark films on windows (Schaefer et al. 1997); sand-blasted glass; perforated solar screens (Mashrabiya). These options were discussed in Chapter 1 and Table 1.3, and the use perforated solar screens was selected as the most appropriate solution as it used to be successful in vernacular built environment as discussed above.

There is very little available literature in the field of architecture and buildings discussing the issue of visual privacy in buildings (Sherif et al. 2010b). In order to study the relationship between the various solutions to maintain privacy needs as discussed above to identify successful cases in maintaining privacy, the author had to define privacy in buildings. For the purpose of this study, the maintenance of privacy in school buildings for girls can be provided by windows which do not allow a view; having a view from outside to inside the building through an opening means that there is no privacy and vice versa. The next section of this chapter will provide a review of the literature on the subjects of optometry, vision science and the optical physics of light. Discussion focuses on the factors that affect people's ability to view from outside to inside a building through openings. Following this a methodology will be set up to evaluate visual privacy by testing visibility through openings from outside to inside.

2.2.5 Assessing visual exposure

The aspect of studying how the applied strategy to windows can affect the visual exposure inside buildings has not been extensively researched and documented in the academic literature. There is very little available literature in the field of architecture and buildings discussing the factors affecting visual exposure through windows (Sherif et al. 2010b). The most dominant attribute found in the literature survey affecting visual exposure is the distance between buildings (Day 2000; Al-Kodmany 1999; Merry 1987). Shach-Pinsly et al. (2011) stated that there is no approach that systematically classifies distances between buildings in relation to visibility. When evaluating visual exposure in buildings, Shach-Pinsly et al. (ibid.) used measured distances between the studied opening and the outside viewer and categorised the distance (X) into four categories:

1. $X < 10m$: High level of visual exposure
2. $10m < X < 25m$: Medium level of visual exposure
3. $25m < X < 50m$: Low level of visual exposure
4. $50m < X$: Very low level of visual exposure

These categories can be used to assess reducing visual exposure to the minimum, however, this cannot be applied to the case of Saudi Arabia as the required level of privacy is restricted to zero visual exposure.

In order to assess whether or not an applied strategy on windows was successful in diminishing visual exposure, therefore, the author suggests that zero visual exposure means not having visibility. Any visibility from outside to inside buildings through an opening means that there is still visual exposure and vice versa. The author also suggests that distance is not the only factor affecting visual exposure, although it is the only factor found in literature related to architecture and the built environment. Hence, prior to setting up a methodology for evaluating visual exposure and testing visibility through openings from outside to inside buildings, a review of the literature on the subjects of optometry, vision science and optical physics of light and glass is conducted to discover the factors that affect the ability to view from outside to inside buildings through openings.

The visual effect of the distance between subject and human eye is widely known and well discussed in optometry and has resulted in the use of Snellen fraction or Snellen charts (Jackson and Bailey 2004; Kosslyn et al. 1978). Therefore, the distance between the eye of the viewer and the target inside the building can be considered as a factor affecting visibility when assessing visual exposure. A normal human eye with a Snellen fraction of 6/6 has the ability to recognise a letter size 6 from $6m$ away, whereas an eye with 6/18 can recognise a letter if it was size 18 from $6m$ away (Figure 2.1). A letter size 18 is a letter that can be recognised by an eye with 6/6 visual acuity from $18m$ away using the same viewing angle 5 minute of Arc (5 MAR). Snellen charts are explained in detail in Section 2.2.6.

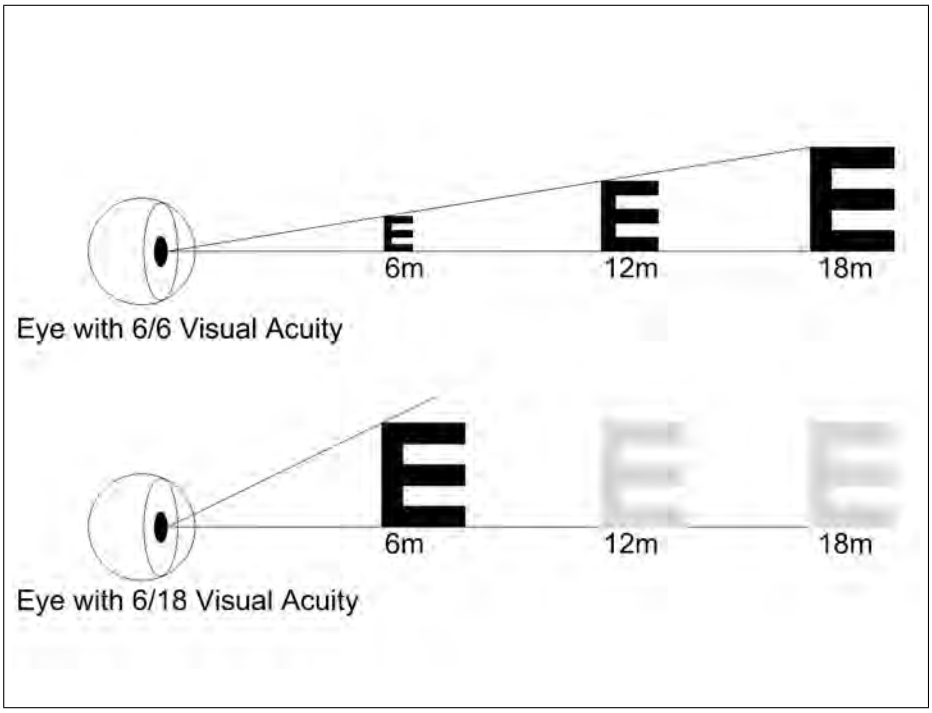


Figure 2.1: Effect of size of target on the viewing distance (adapted from: Jackson and Bailey 2004).

When reviewing properties of Snellen charts, the size of target has been found to play a significant role in testing visibility. The visual acuity charts are based on that principle since it was first introduced more than a century ago by Snellen (1862) (Figure 2.1). Visual acuity tests are discussed in detail in Section 2.2.6. Hence, the target size can be considered as a factor affecting visibility when assessing visual exposure.

It appears from reviewing the visual acuity of the human eye that a person with lower visual acuity can detect less details about a target than a person with normal visual acuity when viewing the same target from the same distance (Jackson and Bailey 2004). Thus, viewers with lower visual acuity could find it difficult to view targets depending on their level of vision. Therefore, the visual acuity of the viewer is considered as a factor affecting visibility when assessing visual exposure.

It has been also found in the literature of optometry that contrast sensitivity is one of the most important aspects affecting the recognition of any target to the human eye (Barten 1992). Higher luminance of the background produces higher levels of sensitivity and vice versa (Cox et al. 1999; Mayyasi et al. 1971; Ochoa et al. 2014). According to O'Carroll and Wiederman (2014), visibility becomes more difficult to the human eye as the contrast in brightness between an object and its background decreases. The reason for that is the random nature of photon emission or reflection by features of the environment, which leads to variability in the photon numbers sampled by photoreceptors within a given neural integration time (Barlow 1964; Land 1981; Pirenne 1967). Therefore, the author considers the luminance contrast between the target and its background as a factor affecting visibility.

Reviewing literature related to the anatomy of the human eye showed that it has a property called pupil mimicry (Derksen et al. 2018). The human eye accommodates itself to the surrounding illuminance by decreasing or increasing pupil size using the iris circular muscles (Campbell and Westheimer 1960; Toates 1972). The iris is a coloured muscle tissue that controls the amount of light entering the eye by dilating the pupil. The pupil is the central opening of the iris in Figure 2.2.

The relationship between the iris and pupil is similar to the mechanism of the aperture in cameras to control exposure by reducing or increasing the pinhole (Derksen et al. 2018). Therefore, the general illuminance between outside and inside can be considered as a factor affecting visibility when assessing visual exposure.

Reviewing the anatomy of the eye also showed that the retina of the eye has two

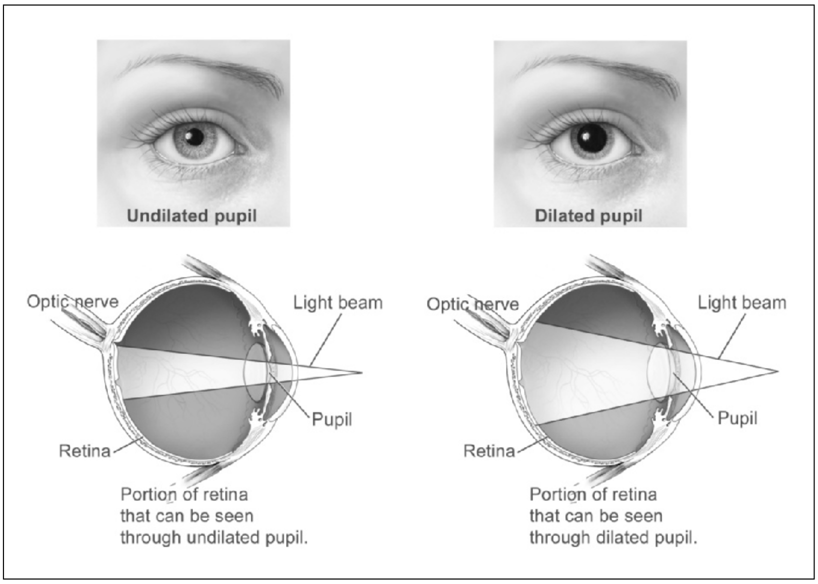


Figure 2.2: Dilated and un-dilated pupils. Licensed by National Eye Institute NEI (Appendix G).

kinds of photoreceptor cells: rods and cones (Osterberg 2006). Hence, the human visual system has two type of visions: central vision and peripheral vision. To view the former, the human eye uses cones which provide better information to the brain regarding the colours and clarity of the target, whereas for peripheral vision the eye uses rods that provide less details (low spatial acuity) and are not capable of detecting colours (Kaschke et al. 2014) (Figure 2.3).

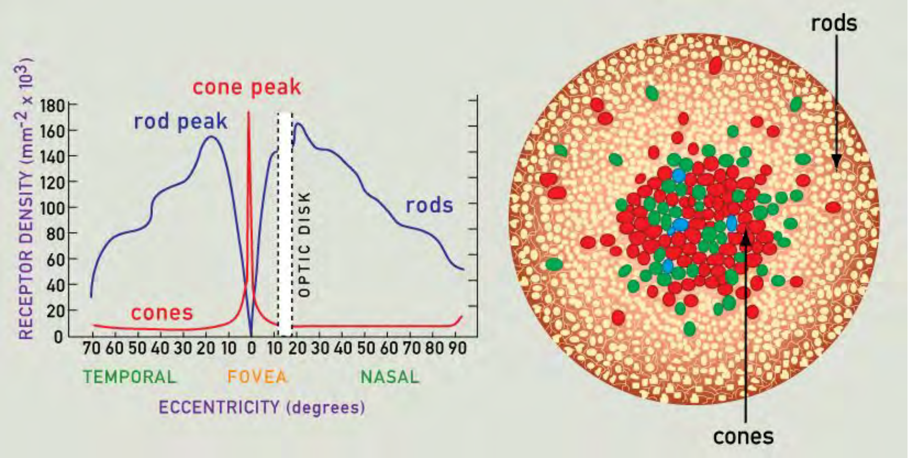


Figure 2.3: The difference between cones and rods in human eye. Licensed by: WebExhibits (Appendix G).

Therefore, the eye movement would cause the target to move out of the central vision (Brandt et al. 1973; Brown 1972a,b). When the target is moved out of the central vision of the eye, it could be seen with the peripheral vision of the eye which is less capable than the central vision (Demer and Amjadi 1993). Thus, eye movement is considered a factor affecting visibility.

Reviewing the optometry and vision science has also revealed that there are two types of targets: the static target and the dynamic target. The former represents any static object and the latter represents moving subjects (Brown 1972a,b). Dynamic visual targets need higher visual acuity than static visual targets to be detected, because when detecting moving targets the eye moves accordingly trying to position the target at the central vision rather than the peripheral vision. This would increase the exposure duration needed for the eye to detect the target (Baron and Westheimer 1973), and thus decrease visual acuity level (Brown 1972b; Ludvigh and Miller 1958; Miller 1958). Therefore, target movement is considered a factor affecting visibility in assessing visual exposure.

The properties and physics of materials has also been reviewed. It was found that the level of transmission of glass can affect visibility through windows (3M-Glass-Finishes 2017). Each glass material has a transmittance ratio ranging from 0 to 1, the darker the glass material, the lower is the transmission ratio. Research related to windshields glass in vehicles has revealed that the transmittance ratio can affect the distance over which a driver can see and recognise targets (Derkum 1993; Sayer and Traube 1994). Since vision is actually seeing light reflected from objects, transmittance ratio can be calculated by dividing the intensity of incident light I_O by the light leaving the glass from the other side $\tau = I/I_O$. It will be ≤ 1 because I_O is always $> I$ (Figure 2.4).

Another property of glass material that can be found in related literature is the glass refractive index (Beadie et al. 2015), which is defined as the ratio of the speed of light in a vacuum to that of light in the material (Galbraith 2015). Light travels through a medium whether it was a vacuum space or a transparent material, namely, glass, liquid and air including any kind of gas (Koks 2006). Light travels the

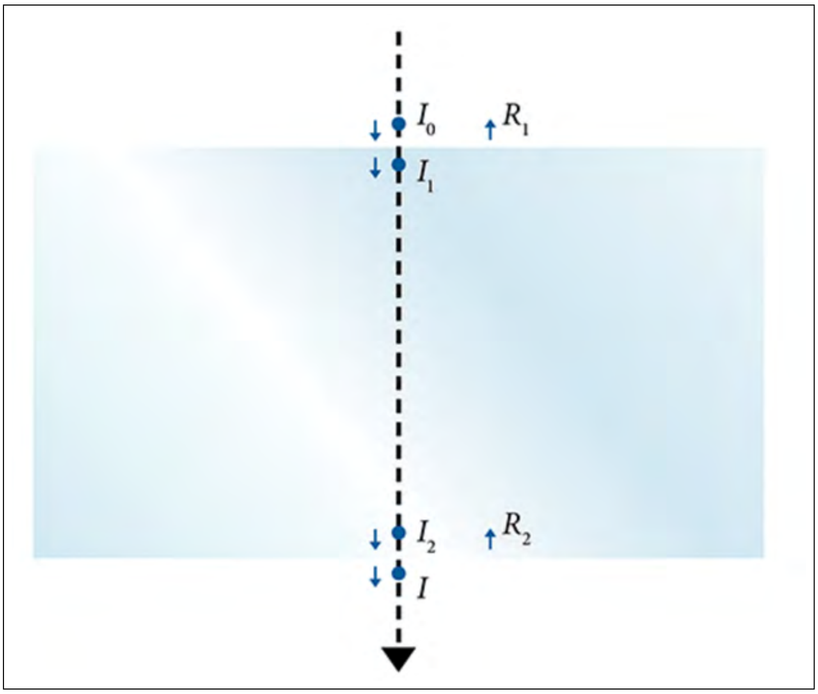


Figure 2.4: The transmittance of glass is calculated by dividing I by I_O (source: Galbraith 2015).

fastest in a vacuum space whereas light speed is reduced when travelling through a medium because the photons interact with electrons. Mediums with higher electron densities reduce light speed (Koks 2006). That change in light speed can cause the light to be refracted. The angle of refraction can be calculated using the refractive index of the material and the angle of incident ray which is the angle between the incoming ray and the perpendicular to the surface of a medium (called the normal) using this equation: refractive index = $sin\theta_i/sin\theta_r$ (Figure 2.5).

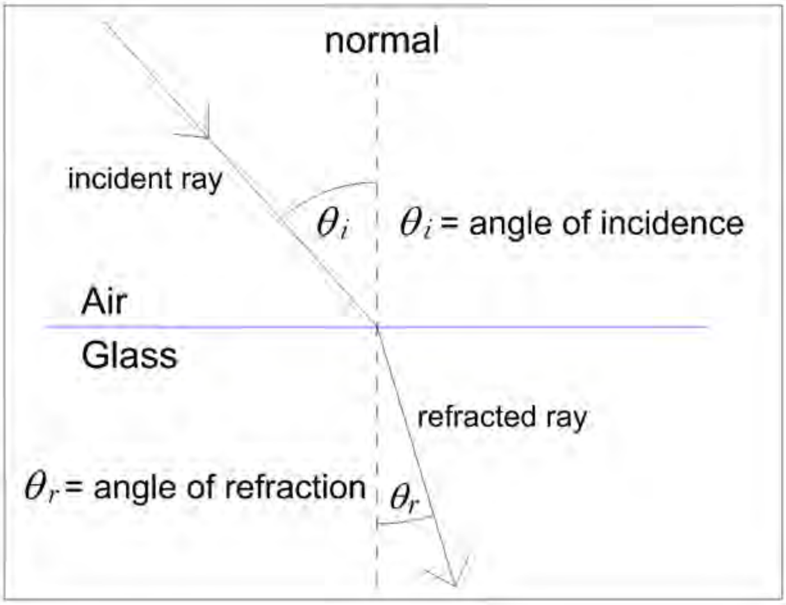


Figure 2.5: The effect of refractive index (adapted from: Britannica 2012).

Thus, if the angle of incidence was 0° then the angle of refraction = 0°, because $Sin0 = 0$ which means there is no refraction. In this it appears that a straight view through glass would provide an image of what is behind the glass without any distortion caused by the refractive index of the glass. Moreover, the refractive index not only affects the angle of the ray, it also causes some of the light intensity to be reflected by the glass (Galbraith 2015). The amount of reflected light by a glass can be calculated using this equation: $R = 100 \times (\frac{n_{air}-n_{glass}}{n_{air}+n_{glass}})$ where R is the percentage of reflected light out of the incident light and n is the refractive index (ibid.). Clear glass material used in windows has an average refractive index of 1.5, and knowing that air has a refractive index of 0.9 means that the light loses at least 4% of its intensity (ibid.). Therefore, the author considers the viewing angle as a factor affecting the visibility through windows.

As pointed by many researchers (Abu-Lughod 1993; Al-Kodmany 2000; Omer 2010b; Sherif et al. 2010b; Tomah 2011), external shading devices such as vertical or horizontal louvres, and external solar screens in particular have an effect on reducing visibility through windows to buildings' interior and thus, decreasing visual exposure. In theory, any shading strategy can affect the visibility from outside to inside buildings whether it was a low-e film or a screen or a shading device.

The factors affecting visual exposure in buildings discussed above can be summarised as the following 11 factors:

1. The distance between the eye of the viewer and the target inside the building.
2. Glass transmittance.
3. Viewing angle.
4. Luminance of the background of the target inside the building.
5. Eye movement.
6. Illuminance contrast between outside and inside.
7. Luminance of walls surrounding the opening.
8. Movement of the target.
9. Visual acuity of the viewer.
10. Size of the target.
11. Shading strategies.

Studying the effect of using a shading strategy on visual exposure is one of the main objectives of this project. Controlling all other factors would allow the research to assess whether the selected shading strategy can reduce visibility through windows for a viewer outside looking into a building and thus providing privacy for occupants.

2.2.6 The visual acuity test

Since maintaining privacy has been translated to not having visibility to view, evaluating visual exposure in buildings can mean testing visibility. In the optometry field, the most reliable method of testing visibility and assessing visual acuity of humans is using visual acuity charts. The visual acuity chart was introduced by

Snellen (1862), hence, some charts and tests used for this purpose still carry his name (Snellen charts, Snellen test). He used letters with a stroke width equal to one fifth of the letter height in a 5×5 grid. According to Bennett (1965), at first the charts used the imperial units, and by 1875 charts were calibrated to the metric units. Then, the British Standard Institute chose to adopt the same letters in a 5×4 grid format as the standard for visual acuity testing in the UK using metric units, whereas the 5×5 grid is still the standard for tests in the US with the imperial units. The difference between the two grids format can be seen in Figure 2.6.

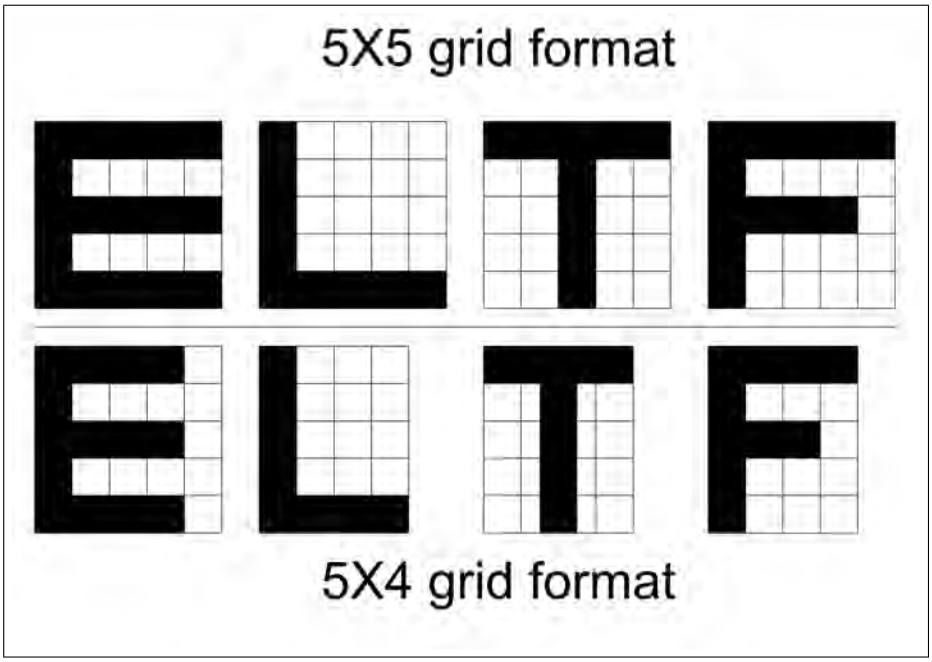


Figure 2.6: The difference between 5×5 grid and 5×4 grid format.

To test adults that cannot read English letters due to illiteracy or linguistic deficiency, a chart with rings with a gap, that looks like a **C** letter, called Landolt rings, was introduced by Landolt (1899). Rings can be rotated left, right, down and up as can be seen in Figure 2.7 and the observer is asked to detect the direction of the gap in each ring.

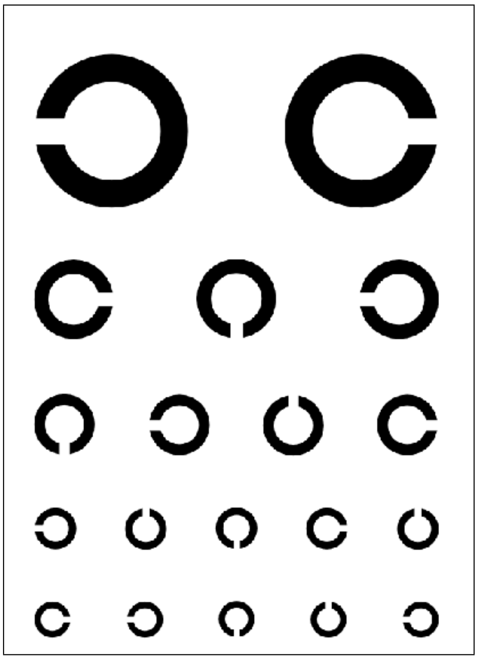


Figure 2.7: Landolt rings chart, the subject is asked for the direction of the gap (adapted from: Landolt 1899).

The main principle of these charts is the fact that a human eye with normal visual acuity can detect a detail using viewing angle of as small as 1 minute of arc, which is called the Minimum Angle of Resolution (MAR) (Bennett and Rabbetts 1984). Therefore, the height of the letter in the Snellen charts is five times the stroke size and the viewing angle for the whole letter is 5 MAR (Figure 2.8).

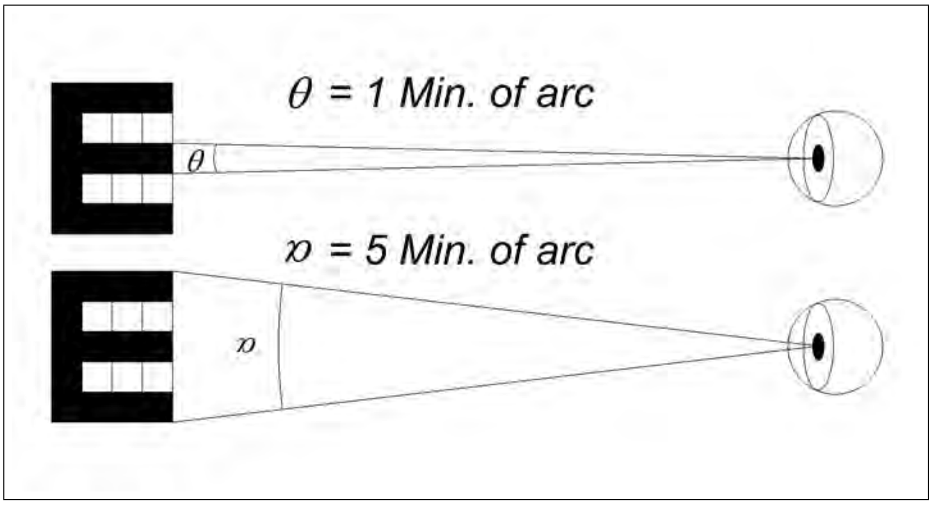


Figure 2.8: The viewing angle of the stroke of a letter and for the whole letter for an eye with normal visual acuity.

To determine the actual size of letters in mm, this equation is used: $\theta = \frac{X}{L}$

(McGraw et al. 1995) where X is the stroke size and L is the distance between the eye and the chart (Figure 2.9). Knowing that viewing angle should be 1 min of arc, the letter size can be calculated according to the distance. For example, if the chart was placed $6m$ away, the stroke size should be $6 \times Tan(\frac{1}{60^\circ}) = 1.745mm$ and the letter height should be $5 \times 1.745 = 8.787mm$. Some charts are designed to be placed at $1m$, $4m$, $5m$ or $6m$ away, they all were designed according to the same equation to determine the height of letters.

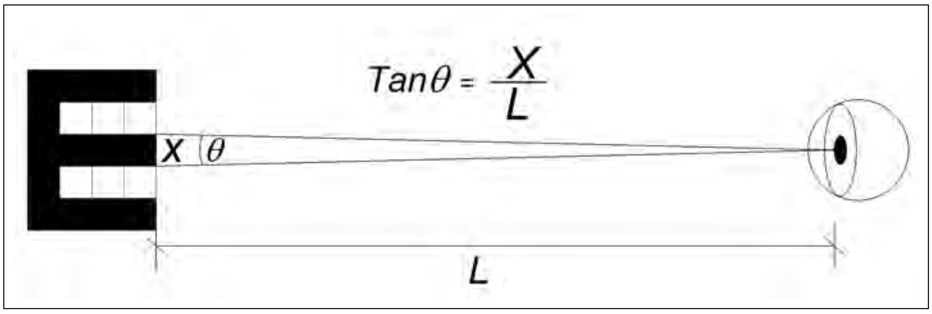


Figure 2.9: The relationship between the letter size and the distance (adapted from: McGraw et al. 1995).

Each visual acuity chart has about nine lines of letters or symbols, and each line has a different size according to the logarithm of the MAR in 0.1 steps (Jackson and Bailey 2004) (Table 2.1). Then the letter size is calculated according to the MAR angle using the same equation. According to the result of each observer when taking the visual acuity test, there are ranges to describe the range of the visual acuity such as: super normal vision, normal vision and low vision. In order for a person with visual acuity of 6/24 (low vision) to see a letter clearly from $6m$ away, that letter should be 4 times bigger. In other words the letter should be as big as the letter that can be seen $24m$ away by a person with a normal vision, because a person with low vision needs at least an angle of 4 MAR to detect the same detail that a person with normal vision needs 1 MAR to detect (Table 2.1).

Table 2.1: Ranges of visual acuity tests (adapted from: Jackson and Bailey 2004).

Visual Acuity Ranges	**Snellen fractions** (Numerator = distance)	**Visual Angle Notation** **MAR**	**log MAR**
Super-normal vision	6/3.8	0.63	-0.2
	6/4.8	0.8	-0.1
Normal vision	**6/6**	**1**	**0**
	6/7.5	1.25	0.1
Near-normal vision	6/9.5	1.6	0.2
	6/12	2.0	0.3
	6/15	2.5	0.4
	6/19	3.2	0.5
Low vision	6/24	4	0.6

Using this main principle, researchers have created new sets of charts using symbols and pictures aiming to simplify testing the visual acuity of children, such as LEA Symbols introduced by Lea et al. (1980), and “Kay pictures” introduced by Kay (1983). These pictures were drawn using stroke width that achieves a viewing angle of 1 MAR to follow the same principle of Snellen charts. LEA symbols contain only four symbols representing a square, an apple, a house and a circle (Figure 2.10).

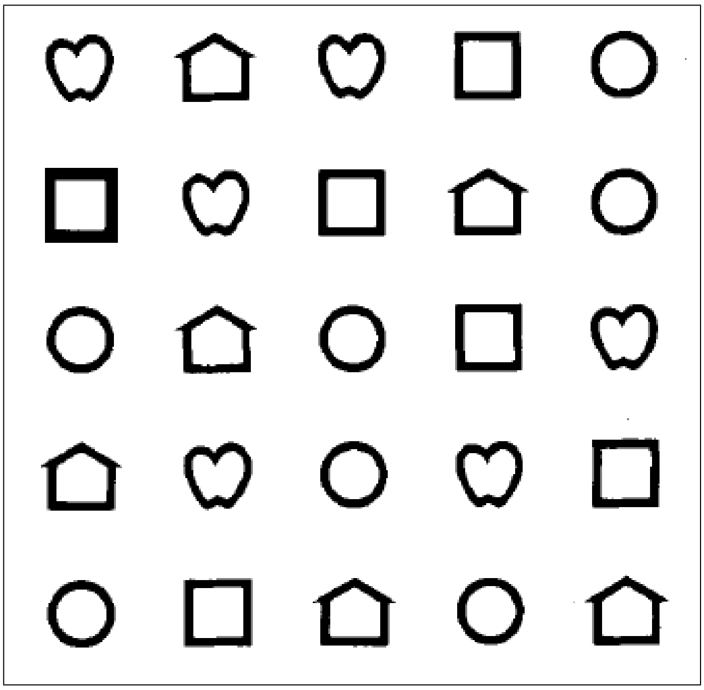


Figure 2.10: LEA symbols to test visual acuity of children (source: Lea et al. 1980).

Kay pictures were drawn with a size twice as big as its equivalent in Snellen charts while using the same stroke width (Figure 2.11).

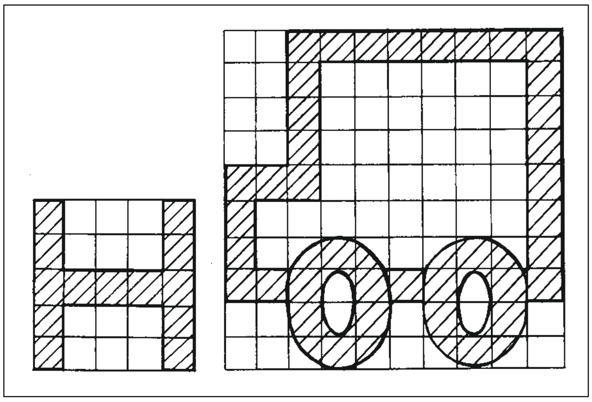


Figure 2.11: comparing the size of Kay pictures with the size of a letter in Snellen charts while using the same stroke width (source: Kay 1983).

Lalor et al. (2016) used adults subjects to validate the use of LEA symbols and Kay pictures by comparing them with results of using Snellen charts with the same subjects. Milling et al. (2016) have redeveloped new pictures for Kay pictures; they have proposed and tested 25 new and different pictures to see which are the most recognisable by subjects. They concluded six pictures to be the latest version of Kay pictures (Figure 2.12). They have also validated the new designs by comparing results with LEA symbols and Snellen charts.

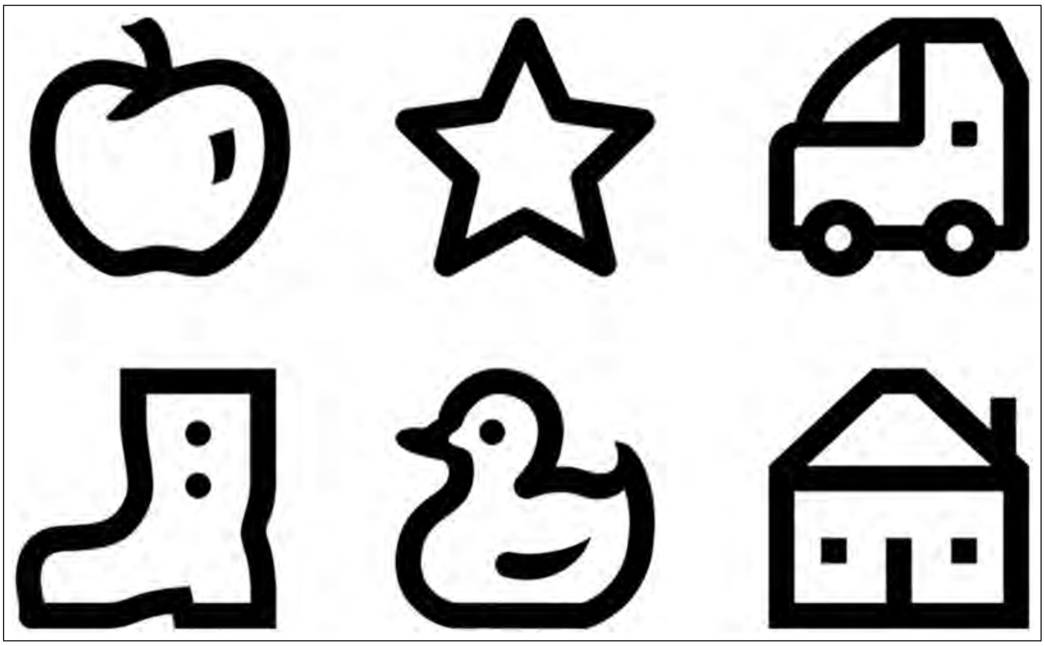


Figure 2.12: The newly developed Kay pictures (source: Milling et al. 2016).

2.3 Daylight

This section reviews the published literature on the broader subject of natural light, looking at benefits for introducing natural light in buildings, its energy saving potential and health and productivity benefits. The discussion refers mainly to daylight which Julian (2006) describes as a combination between sunlight and skylight. Sunlight refers to direct light from the sun, whereas skylight is the light from the sun following diffusion and scattering by particles. The size of these particles determines the colour of the sky, the smaller the particles, the more blue and clear is the sky, whereas large particles (e.g. water vapour) produce overcast or cloudy skies.

2.3.1 Daylighting in buildings

Daylighting in buildings can be defined as the natural illumination experienced by the occupants of any man-made construction with openings to the outside (Mardaljevic 2013). It is the pattern of light in the sky telling us a story in the building's form and details (Loveland 2002). Waldram (1909) was the first to write about natural light inside buildings at the beginning of the twentieth century. Walsh (1961) and Hopkinson et al. (1966) explained the relationship between daylight and building design for architects and architectural students. Lynes (1968) has also talked about the physical differences between sunlight and daylight in her book *Principles of Natural Lighting*.

Waldram (1909) has also introduced the concept of Daylight Factor (DF), which is the ratio of the internal illuminance at a point in a building to the external horizontal illuminance under an overcast sky. His later work explained the DF in more detail and the methodology to use it to evaluate interior daylight in buildings (Waldram 1925, 1950). The DF was initially introduced to be used to evaluate interior daylight in existing buildings. Then after architects and designers started considering interior daylight in their designs the DF method was adopted in more detail during the design process using physical models in an approach some times called Daylight prediction (Hopkinson et al. 1966; Lynes 1968; Walsh 1961).

However, there is confusion relating to the definition of daylight in buildings; Crisp et al. (1988) define daylighting in buildings as an effective means to reduce artificial lighting requirements of buildings. In 2007, a lighting perception survey was conducted by Reinhart and Galasiu (2006) with the participation of 177 designers and engineers. Most designers defined daylighting as being “the interplay of natural light and building form to provide a visually stimulating, healthful and productive interior environment”, however, most engineers thought daylighting is “the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements heating, cooling and lighting” (Table 2.2). This reveals that the interpretation of good daylight can differ from one person to another according to their background. Therefore, the analysis of good interior daylighting often takes a more holistic approach, considering different aspects such as: daylight availability, visual comfort and solar radiation, and thus energy consumption (Galasiu and Reinhart 2008).

Table 2.2: Five examples of definitions for daylighting in buildings (source: Reinhart and Galasiu 2006).

Architectural definition:	The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment
Lighting Energy Savings definition:	the replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting
Building Energy Consumption definition:	the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)
Load Management definition:	dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape
Cost definition:	the use of daylighting strategies to minimise operating costs and maximise output, sales, or productivity

2.3.2 Saving energy by using daylighting

Electrical energy consumption could be excessive when the potential contribution of natural light to interior illumination is ignored (Hansen 2006; Muhs 2000). In many non-domestic buildings, artificial lighting is the key consumer of electricity, estimated to be about 20%–30% of the total building energy load (Li and Tsang 2008). The US Department of Energy estimates that 25% of energy expenses of US schools could be reduced through better building design and using energy-efficient technologies combined with improvements in operations and maintenance (Erwin and Heschong 2002; Perez and Capeluto 2009). Bingler et al. (2003) declare that schools should be designed to make the most of freely available natural resources. Although Saudi Arabia is one of the most privileged places in terms of solar availability and sky conditions (Solar GIS 2013), using solar radiation as a natural resource to generate energy is still ignored (Rehman et al. 2007). It was proven that daylighting alone could provide adequate lighting levels in more than half of the year inside buildings in hot sunny areas (Li and Lam 2000). Li and Tsang (2008) have indicated that employing a proper daylighting scheme could result in good visual performance and reduced building energy use. However, the development of energy saving LED has improved the efficacy of light bulbs, therefore saving energy used for artificial lighting; further reductions by using indoor lighting would be minimal.

2.3.3 Benefits of daylighting

Windows are important for the visual connection they provide between inside and outside, but more importantly, windows have the biggest role in the admission of natural light into a building. It has been suggested by previous studies that daylighting can bring other advantages beyond the obvious economic benefits of reducing energy used for electrical lighting. It has also benefits to the health and the well-being of humans (Altomonte 2009; Gugliermetti and Bisegna 2006). Evidence that daylight is desirable can be found in research as well as in observations of human behaviour and the arrangement of interior spaces (Ruck 1989). Previous studies have shown that providing daylit spaces can increase retail sales (Heschong et al. 2002b), increase office rental values (Boyce et al. 1996), and enhance worker health (Heschong and Mahone 2003). Daylight not only has an impact on financial return of investment, but also on the human performance, work place productivity and human health (Boyce et al. 2003).

2.3.4 Daylight and human health

Rea and Boyce (1999) who studied the reaction of people to indoor environments, found that people desire daylight because it fulfils two basic human requirements: providing better vision for a task as well as to the space, and allowing individuals to experience some environmental stimulation. The light has also a positive impact on human health, as it controls the circadian rhythm of hormone secretions and body temperature with implications for sleep-wake states, alertness, mood and behaviour (Commission Internationale de l'Eclairage CIE 2004). The skin also responds to solar radiation, producing vitamin-D that is essential for calcium metabolism and skeleton health, plus a range of other potential benefits (Webb 2006), this is important to know about daylight although emitted daylight through glass does not produce as much of vitamin-D.

Many studies have discussed the benefit of indoor daylight to humans' health and well-being, According to Ruck (1989), working for prolonged periods of time under electrical lighting is believed to be deleterious to health, whereas, working in a space with a high level of daylight is believed to result in less stress and discomfort. Edwards and Torcellini (2002) as well as Estes et al. (2004) have shown that daylighting has been associated with higher productivity, lower absenteeism, fewer errors or defects in manufacturing under those conditions, positive attitudes, reduced fatigue and reduced eye strain.

Daylight is proven to have an effect on humans' health physiologically and psychologically (Aries et al. 2015), and the lack of indoor daylight has negative impacts on health and well-being (Shishegar and Boubekri 2016; Solt et al. 2017). Research found evidence that the amount of daylight children receive as they grow has a strong relation with developing myopia (an eye disorder causing short sight); it is argued that daylight in classrooms might prevent myopia (Hobday 2016). Another study has also indicated that indoor daylight is associated with the health outcomes of children in paediatric wards in hospitals (Diab et al. 2017).

2.3.5 Daylighting in schools

As mentioned above, many studies have conducted research about the benefits of daylight in buildings in general, considering a range of occupant types. This section focuses on studies that have discussed the benefits of daylighting in schools indicating that it can lower the running cost of educational buildings (Edwards and Torcellini 2002; Hathaway 1995; Küller and Lindsten 1992). Daylight has been shown to significantly enhance the learning environment and increase students' academic performance and scores. It promotes better health and physical development, by providing a less stressful environment for both students and teachers. These advantages have been extensively proven in many research studies (Erwin and Heschong 2002; Graça et al. 2007; Halliday 2008; Heath and Mendell 2002; Krüger and Dorigo 2008; Lee et al. 2012; Plympton et al. 2000). It was also proven that good views to the outside environment are associated with improving students' performance, and classrooms without outside views can cause stress in students (Theodorson 2009). It has been demonstrated that students' performance can be increased 14% in schools receiving daylight and absenteeism rates can be decreased by 3.5% in comparison with classrooms with no daylight (Nicklas and Baily 1997). Furthermore, research has shown that students in windowless classrooms are likely to be more hostile, hesitant, and maladjusted, and tend to be less interested in their work and complain more (Edwards and Torcellini 2002).

In a study conducted in Sweden (Küller and Lindsten 1992), 90 students were monitored during one year in four different classrooms with variable daylighting levels. The researchers monitored and studied their behaviour, health, and cortisol (a stress hormone) levels. They concluded that the absence of daylight could upset the basic hormonal pattern, and this in turn may influence the children's absenteeism and their ability to concentrate or cooperate, and eventually have an impact on annual body growth.

Nicklas and Baily (1997) have analysed the performance of 1,200 students in three schools receiving indoor daylight in the US. They compared their final scores with the national average. The results showed that the students in schools receiving indoor daylight outperformed the national average by 5% to 14%.

In a study conducted in Canada over two years, the attendance and health of 233 students in schools with different light sources were monitored and compared. It was found that students in the full spectrum light with ultraviolet supplements were healthier and had better attendance, achievement and development than students under other light sources. This finding indicates that light has non-visual effects on students since they are regularly exposed to light sources in classrooms (Hathaway 1995).

The biggest study about daylight and student performance to date was conducted by the Heschong-Mahone-Group (1999) and considered 21,000 students in 2,000 classrooms. The study analysed student performance marks in maths and reading subjects of elementary school students from 100 schools in three different states: California, Washington and Colorado. The researchers tried to control demographic and educational variables to examine the effect of daylight on students' performance. In California, it was found that students with the most exposure to indoor daylight were 20% faster in maths and 26% in reading in comparison to students who occupied classrooms with less available daylight. In the other two districts, the percentages by which students completed tasks more rapidly were 7% in maths and 18% in reading. The recommendations resulting from this study are for a classroom to have windows in more than one side wall, and if this is not possible, the detailing of the window needs to be carefully considered to achieve better daylight. This study was re-analysed again in 2002 after being criticised for not taking into account the variable characteristics of teachers between the different schools, revealing that there were no effects from this additional factor (Heschong et al. 2002a).

2.3.6 Disadvantages of daylighting in buildings

As mentioned before, Daylight Factor (DF) has been the method used to evaluate the daylight in a specific point in internal spaces. DF can be calculated manually or by computer, it is the percentage between internal illuminance and external illuminance (Waldram 1925). Knowing the distribution of DF in a daylit room according to the distance from the window provides information about the quality of illuminance from daylight. The uniformity of DF is the ratio between the minimum to average DF (Julian 2006). Direct sunlight often reduces uniformity especially in deep rooms. If uniformity was less than 0.4 when using daylight, or the average DF was less than 5% then supplementary electrical light is needed to improve the visual conditions (ibid.).

Another downside of using daylight is the risk of causing glare, not only by direct sunlight but also by high sky luminance or high contrast, for instance, when using windows in dark walls (ibid.). Glare problems reduce the quality of visual comfort in the interior (Chauvel et al. 1982; Heo et al. 2012; Poirazis et al. 2008). In hot arid regions, heat gain is the most negative aspect of daylighting, as the heat that can be transmitted through windows needs to be offset by a significant amount of cooling energy. Regarding daylighting in schools, researchers found that placing desks close to a window could cause significant discomfort from passive solar heating and/or glare (Lynes 1968; Wagdy and Fathy 2015, 2016).

2.3.7 Shading devices

All of the disadvantages of daylight discussed above can be overcome or minimised by using design solutions, such as proper shading devices. According to Li and Tsang (2008), the quality and quantity of natural light entering a building depend on both internal and external factors. The shading device is considered a main factor that can be controlled in order to increase the availability of daylight benefits and minimise the disadvantages of sunlight as far as possible. Research has shown that shading devices could reduce the cooling load between 23%-89% (Dubois 2000). Research also proved that the use of shading devices could present a way to prevent the effects of glare (Chauvel et al. 1982; Dubois 2003; Gugliermetti and Bisegna 2006). Glare from daylight inside buildings can be avoided by preventing direct sunlight from entering the field of view. In order to make the most benefit of daylighting, a window surface should not be sunlit (Paix 1982).

Shading devices could maintain the distribution of DF, thus, help in achieving a satisfactory uniformity ratio (Julian 2006; Poirazis et al. 2008). The uniformity ratio is the ratio between minimum illuminance and the average illuminance in a lit space. It was proven that exterior shading devices in buildings are more effective in blocking solar heat and direct sunlight than interior shading devices such as curtain blinds and Venetian blinds (Li and Tsang 2008). Another research study has also shown that external shading devices are more effective in reducing solar radiation than an internal solution by 30%–50% (Olgyay 1963).

Maximum use of indirect and internally reflected light is the most appropriate form of daylighting to avoid glare and heat gain (Koch-Nielsen 2002). Previous work has discussed how the most important benefit of using sun shading devices in hot climate regions is to minimise heat gain through glass by blocking direct sunlight from the glass surface which is the main cause for transmitting heat inside buildings. Ho et al. (2008) compared variations of shading devices in a classroom in Taiwan, and found that the best configuration of shading devices can achieve the minimum illuminance requirement of $500lx$ in classrooms. The lighting uniformity ratio was also found to improve from 0.25–0.35 without shading to 0.40–0.42 with the use of a shading device, although this is still below the required 0.5 ratio, it can be easily achieved by using some of the artificial light already installed. The same study (Ho et al. 2008) has also proven that using shading devices does not only improve the illuminance conditions within the classroom, but also reduces the artificial lighting power cost by 71.5%.

2.3.8 Perforated solar screens

External shading devices can come in different forms (Jain and Garg 2018; Stazi et al. 2014), such as horizontal overhangs and louvres (Freewan 2014; Hammad and Abu-Hijleh 2010; Palmero-Marrero and Oliveira 2010), and solar screens (Alawadhi 2018; Chi et al. 2017a,b).

One of the types of shading devices is the perforated solar screen, which is defined by Harris (2006) as external perforated panels that are fixed in front of windows. According to Alawadhi (2018) the exterior solar screen is one of the most effective shading devices to control sunlight entering the indoor space. They are relatively inexpensive, lightweight, easy to install and have aesthetic value (Ayssa 1996).

Many researchers mentioned that the perforated solar screen and the Mashrabiya are the same device with different names (Fathy 1986; Sabry et al. 2014, 2010; Sherif et al. 2011). The Mashrabiya is a shading device traditionally used in the Middle-Eastern and Muslim countries (Fathy 1986). Due to the relevance of this type of solar screen in the maintenance of privacy (discussed in Section 2.2.4), the Mashrabiya will be considered in the following section. The author aims to investigate its history and parameters in order to attempt to apply it as an effective shading device to improve interior daylighting and maintain privacy in girls' schools in Saudi Arabia.

2.4 Mashrabiya

For centuries, the hot arid climate of many parts of the Middle East forced those living there to develop a set of architectural elements that suit such climatic conditions. The Mashrabiya functions as a sun shading device attached to windows that also provides the advantage of maintaining privacy for occupants, which is a crucial issue in Islamic countries. Researchers claim that old vernacular Islamic architectural elements were not only built in regard to physical and environmental parameters. There were also other important principles stemming from Islamic values to determine the form and shape of the built environment such as the privacy and rights of neighbours (Ahmed 2014; Akbar 1989; Akbar and Hakim 1992; Sherif et al. 2012b; Sidawi 2013). The ability of the Mashrabiya to satisfy so many functions appears to be the reason for its extensive use as a basic architecture element in the traditional buildings in the Middle East.

Recently however, the Western modern architecture was brought to the Middle East without considering the local climate resulting in an increase in energy consumption in buildings, mainly for space cooling (Al-Ibrahim 1990). It was suggested by Asfour (1998) that Arabian architectural history should be reinterpreted by architects, to generate design strategies relevant to the context. This can be achieved by interpreting correctly the hidden values of elements of the historical Islamic architecture (Sidawi 2013). After discussing the advantages of sun shading devices to optimise daylighting in buildings, it is predicted that applying Mashrabiya or a Perforated solar screen would provide many benefits to buildings and occupants in the Middle East.

2.4.1 History and definition

The earliest authenticated examples occur in the Ayyūbid cenotaphs (thirteenth century) in the mosque of Imām ash-Shāfi'I from the year 1285, and in the wall surrounding the tomb of Sultan Qalāwūn, (Briggs 1974; Herz Bey 1907) (Figure 2.13).

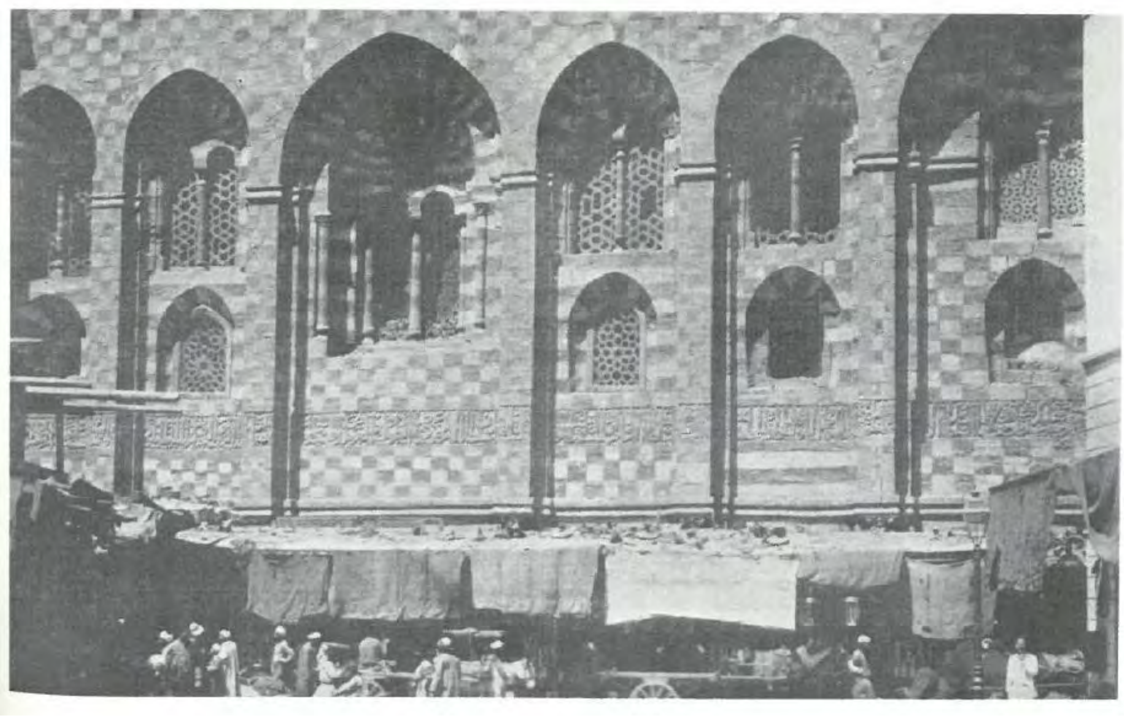


Figure 2.13: Mausoleum of Qalawun in Cairo (source: Briggs 1974).

According to the Arabic-English dictionary, the name Mashrabiya is believed to be derived from an Arabic word “shrab” which means “drink”. Hence, it was originally called “the drinking place”, because it was a place where water jars were stored to be cooled by the air flow and at the same time to humidify the air entering the building by the evaporation effect (Edward 1973; Gallo 1996; Kenzari and Elsheshtawy 2003; Paccard 1981). Since the word was translated from Arabic language, various spellings can be found in literature, such as, mashrabiy’ya, meshrebiya or mushrabiyyah; meshrebeeyeh, mashrebiyya or mashrebeeyah (Ajaj and Pugnaloni 2014; Alitany 2014; Almansuri et al. 2010; Briggs 1974; Gallo 1996; Al-Hashmi and Semidor 2013; Mohamed 2006; Sidawi 2013); moucharabieh or moucharaby in the French language (Citherlet et al. 2001; Depaule and Arnaud 1985); musharabie or musharabia in Italian and German (Almansuri et al. 2010); muxarabi in Portuguese (Bruna et al. 2008). The use of Mashrabiya can be found in traditional architecture in many regions in the Middle East and North Africa, some regions however, use different names, namely, kharjah in Syria and Jordon (Alitany 2014), takhrima in Yemen, barmaqli in Tunisia and Algeria, shanashil in Iraq (Alitany 2014; Samuels 2011), rowshan or roshan in Saudi Arabia (Akbar 2012; Aljofi 2005; Hariri 1992; Al-Hashmi and Semidor 2013; Jomah 1992; Oliver 1990), roshan is also the name used in Sudan (Greenlaw 1976), it can be seen also in India and Pakistan where it is called jali and found in old mosques and tombs (Batool and Elzeyadi 2014; Fathy 1986; Thapar 2012; Vyas 2005). Interestingly, such devices are also found in Peru in South America, perhaps due to the Spanish and Moorish influence (Bruna et al. 2008; Kenzari and Elsheshtawy 2003). Some authors argued that the modernist architect Le Corbusier may have been influenced by Mashrabiya during his travel to Istanbul in 1911 and later to North Africa, when he used “Brise soleil” in his designs (Kenzari and Elsheshtawy 2003; Vogt 2000).

Despite all these variations of the name, “Mashrabiya” is the most common name for the wooden lattice window among the Arabic speaking nations (Kenzari and Elsheshtawy 2003). The name Mashrabiya according to Gallo (1996) is used to describe any opening with a wooden lattice screen composed of small wooden balusters arranged at specific fixed intervals, often in a decorative geometric pattern. In more recent research studies it is referred to as an “external perforated solar screen”, which is the scientific translation used by some researchers (Sabry et al. 2011; Sherif et al. 2012c). They all are the same device with different names.

2.4.2 Description

According to “the Encyclopaedia of Islam” (Behrens-Abouseif 1991), Mashrabiya is a “designated technique of turned wood used to produce lattice-like panels to adorn the windows in traditional domestic architecture”. It is a vernacular architectural device made of a combination of wooden strips, used mainly to adapt to a hot climate. It has effective specifications that are used for thermal comfort, ventilation and day-lighting control, whilst providing privacy and security solutions for the occupants. It is an element to provide shading which is essential in hot climates, and provides both thermal and visual comfort by protecting against direct solar radiation and sun glare, and it works as a tool to provide privacy for the inhabitants (Al-Hashmi and Semidor 2013; Sherif et al. 2012b). It is composed of a lattice of wooden cylinders connected with spherical wooden joints, to provide shading and diffuse natural light, thus eliminating unwanted direct solar penetration (Sabry et al. 2011).

Figure 2.14: A photo of an old Mashrabiya taken by Sam Valdi (2015).

It is assembled as a narrow three sided box projecting from the façade of the building in front of windows, with strong wooden beams fixed firmly into the thickness of the house wall to secure its great weight below. These supports are sometimes visible, but they are often concealed by ornamental wooden stalactites, or by decorative wooden panels. The lower and upper walls of Mashrabiya are wooden panels, cut in simple geometrical patterns, and the screens that fill these shutters are made of flat wooden mesh (Al-Hashmi and Semidor 2013). The average dimensions would be 2.4–2.8m in width, 0.4–0.6m in depth, and 2.7–3.5m in height (Greenlaw 1976; Jomah 1992); it could however, be larger or smaller depending on the timber used (Alitany 2014). It is nearly impossible to find two identical historical Mashrabiyas since they were hand-made and have endless varieties of size, shapes, treatments and organisations (Alitany 2014; Jomah 1992).

2.4.3 Function

In general, the main functions of Mashrabiya are in providing: cross ventilation, light control, humidity control, cooling of water in clay jars, and ensuring social privacy for occupants (Al-Hashmi and Semidor 2013). These can be categorised as social and environmental functions, of which the most important social function of Mashrabiya is to maintain privacy from the outside for the inhabitants while allowing them to view the outside through the screen at the same time (Belakehal et al. 2004; Fathy 1986; Gallo 1996). There are four main environmental functions of Mashrabiya, namely, controlling the passage of light, controlling the air flow, reducing the temperature of the air current as a result of combination with evaporative cooling, and increasing the humidity of the air current (Ajaj and Pugnaloni 2014; Gallo 1996; Sidawi 2013). Each Mashrabiya is designed to fulfil several or all of these functions (Ajaj and Pugnaloni 2014; Fathy 1986).

Some researchers argued that there is a third category of its functions, which is the aesthetic role. It can be suggested that Mashrabiya's configuration, shape, colour, complexity and richness of ornamentation, size and material are constrained by the financial status of the house owner (Samuels 2011; Sidawi 2013). Pesce (1976) cited a traveller writer called John Russell, who when describing Mashrabiya in Jeddah said "there is nothing more pretty, more aerial than sculptured wood balconies that adorn the façades of rich mansions". Of particular relevance to this work is the role that the Mashrabiya have in maintaining privacy and controlling the light, which has three aspects: controlling the solar radiation emitted to buildings "thermal gain"; controlling the daylight quality in buildings "illumination and uniformity"; and visual comfort inside buildings "reduction of glare" (Samuels 2011).

2.4.4 Parameters

This section discusses the design parameters of Mashrabiya, as these have been previously studied. Their influence on the performance of the solar screen are discussed in the following Section 2.6.

It would be easier to construct a Mashrabiya by carving a large piece of timber, but the problem is that most countries in the Middle East are sparsely planted, therefore, timber was hard to find in great quantities and only small branches and sticks were available. This means that the Mashrabiya had to be constructed using a large number of small interconnected elements, with sticks converted to long balusters between 10–100cm long (Briggs 1974; Samuels 2011). These balusters are the most important unit of Mashrabiya. The craftsman could control the internal environment by changing the length or/and diameter of each baluster. The ratio between them defines the porosity of the screen, which directly affects the way it regulates light, heat and airflow (Fathy 1986). Historically, it was up to the craftsman to determine these sizes during production and thus control the internal climate of the building with precision; they were mostly aesthetic decisions and the environmental benefits were derived accordingly. The amount of diffused light that enters a room depends primarily on the size and porosity of the Mashrabiya, along with the reflectivity and materiality of the balusters (Aljofi 2005).

Parameters of Mashrabiya from literature can be summarised as follows:

- Perforation percentage (Sherif et al. 2012b) or porosity (Samuels 2011).
- Depth ratio (Sherif et al. 2012c).
- Opening aspect ratio (Sabry et al. 2014).

- Colour and reflectivity (Aljofi 2005; Wagdy and Fathy 2015).
- Shape (Aljofi 2006; Chi et al. 2017c).
- Tilt angle (Sabry et al. 2012b).

According to previous research, parameters of Mashrabiya can be listed and explained as following:

2.4.4.1 Perforation percentage

According to Samuels (2011), it is the most important parameter of the perforated solar screen to control the redirection of direct sunlight during hot summer months. Although he called it the porosity factor, it is the same parameter that was called perforation percentage by other researchers (Batool and Elzeyadi 2014; Chi et al. 2017c; Sabry et al. 2011; Sherif et al. 2010a, 2012b).

The porosity factor is calculated by dividing the total area of openings by the area of interstices. It has a range from PF0 to PF1 where PF0 means the screen has no porosity, and a window with PF1 is a window without a solar screen (Samuels 2011). Sherif et al. (2010b) and Sabry et al. (2011) used a percentage ranged from 0% up to 100% to describe the perforation percentage. This parameter has been studied before, as Sherif et al. (2010a, 2012c) have studied the effect of perforation percentage on energy loads of residential buildings. Sherif et al. (2012b) have studied the same parameter in relation to the daylight performance in residential buildings. Chi et al. (2017c, 2018) have studied the effect of the perforation percentage on the performance in solar screens in balancing daylighting and energy saving using four cases in 12.5% intervals (Figure 2.15).

2.4.4.2 Depth ratio

Depth ratio is the ratio between the thickness of the screen and the width of each opening. It was proved that different depth ratios have an impact on the performance

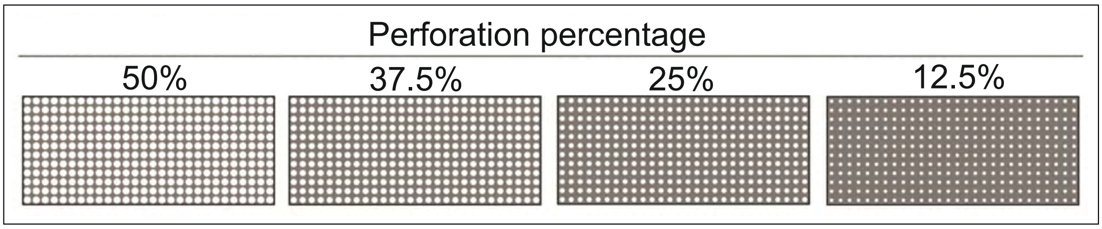


Figure 2.15: Examples of perforation percentage (source: Chi et al. 2017).

of the solar screen (Sherif et al. 2012c) (Figure 2.16). The effect of this parameter on energy load in residential buildings have been studied previously (Sherif et al. 2012c, 2011).

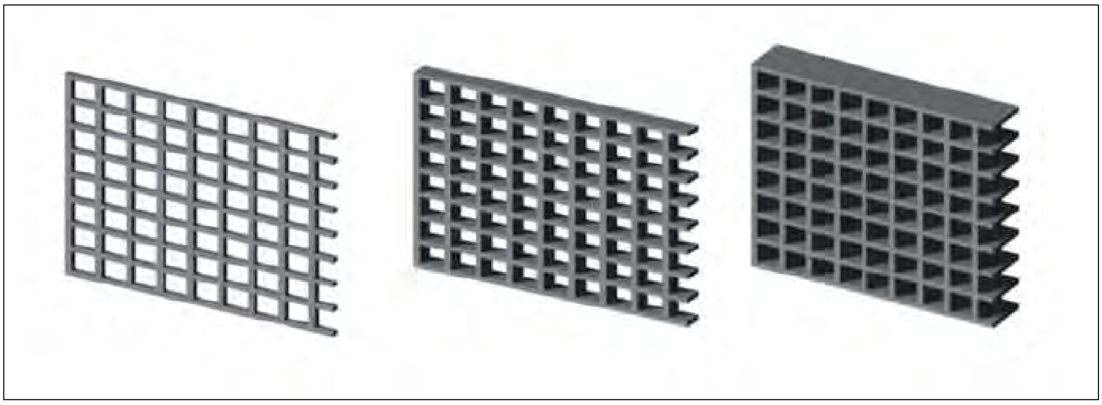


Figure 2.16: Geometrical effect of depth ratio (source: Sherif et al. 2011).

2.4.4.3 Aspect ratio of openings

The opening aspect ratio is the ratio between the width and height of the opening in the solar screen. An opening can be horizontal if the width is higher than the height, or it can be vertical if the height is more than the width. It could also be square when the ratio is 1:1 (Figure 2.17). The effect of this parameter on daylight performance and energy load was studied in previous research (Sabry et al. 2014; Sherif et al. 2011). The effect of combining this parameter with another parameter "tilting angle" on the daylight performance was also studied previously (Sabry et al. 2012a,b; Sherif et al. 2012a). The effect of the same combination was studied on the energy performance as well (Sherif et al. 2013).

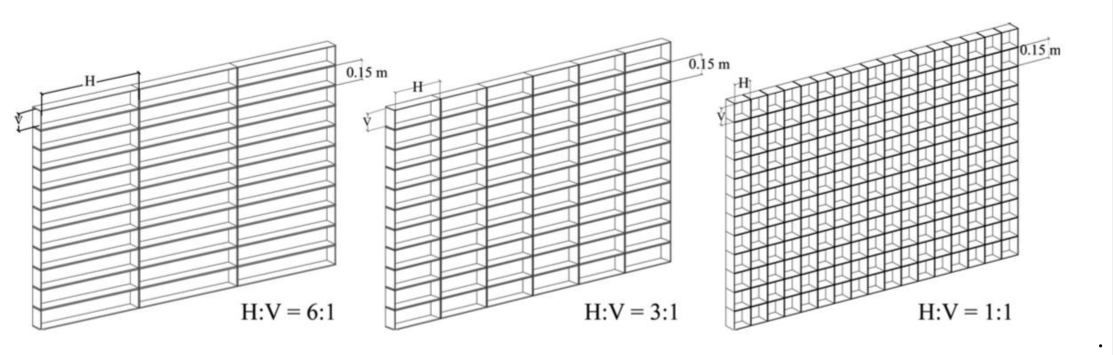


Figure 2.17: Geometrical effect of aspect ratio (source: Sherif et al. 2012).

2.4.4.4 Colour and reflectivity

Traditionally, Mashrabiya is made of the available type of wood according to the location and surroundings, mostly in dark oak colour, but sometimes in light oak colour; each colour has different reflectivity and thus produces a different performance from the screen. Aljofi (2005) has proven that this can affect the performance of Mashrabiya. Hegazy and Attia (2014) have studied the effect of reflectivity levels on the daylight performance of a shading device. El–Zafarany et al. (2013) have studied the effect on energy efficiency when using different reflectance for perforated solar screens. Wagdy and Fathy (2015) have studied the effect of two reflectivity ratios: 0.35 and 0.8 on the daylight performance of perforated screens.

2.4.4.5 Cell shape

Depending on the cell, a Mashrabiya can have different shapes. Aljofi (2005) studied cell shapes and concluded that there are six traditional shapes of cells displayed in Figure 2.18, and he found that different cell shapes can provide different levels of interior daylight. He proved that a solar screen with square-shaped opening can provide better daylight performance than any of the five other shapes that he has tested, and the circle-shaped openings provide less daylight than other shapes. Chi et al. (2017c, 2018) have compared the performance of screens with quadrangular, circular, triangular and hexagonal cells (Figure 2.19). Their results confirmed the results of Aljofi (2005) that screens with quadrangle shaped cells performed better than other shapes.

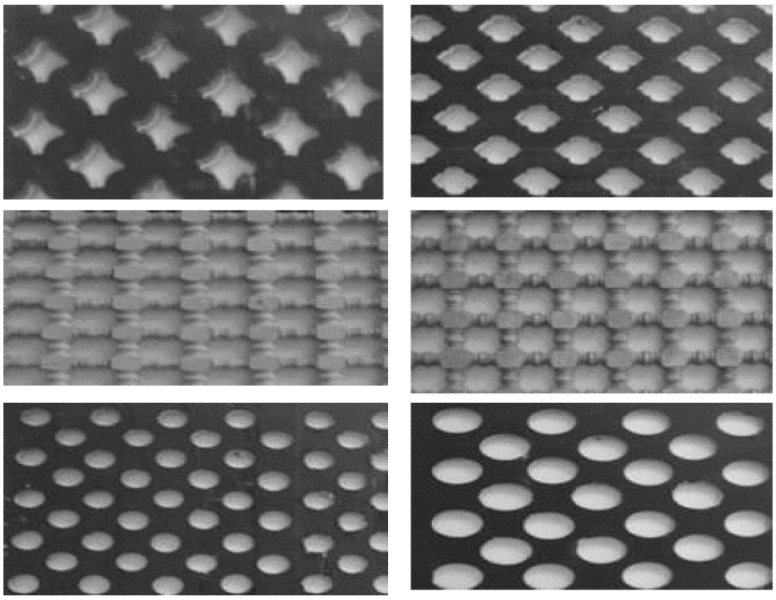


Figure 2.18: Different cell shapes of Mashrabiya studied by Aljofi (source: Aljofi 2005).

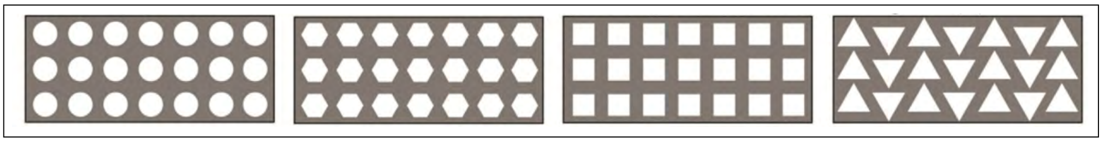
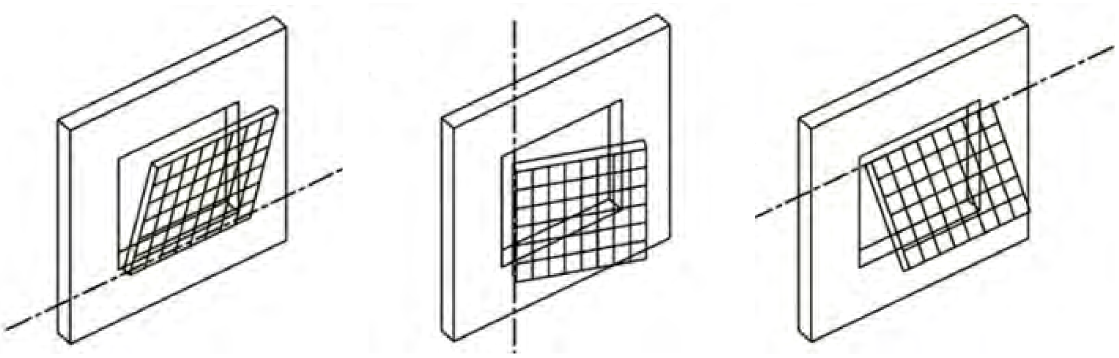


Figure 2.19: Different cell shapes of Mashrabiya studied by Chi et al. (source: Chi et al. 2017).

2.4.4.6 Tilting angle

External perforated screens can be tilted or rotated on either of the vertical or horizontal axis. The axis usually is one of the edges of the screen. Sabry et al. (2011) called it axial rotation and they have studied the effect of it on the daylight performance (Figure 2.20). They have however, studied different directions of rotation for different orientations. Horizontal lower axis rotation for north, horizontal upper axis rotation for south, and vertical axis rotation for west and east. They used 10° intervals to study the effect of axial rotation from 10° to 30°. Some researchers used the results of that experiment to test the effect of combining this parameter with the opening aspect ratio on daylight performance and energy loads (Sabry et al. 2012a, 2014, 2012b; Sherif et al. 2012a) or on energy loads alone (Sherif et al. 2013).



(a) Horizontal lower axis. (b) Vertical axis. (c) Horizontal upper axis.

Figure 2.20: Different tilting directions according to the axis (source: Sabry et al. 2011).

2.4.5 Summary of Mashrabiya

After investigating the functions of Mashrabiya “the perforated solar screen”, it appeared that it would be a solution for the current problem in girls’ schools in Saudi Arabia since it can maintain privacy and increase the quality of interior natural light by blocking direct sunlight and allowing reflected daylight.

The section also discusses the parameters of perforated solar screens that have been described and tested in previous research. It appeared that to the author’s knowledge there are a scarcity of references related to the effect of cell size on the performance of the perforated solar screens while maintaining other parameters, especially the depth ratio. Studies that tested cell sizes and cell shapes used the same depth value and not the same depth ratio. The author believes that using the same depth value would give different depth ratios with each cell size, that would bias the result and would make big cells emit more daylight. The author suggests that in order to test the cell size, all other parameters should be isolated and the depth ratio should be the same.

Each screen has a module for its grid, different screens could have different grid modules or cell sizes even though they share the same aspect ratio of say 1:1, and the same perforation percentage and depth ratio. Figure 2.21 shows examples of three different screens with different cell module size while keeping dimensions and all other parameters constant. Since no previous work known to the author has discussed the effect of this parameter, it is added to the parameters investigated in this research.

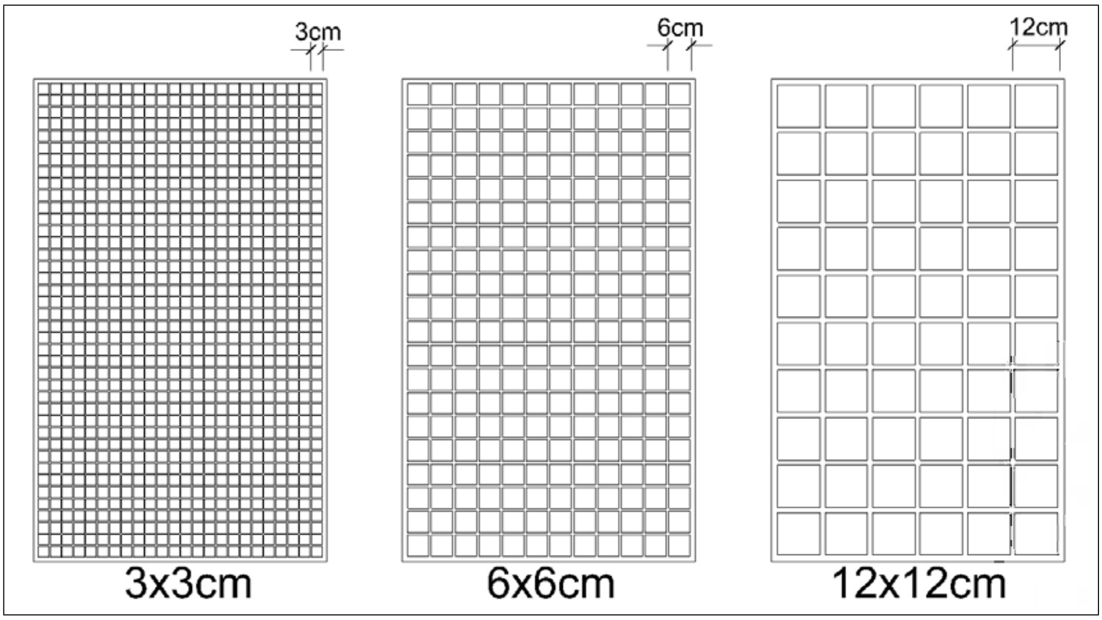


Figure 2.21: Geometrical effect of cell size (by author).

2.5 Measuring Daylight

Since shading devices in buildings were widely re-introduced in the 40s, much research have investigated the properties of them and their effect on both interior illumination and energy consumption (Dubois 1997). Daylighting is a particularly difficult performance strategy to evaluate (Reinhart et al. 2006). Daylighting analysis can be categorised into three methods: physical scale models, graphic techniques, and calculations (Bryan and Autif 2002). To predict daylight performance researchers historically used a range of simple rules of thumb through to calculation methods like the lumen method, graphic methods like the Waldram diagrams or BRE protractors, through to the use of physical models tested under either a real or an artificial sky (Baker et al. 1993; Hopkinson et al. 1966; Robinson 1986; Ubbelohde and Humann 1998). These methods rely mostly on predicting the illuminance levels in buildings. Then simulation software were introduced and were assumed to bring a highest possible level of accuracy (Ubbelohde and Humann 1998). Since they are able to provide more data to the designer, such as, distribution patterns, intensity, luminance gradations and potential glare. However, at the beginning they came with serious barriers, mostly the low speed and the memory need of computers (Ubbelohde et al. 1989). Obviously, these barriers were overcome recently as computers have become more powerful, with high capacity. Therefore, most researchers now use digital methods to predict daylight performance and estimate the interior daylight levels.

2.5.1 Daylight metrics

Whether a physical model or computer simulation is used, a metric should be used to evaluate the predicted interior daylight in space. Building performance metrics work as quality measures. According to Mardaljevic et al. (2009) a metric is a mathematical combination of measurements and/or dimensions and/or conditions represented in a continuous scale, and daylight performance could be described with one or more than one metric. Daylight metrics were initially introduced to evaluate daylight in interior spaces in existing buildings, then with the use of models they started to be used to predict interior daylight during design stages. Daylight metrics can be divided in two groups: Static daylight metrics and dynamic daylight metrics (Mardaljevic 2000a). The former represents metrics related to specific points and a specific time whereas the latter results in annual time series and takes into account the weather data of the location for a period of time according to the occupation schedule (the hours when the space is occupied during one calendar year). The major advantage of dynamic daylight metrics is considering the quantity and character of daily and seasonal variations daylight for a building site with irregular climatic events (Reinhart et al. 2006). However, static metrics are also useful in some situation such as knowing whether more shading or artificial lighting is required in an exact point of time.

2.5.1.1 Static daylight metrics

Static daylight metrics can be listed as follows.

Illuminance on a horizontal plane

Illuminance values on a horizontal working plane, is used to determine if the illuminance is adequate to carry out a task. Each task has a recommended illuminance value according to the referred standard reference book, for example, $500lx$ is the recommended value for detailed office and clerical work (Phillips 2000). Although this metric cannot describe the visual quality of the space, it is the most commonly used metric to evaluate illumenance levels in a space (Mardaljevic et al. 2009). A specified grid of measuring points on the working plane can be used to evaluate a whole space rather than just one point, the grid can be divided in zones of interests or specific task areas (ibid.). This method was used in a lot of research to evaluate spaces (Sabry et al. 2011; Sherif et al. 2012a, 2010). Where a grid of measuring points was spread on the working plane level of the studied space. Then the grid was divided into three zones according to the distance to the window: Near zone; Mid zone; and Far zone (Figure 2.22). An average illuminance level can also be calculated for each zone in a specific time of the year.

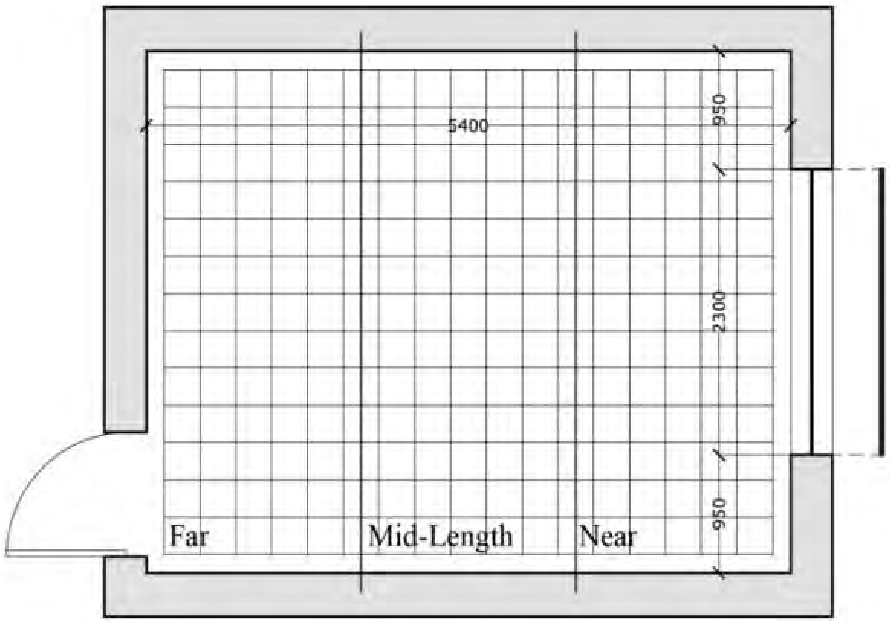


Figure 2.22: Zones as used in previous research (source: Sherif et al. 2010).

Daylight Factor (DF)

As mentioned previously in this Chapter, DF can be defined as the ratio of internal illuminance at a point inside a building to unobstructed external horizontal illuminance under standard CIE overcast sky conditions (Hopkinson 1963). The CIE overcast sky is a standard sky defined and explained by Moon and Spencer (1942). The concept of using DF to quantify daylight in building was first proposed in the early 1900s when Waldram (1909) introduced a measurement technique based on the approach. It used to be called Sky Factor at the beginning when it used to consider only direct light from the sky. Then the Sky factor developed into the DF as reflected light from external obstructions and internal reflectance and light loss through glass were added into consideration (Waldram 1950).

Initially, the DF was primarily used as legal evidence in courts (Reinhart et al. 2006), the UK perception Act of 1832 states that a violation of a window's right to light was found when a new neighbouring structure caused inadequate indoor daylight levels (Waldram 1950). Therefore, the critical question was what is considered to be adequate daylighting levels and DF was first introduced to answer this question. Similar to Illuminance levels, a grid of DF values can be used to evaluate the light distribution of a space, this method was used before in research (Brembilla et al. 2016). Many opponents of the DF method do not consider it a tool to measure good lighting rather than just a minimum legal lighting requirements (Reinhart et al. 2006). They argue that the reference overcast sky used by DF is the worst case sky condition, therefore, any other sky would lead to more daylight and probably oversupply of light and cause glare problems. They also argue that the DF does not consider movable shading device operated by occupants as they are not needed under the case of overcast sky conditions (ibid.). Calculating the DF using an overcast sky means also that DF is insensitive to either the building location nor the building orientation because the sun is not considered and the overcast sky is asymmetrical (Mardaljevic et al. 2009). However, DF is still widely used measure for daylighting due to its ease of use and easy to communication within a design team (Reinhart et al. 2006).

DF and avoidance of direct sunlight

Since the limitation of the DF method was revealed, some designers tried to consider using a clear sun instead of an overcast sky taking sun movement and direction into consideration. Using a combination method between DF and avoiding direct sunlight, they aimed to design a façade that avoided direct sunlight penetrating into the building. Then the opening is resized until the required DF is achieved. This method is mostly used as an indicator during the early design stages rather than predicting the exact performance of a specific design. Although this combined approach considers sun position and building orientation, it does not consider either the actual climate of the location nor the occupancy time of the space (Reinhart et al. 2006).

Disadvantages of static daylight metrics

The use of average illuminance and the DF with scale models to predict daylight performance in buildings have been questioned before by some researchers (Piccoli et al. 2004; Tregenza and Waters 1983). Anecdotal evidences and control studies have indicated that the horizontal illuminance is not the only important aspect. Many other aspects must also be considered in order to evaluate light throughout the whole space (Boyce 2004; Goodman 2009; Piccoli et al. 2004). Some researchers also claimed that DF is insufficient due to its intrinsic limitations (Love and Navvab 1994; Nabil and Mardaljevic 2005; Reinhart et al. 2006; Tregenza 1980).

2.5.1.2 Dynamic daylight metrics

Internal daylight should not be proportional to the external illuminance, it should depend on the sky luminance distribution at that time exactly. An internal point receives direct light only from certain areas from the sky and the internal illuminance inside a room is not equally sensitive to variations in the luminance of different parts of the sky (Li et al. 2006). Therefore, the Daylight Coefficient (DC) was developed by Tregenza and Waters (1983) to relate the luminance distribution of the sky with the illuminance inside buildings.

In this context, “Dynamic” means variable with time due to changing sky conditions (Bourgeois et al. 2008). All dynamic daylight metrics are based on the DC approach. Therefore, it is essential to explain the DC approach before listing the dynamic daylight metrics.

Daylight Coefficient DC

In theory it means dividing the celestial hemisphere into disjoint sky segments, then calculating the contribution of each sky segment to the total illuminance at sensor points in the studied space. It can be described as mathematical functions that relate the luminance distribution of the sky to the illuminance at a point in a room. Tregenza (1987) then explained the subdivisions of the sky, and explained the adaptive radiosity (1994), and Littlefair (1992) explained its computational method. The fundamental equation 2.1 of daylighting links the size and luminance of a small patch of the sky to the produced illuminance E at a given location (on the reference point) (Tregenza 2017).

$$E = L.d.\omega \tag{2.1}$$

Where L is the luminance, ω is the angular size of the sky patch, and d is the fraction of light emitted by the sky patch that falls on the reference point.

Therefore, the DC from direct sky can be defined by equation 2.2 (Li et al. 2006; Mardaljevic 2000b; Tregenza and Waters 1983):

$$DC_{\theta\alpha} = \frac{\Delta E_{\theta\alpha}}{L_{\theta\alpha}\Delta S_{\theta\alpha}} \tag{2.2}$$

Where $L_{\theta\alpha}$ and $\Delta S_{\theta\alpha}$ are the luminance and angular size (solid angle) of the sky patch, θ is its altitude angle and α is the azimuth angle. This can be used to calculate DC for an external unobstructed location. For an interior position however, DC considers also daylight reflected of the ground, the external obstructions and any reflectance inside the studied room. Therefore, DC is calculated as a matrix of three components: Direct components, externally reflected components and internally reflected components (Tregenza and Waters 1984).

DC was developed initially to evaluate daylighting in buildings instead of the Daylight Factor. With the use of a climate data file, DC then became a useful approach to predict or evaluate daylighting in building during design stage with the use of three dimensional drawings.

Once a set of DCs is calculated, it is easy to find daylight illuminance under many conditions of sky luminance distribution with minimal additional effort (Littlefair 1992; Reinhart and Walkenhorst 2001; Tsangrassoulis et al. 1996). DC can be used to accurately calculate time series of luminance and illuminance in buildings with openings to outside (Mardaljevic 2000a; Reinhart 2001; Reinhart and Andersen 2006). These time series can then be used to perform annual daylight metrics either using simulation or calculations. Equation 6.3 and Figure :2.23 (Bourgeois et al. 2008) explain how to calculate DC on one sensor x, a DC related to the sky segment S_α is defined as the illuminance E, at sensor x caused by the sky segment, divided by the luminance L_α and the angular size ΔS_α of the segment.

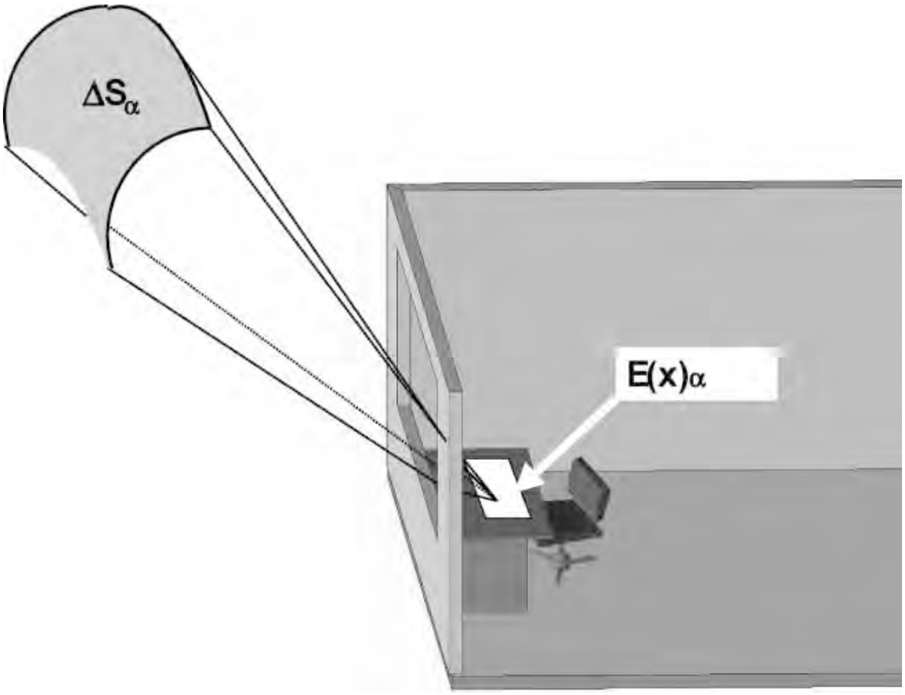


Figure 2.23: Definition of DC (source: Bourgeois et al. 2008).

$$DC_\alpha(x) = \frac{E_\alpha(x)}{L_\alpha \Delta S_\alpha} \tag{6.3}$$

where:

x	sensor point,
$DC_\alpha(x)$	daylight coefficient at sensor x,
S_α	sky segment,
ΔS_α	angular size of S_α,
$E_\alpha(x)$	illuminance at x due to S_α,
L_α	luminance of S_α,

The total sensor approach illuminance $E(x)$, in equation 6.4, is calculated by linear superposition of each DC $DC_\alpha(x)$, coupled with the luminance L_α of its matching sky segment S_α:

$$E(x) = \Sigma_{\alpha=1}^{N} DC_\alpha(x) L_\alpha \Delta S_\alpha \tag{6.4}$$

where:

$E(x)$	total sensor illuminance,
N	number of sensors,

This method faced many difficulties at the beginnings as it used to take a long time for calculations and software and powerful computers were not widely available at that time. Although it was time-consuming, it was by all means more exhaustive (Li et al. 2006). That however, was changed lately and this method became widely used, There has been extensive development of software based on the concept of DC (Bourgeois et al. 2008; Heschong et al. 2012a; Nabil and Mardaljevic 2006; Reinhart et al. 2006).

Using DC approach to predict annual illuminances inside buildings according to the climate data of the studied location is recently known as the Climate Based Daylight Modelling (CBDM). Using sun and sky conditions that are derived from a weather file, CBDM predicts various radiant or luminous quantities, namely, irradiance, illuminance, radiance and luminance (Mardaljevic et al. 2009). The idea of using the climate data of the specific location to predict light quantities started in the mid of the 90s (Mardaljevic 2015) when data was collected by the Building Research Establishment (BRE) as part of the International Daylight Measurement Programme, these data are referred to as BRE–IDMP data set (Mardaljevic 2001). That study compared predicted illuminances with actual measured values and found them to lie within ±10% of measured values. The principles of CBDM were described further in 2000 by Mardaljevic (2000b) and Reinhart and Herkel (2000), the former researchers tried to call it Annual Daylight Profiles (ADPs) (Mardaljevic 2001), and the latter tried to call it New Daylight Coefficient method. In that paper, Reinhart and Herkel (2000) validated the new method by comparing simulated results with measured illuminance values on a grid in an actual space for 4703 working hours of a whole year.

The name CBDM, was first introduced by Mardaljevic (2006) with more explanation. CBDM delivers predictions of absolute quantities of illuminance that depend on both the orientation (solar position and non-uniform sky conditions) and the locale (climate data of the location), and finally the configuration of the building (geometry and reflectance) (Mardaljevic and Janes 2012). According to Mardaljevic et al. (2009) CBDM is generally taken to mean any evaluation that is founded on the totality (i.e. sun and sky components) of time-series daylight data appropriate to the locale. These time series could extend over a whole year and based on annual solar radiation data for the building location (Reinhart et al. 2006). These time series cover the occupancy hours during daytime in a calendar year and are based on external, annual solar radiation data for the building site. Many studies have proven that using a DC approach and the all-weather sky luminance model by Perez et al. (1993) can effectively calculate time series of illuminance and luminance in buildings (Mardaljevic 2000b; Reinhart and Andersen 2006; Reinhart and Walkenhorst 2001).

2.5.2 Simulating CBDM

Simulating light using the CBDM involves two steps (Reinhart et al. 2006):

- A pre-processing step when a set of daylight coefficient is calculated for each sensor point.
- A post-processing step when the DC is coupled with climate data resulting in the annual time series of interior illuminance and luminance

These two steps are fully automated when using a simulation software tool.

In order to simulate CBDM correctly, these variables need to be addressed and prepared (Reinhart et al. 2006; Rogers and Goldman 2006):

1. A three dimensional CAD model.
2. Specifying the properties of optical surfaces, inside and outside the building.
3. Specifying a grid of sensor points, on the working plane.
4. Defining time frame.
5. Providing an annual climate file for the location, includes hourly data of direct and diffused irradiances.
6. Target illuminance threshold, according to the activity or work carried out in the studied space.

Specifying these CBDM variables according to this project is discussed in detail in research methods in Chapter 3.

Preparing and selecting these variables is the first step to simulate CBDM. Simulating CBDM is performed by following these basic steps: (Mardaljevic et al. 2012)

1. Obtain and prepare all variables for the location.
2. Generate a sky luminance distribution using a sky model based on the values

for diffused horizontal illuminance in the climate data.

3. Create a sun description (luminance and position) from the values of direct illuminances of the climate data.

4. Calculate the internal daylight illuminance distribution.

5. Repeat steps 2–4 for each sensor point for each time steps according to the sensor grid positions and the time frame used until illuminance is calculated at all sensor points.

2.5.3 Dynamic Daylight Performance Metrics DDPMs

CBDM provides thousands of data for each sensor point, basically an illuminance value for each hour of the time frame at each sensor point. This voluminous illuminance data need to be demonstrated in a way it is easy to understand for a non-expert designer (Mardaljevic 2006). Therefore, researchers started to introduce metrics to help in representing the data that resulted of the CBDM simulation.

CBDM has two principal analysis methods: 1) A cumulative method, which can be used by predicting the solar access and micro-climate in urban environments and the long-term exposure to daylight. 2) Time series analysis that predict instantaneous measures like illuminance, based on the hourly values from the climate data file, which can be used to evaluate daylighting potential for an interior space (Mardaljevic et al. 2009). Some metrics analyse data based on the cumulative method, such as Total Annual Illuminance (TAI) and Sulight Beam Index (SBI). TAI is defined as the sum of all the illuminance values of the occupied time. Although this metric is usually used to study how much illumination an art work receive in a museum or to study the effect of different reflectance values for materials of furniture, it has been used before as a method to evaluate daylight in buildings (Brembilla et al. 2016, 2015b). While SBI concerns on how big is the area of incident on windows to receive potential direct sunlight and for how long by using a sensor grid on windows. It can also have a volumetric display by using layers of sensor grids as can be seen in Figure 2.24 (Mardaljevic and Roy 2016). However, SBI does not consider the required illuminance level nor the working plane height, in other words the cumulative method considers the quantity of light rather than the quality, therefore, it cannot be used to compare results with previous related research as it has not been used to analyse the quality of daylight before as to the author's knowledge. What is relative to this research is the dynamic daylight metrics which are based on a time-series of instantaneously occurring daylight illuminances and cannot be reliably inferred from the cumulative method.

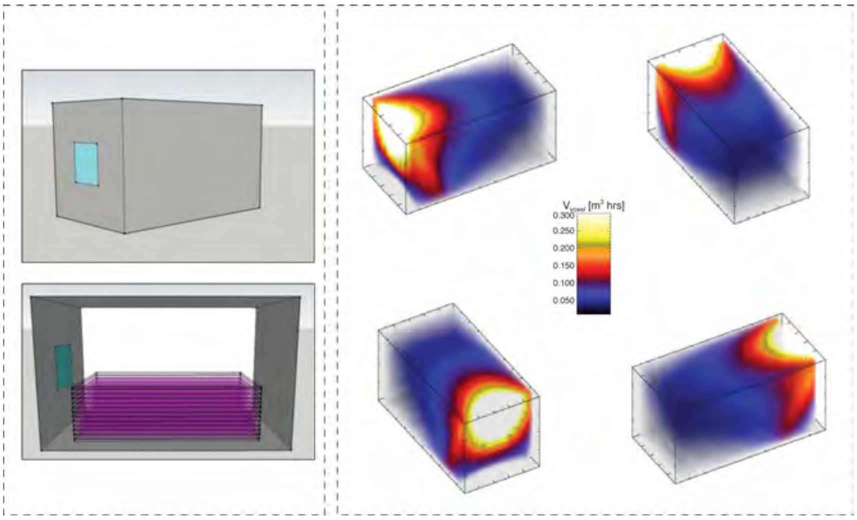


Figure 2.24: Volumetric display of SBI (source: Mardaljevic and Roy 2016).

Reinhart et al. (2006) were the first to call these metrics: Dynamic Daylight Performance Metrics (DDPMs), different DDPMs have been used in previous research. In order to justify selecting the appropriate metric in this research, properties of most used metrics were reviewed as follows:

Daylight Autonomy (DA)

Daylight Autonomy (DA) calculation is proposed to quantify annual daylight saturation (Rogers and Goldman 2006). The first definition of DA appeared in a Swiss standard published by Association Suisse des Electriciens (1989), it was defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone. Then Reinhart and Walkenhorst (2001) redefined DA as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone. DA uses work plane illuminance as an indicator of sufficient daylight in a space (Reinhart 2002; Reinhart et al. 2006). Accordingly, the space is then categorised into either 'Daylit area' or 'Partlylit area'. Daylit area is the area achieving the required threshold for at least half of the occupied time, whereas, areas that fail to achieve the required threshold are considered Partly lit area (Reinhart and Walkenhorst 2001). The problem with the DA is that it does not account for the area with oversupply of daylight in the results, which is usually accompanied with visual and thermal discomfort especially in hot climates. This metric was used before in research to investigate daylighting in buildings (Brembilla et al. 2015a; Erlendsson 2014; Hegazy and Attia 2014; Hegazy et al. 2013; Reinhart et al. 2006; Sabry et al. 2014; Versage et al. 2010). An example of using DA can be seen in Figure 2.25.

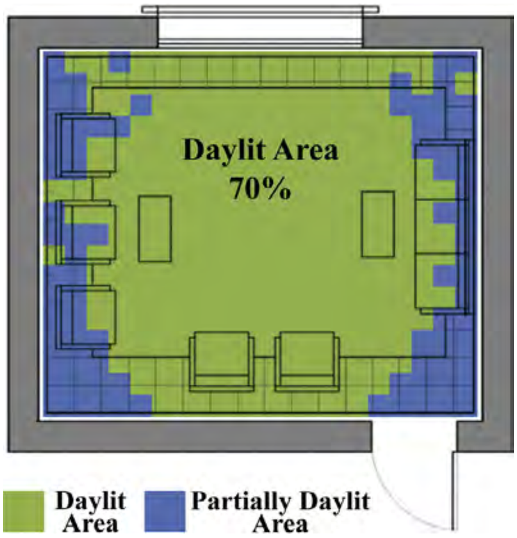


Figure 2.25: DA metric used to analyse daylight in space (source: Sabry et al. 2014).

Continuous Daylight Autonomy (DA$_{con}$)

Another problem with DA is that it only consider a sensor point as 'Daylit' if the illuminance exceeded the target illuminance. For example, if the set target illuminance was $200lx$ and a sensor point received $180lx$, DA would not consider this point as a part of Daylit area. Continuous Daylight Autonomy (DA$_{con}$) however, is a new method introduced by Rogers and Goldman (2006), allowing for fractional levels of daylight illuminance to be counted. Whereby, part credit is given to spaces that receives less than the target illuminance. Hence, the sensor point receiving $180lx$ in the previous example would be credited $180lx/200lx = 0.9 = 90\%$ of the occupied time instead of having 0% when using ordinary DA, it was explained also by Reinhart et al. (2006). This metric was used in previous research in daylight simulation (Chi et al. 2017a). An example of using continuous DA can be seen in Figure 2.25 when Chi et al. (2017a) used the levels of illuminance: 300lx, 500lx and 750 lx to analyse the daylight in a space.

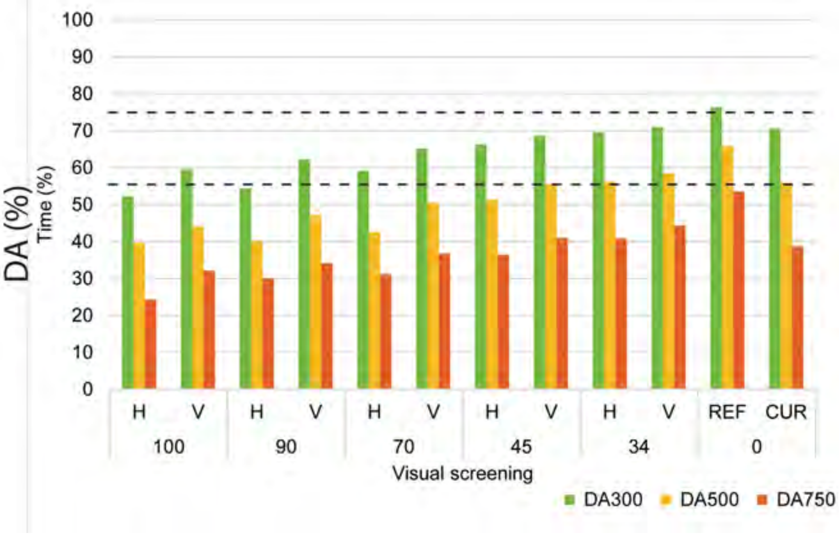


Figure 2.26: Continuous DA metric used to analyse daylight in space (source: Chi et al. 2017).

Maximum Daylight Autonomy (DA$_{max}$)

Maximum Daylight Autonomy (DA$_{max}$) is also introduced by Rogers and Goldman (2006) to consider the occurrence of extreme high illuminances in indoor spaces (usually caused by direct sunlight) which is likely to cause glare. It is reported simultaneously with the DA$_{con}$ and it is defined as the daylight autonomy for illuminance threshold equals to 10 times the initial target illuminance. This metric can give an indication where the high illuminance contrast emerge in a space causing glare problem (Reinhart et al. 2006). However, it is not enough to use this metric alone, it needs to be accompanied with DA and/or DA_{con} to understand the daylight distribution clearly in the studied space.

Spatial Daylight Autonomy (sDA)

Introduced by the Illuminating Engineering Society (IES) in their report "*Approved Methods: IES Spatial Daylight Autonomy sDA and Annual Sunlight Exposure ASE*" (Heschong et al. 2012b) Spatial Daylight Autonomy (sDA) was developed to test the sufficiency of daylight illuminance, using a percentage of floor area that meets certain illuminance level for a certain amount of hours. For example, $\mathrm{sDA}_{(400,60\%)}$ expresses the percentage of space achieving illuminance level more than $400lx$ for 60% of the occupied hours. This metric was used before in evaluating daylight performance (Mohsenin and Hu 2015). Some researchers claim that this metric is called sDA when a dynamic shading is also being simulated, and when simulated without dynamic shading it is called Daylit area (Brembilla et al. 2017; Reinhart et al. 2014), whereas others just call it sDA whether dynamic shading was simulated or not (Batool and Elzeyadi 2014; Chi et al. 2017a; Elghazi et al. 2014; Wagdy and Fathy 2015, 2016) (Figure 2.27). Reinhart et al. (2014) used half of the target illuminance to categorise the studied space into three categories, Daylit, Partlylit and Nonlit areas. For instance, if the target illuminance was $300lx$ the categories would be: "Daylit area" that achieved more than $\mathrm{sDA}_{(300,50\%)}$; "Partlylit area" that achieved between $\mathrm{sDA}_{(300,50\%)}$ and $\mathrm{sDA}_{(150,50\%)}$; and "Nonlit area" that failed to achieve at least $\mathrm{sDA}_{(150,50\%)}$.

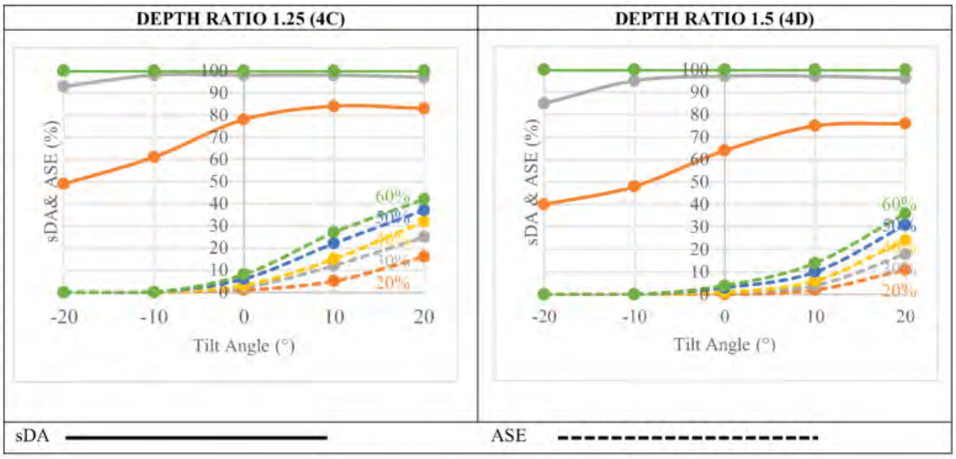


Figure 2.27: Using sDA and ASE metrics to analyse daylight in space (source: Wagdy and Fathy 2016).

Daylit Area

Introduced by Reinhart et al. (2014). The concept is similar to that of sDA, but without considering any model for the operation of dynamic shadings, used in previous research (Brembilla et al. 2017) (Figure 2.28).

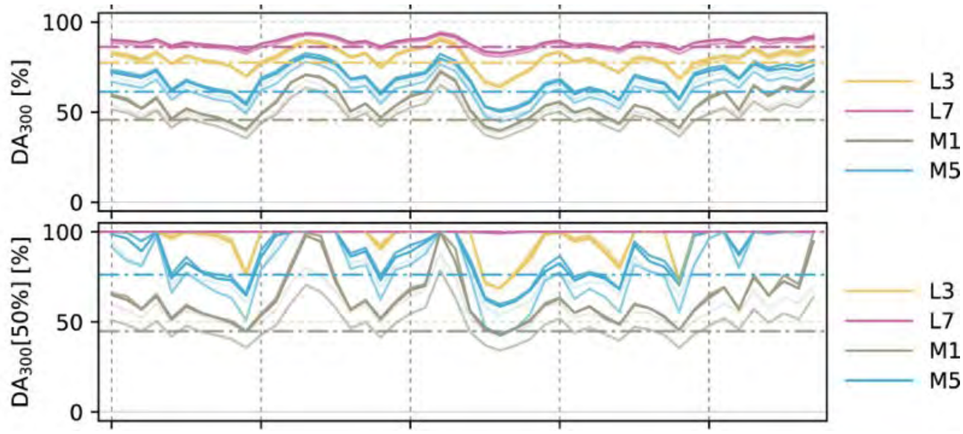


Figure 2.28: Daylit area metric used to compare different cases of daylight in space (source: Brembilla et al. 2017).

Annual Sunlight Exposure (ASE)

Introduced also by IES in their report (Heschong et al. 2012b). Annual Sunlight Exposure (ASE) describes the potential for excessive sunlight exposure by calculating the percentage of the space that exceeds a specified illuminance level more than a certain number of hours. For example, $\text{ASE}_{(1200,200h)}$ expresses the percentage of space achieving an illuminance level exceeding 1200lx for 200 occupied hours. This metric was used before in evaluating indoor daylight performance in many previous research (Batool and Elzeyadi 2014; Brembilla et al. 2015a,b; Elghazi et al. 2014; Mohsenin and Hu 2015; Wagdy and Fathy 2015, 2016). An example of using ASE to analyse light in space is presented in Figure 2.27.

Useful Daylight Illuminance (UDI)

Introduced by Nabil and Mardaljevic (2006), Useful Daylight Illuminance (UDI) is simply the annual occurrence of illuminances across the space that are within a range considered "useful" by occupants (Mardaljevic 2006). The useful range is based on a survey by Nabil and Mardaljevic (2005) with users of non-domestic buildings resulted that a range between 100lx and 2000lx is considered useful. Hence, the UDI uses the lower and upper thresholds of 100lx and 2000lx accordingly to determine illuminance within a useful range, UDI also represents area with oversupply of daylight achieving more than 2000lx, and area fall short of the useful range achieving less than 100lx (Mardaljevic 2006; Nabil and Mardaljevic 2006). To express results of this metric, percentage of occupied hours where the illuminance level falls into each range, the sum of all UDI ranges has to sum into 100% for the studied space. These ranges initially were: the useful range (between 100lx – 2000lx); area fell short ($< 100lx$); area exceeded useful range ($> 2000lx$) (Nabil and Mardaljevic 2005, 2006). This basic form of UDI was used before by many researchers to evaluate daylighting in building (Cantin and Dubois 2011; Versage et al. 2010; Wagdy and Fathy 2015).

Some researchers such as Cantin and Dubois (2011) claimed that the 100–2,000lx range was too wide and divided it into two ranges: 100–500lx and 500–2,000lx. Therefore, at least three charts or results are needed to report the analysis of indoor daylight in space using the UDI metric. In recent research (Brembilla et al. 2016; Mardaljevic et al. 2012), these ranges were assigned with new names and new boundaries: (UDI_{-n}) or (UDI_{-f}) for non-sufficient or fell-short areas with less than

$100lx$; (UDI_{-x}) or (UDI_{-e}) for areas exceeded $3,000lx$; (UDI_{-c}) combined areas between $100lx$ and $3000lx$. The area with a combined useful range is sometimes divided into: (UDI_{-s}) for supplementary area between $100lx$ and $300lx$; (UDI_{-a}) for autonomous area between $300lx$ and $3,000lx$ (Figure 2.29). These UDI indicators were used in most recent daylight simulation research (Brembilla et al. 2016, 2017, 2015b; Chi et al. 2017a; González and Fiorito 2015).

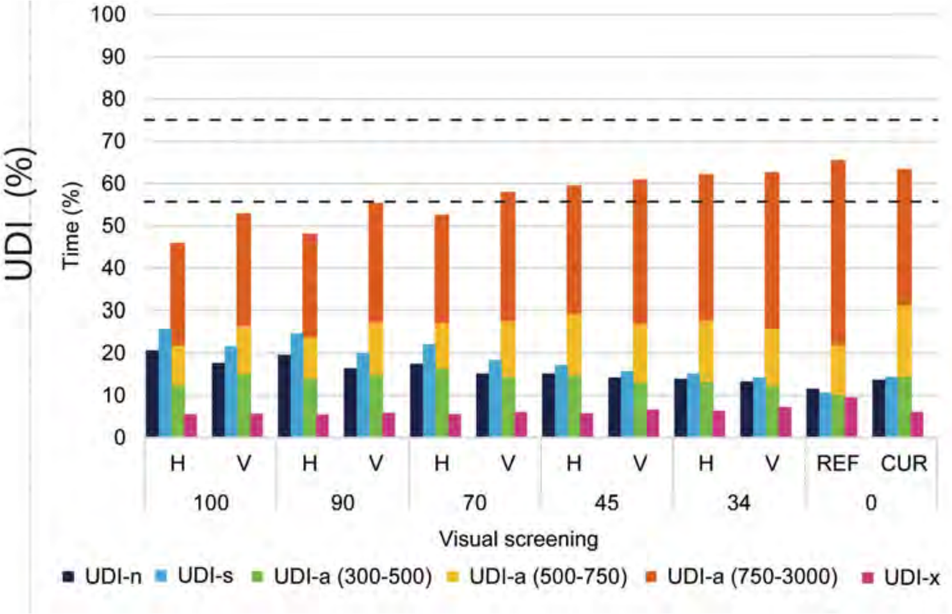


Figure 2.29: Using ranges of UDI to analyse light in space (source: Chi et al. 2017).

Daylight Availability (DAv)

Daylight Availability (DAv) however, was developed lately to combine both DA and UDI, introduced by Reinhart and Wienold (2011). Both DA and sDA take no account of the significance of very high illuminance that is usually associated with thermal and visual discomfort of occupants (Chi et al. 2018). When using the DAv metric, the space is categorised into three classifications according to the percentage of occupied time achieving the set target illuminance threshold: “Daylit”, “Partlylit” and “Overlit area”, where the first two are the same as the ones in DA metric, while Overlit area is the area receiving ten times or more of the target illuminance for at least 5% of the occupancy time (Reinhart and Wienold 2011). This was used in previous similar experiments (Elghazi et al. 2014; Sabry et al. 2012a,b; Sherif et al.

2012a,b). An example of using DAv to compare different cases of shading in a space is presented in Figure 2.30.

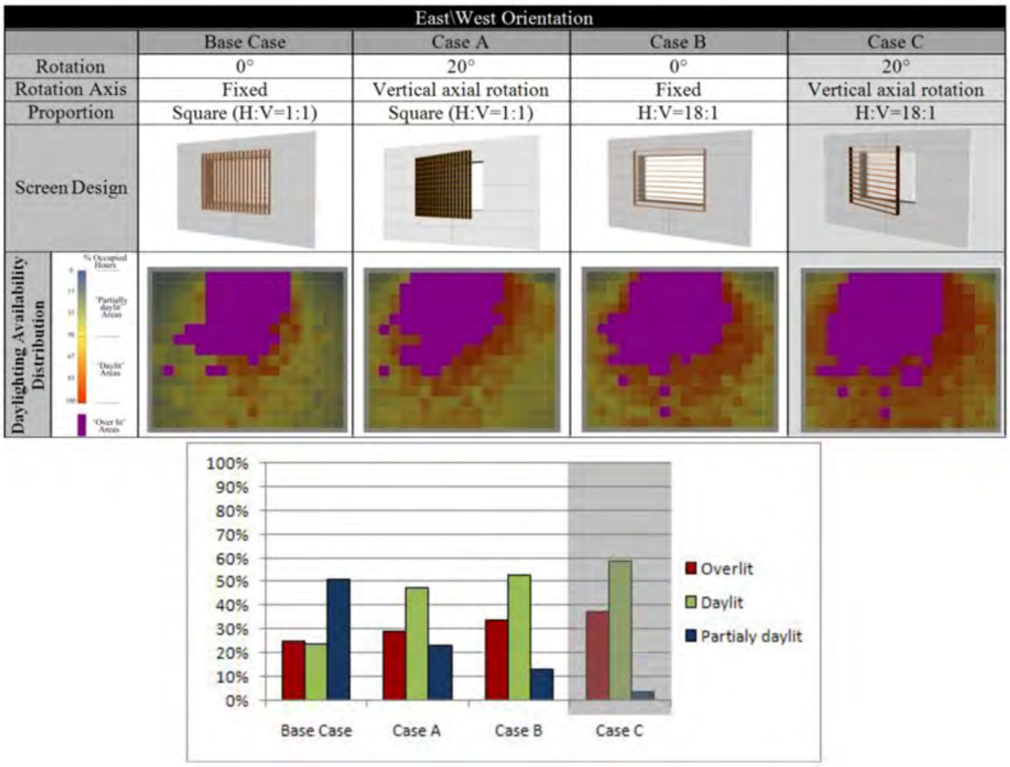


Figure 2.30: Using DAv metric to compare different cases of shading on daylight for the same space (source: Sabry et al. 2012b).

Lately however, Chi et al. (2017b) have modified the DAv metric and called it “modified daylight availability”. In this metric, the Partlylit area includes the area that achieved less than the target illuminance (e.g. $300lx$) and more than half of it (e.g. $150lx$) at least half of the occupancy schedule. They added a new fourth category called ”non-daylit area” which describes the area that failed to achieve at least half of the set target illuminance for 50% or more of the occupancy schedule, an example is presented in Figure 2.31. Chi et al. (2018) have also used this modified version of DAv as well.

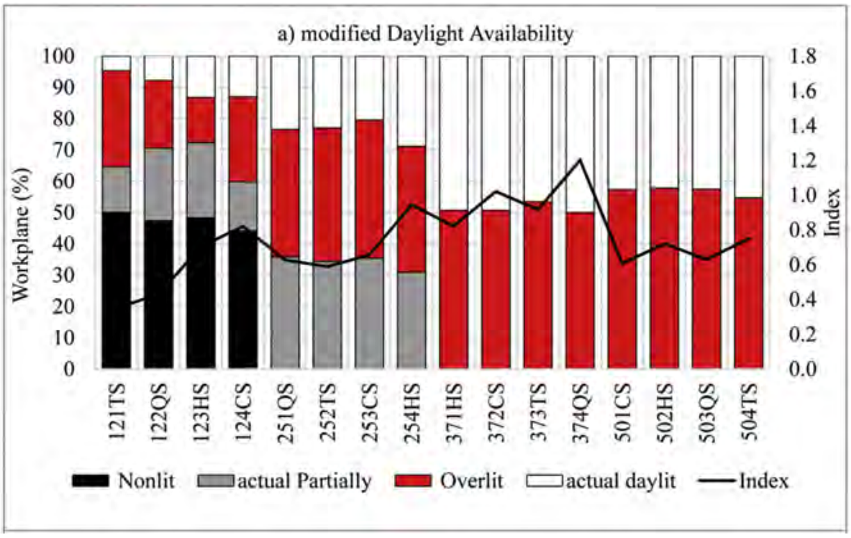


Figure 2.31: Using the new modified DAv metric (source: Chi et al. 2017b).

2.5.4 Advantages of DDPMs

After discussing the static and dynamic daylight metrics, it appears that with the development and availability of computer machines and simulation tools, the advantages of using dynamic metrics have notably overcome the disadvantages. Starting from 2013 (Education Funding Agency 2013), CBDM became a mandatory requirement by the UK Education Funding Agency (EFA) for evaluating the school designs submitted for the Priority Schools Buildings Programme (PSBP) (Mardaljevic 2015). Similarly, in the U.S, from 2012 the Illuminance Engineering Society (IES) added some of the (DDPMs) to the approved calculation methods of Daylighting in buildings in the latest green buildings standard of the Leadership in Energy and Environmental Design (LEED) (Brembilla et al. 2015b; Heschong et al. 2012a). Simulating Dynamic daylight metrics using CBDM are now the most reliable method to evaluate interior daylight metrics in research and design (Mardaljevic et al. 2012). The use of CBDM to simulate light used to be limited because of the need for access to computing with high speed and large memory. These barriers however, began to diminish recently because of these circumstances: Access to enhanced computer power at affordable price for even small architectural firms and students; widespread of computer agility and interest in information technology; and the availability of user friendly interfaces allowing users to generate 3D models, simulate daylight and display results in an easy meaningful way (Reinhart et al. 2006).

2.5.5 Metrics and criteria

After discussing how to use dynamic metrics to evaluate daylight in interior space, it is essential to understand that a metric may not be measurable directly in the field. A metric is some mathematical combination of dimensions and/or measurements and/or conditions displayed on a continuous scale, whereas, a criterion is a demarcation on the metric scale that determines whether a situation achieves the required level. The purpose of a performance metric is in combining various factors that would successfully predict performance outcomes, then performance criteria can be set for different guidelines and recommendations (Mardaljevic et al. 2009). A criterion resolves whether the daylight situation in the studied space is "adequate" or not (Reinhart et al. 2006), for example, 75% of a space achieving at least 2% DF can be set as a criterion to evaluate that space after calculating DF on each sensor points. When using DA_{max} metric, the criterion for a successful space is to not exceed 1% for more than 5% of the work-plane area of that space (Rogers and Goldman 2006).

2.5.6 Simulating daylight metrics

In theory, both static and dynamic daylight metrics can be simulated using either: physical models under real or a sky simulator device (e.g. sky-dome); or three dimension virtual models using computer calculations. However, generally the use of static metrics is associated with physical models especially the DF to utilise the advantage of fast result, whereas, using dynamic metrics is associated with computer calculations.

Physical models Vs. Virtual models

Lighting researchers had used scale models when they first attempted to predict illuminance in real spaces (Hopkinson et al. 1966; Littlefair and Lindsay 1990), using artificial skies with luminance patterns conforms reasonably well to the assumed real life luminance distribution, such as Mirror-box skies (Littlefair and Lindsay 1990). Some researchers insisted on using a physical model and it has been stated that it is a likely method to be used by an architect or consultant (Ubbelohde and Humann 1998) and physical modelling has been validated as an accurate prediction technique within specific limits of scale, detail and metering protocols (Baker et al. 1993; Benton 1990; Hopkinson et al. 1966).

However, Cannon-Brookes (1997) has concerns questioning the accuracy of scale model construction for illumination predictions. He compared scale model measurements with simultaneous measurements of an actual building under real sky conditions (overcast sky conditions and then clear sky). Scale model measurements were found to be $\approx 60\%$ higher than measurements of the actual building under the overcast sky, whereas , under the clear sky the scale model measurements were 100–150% higher. He concluded that this major difference was mostly due to the construction of the scale model and uncertainty in positioning the photocells where there were steep illuminance gradients.

The other method to simulate light performance is calculations. According to (Bryan and Autif 2002), calculations can provide a fast and accurate assessment of illumination levels for typical room and glazing design and present procedures for calculating illumination. They have divided the calculations method into simplified procedures and computer simulation programs. The former is fast, but often make simplifications and assumptions that may reduce flexibility and accuracy. Whereas the latter is more flexible and accurate, but requires preparation of detailed input data.

Although CBDM can be carried out without computer simulation by using scale models, until today CBDM has been carried out using only computer simulation techniques (Mardaljevic et al. 2012) despite the extremely long time needed. There are two reasons for that, the development, availability and ease of simulation tools, and the proven disadvantages of sky simulators. Sky simulators are subject to both fundamental limiting factors, such as parallax error (Mardaljevic 2002), and some operational constraints such as lamp stability, incomplete sky coverage and the demonstrated inaccuracy of the scale model (Cannon-Brookes 1997; Thanachareonkit et al. 2005).

Light simulation engines

Daylighting simulation can be defined as a computerised process that calculate the amount of daylight in a specific zone. Aiming to quantify the illuminance and/or luminance at certain points in that zone. These results are usually presented in numerical values, but scene visualisations or false colour maps can also be used according to the selected analysis metric, either static or dynamic (Versage et al. 2010).

In general, to analyse indoor daylight in buildings all light simulation engines use three different approaches to acquire detailed estimates of the interior illuminance conditions of a building (Bryan and Autif 2002; Ho et al. 2008; Versage et al. 2010). These are:

1. Split-flux
2. Radiosity approach
3. Ray-tracing approach

The split-flux approach uses the lumen method for calculations. It calculates the DF at a point through the sum of the direct and reflected daylighting component (Versage et al. 2010). The most popular engine using this approach is Microlite, which was developed in 1980. It gives simplified results in a form of DF or illuminance values. Although ,it is fast and easy to use, it has not proven accurate enough to be used in research (Bryan and Autif 2002). The split-flux approach require a shorter calculation time, it has however, limitation in dealing with complex geometry (Versage et al. 2010).

The Radiosity approach calculates the radiation transfer off surfaces based on the form factor, and it simulates the light performance in its radiant form (ibid.). The main advantage of the Radiosity technique, is that the calculation depends only on the geometry of the tested space. That means once an initial rendering has been done, rendering of any other view of the model can be done in minutes (Ashmore and Richens 2001). Whereas, the Ray-tracing is a view-dependent process which means every view needs repeating a large part of calculation process (Ho et al. 2008). The most popular daylight simulation engines that are based on the Radiosity approach are:

- SUPERLITE, developed by Lawrence Berkeley National Laboratory and various European centres (Hitchcock and Osterhaus 1994).
- De-Light (Bellia et al. 2000).
- Form-Z RadioZity, which is a version of Form-Z modelling software developed by AutoDesSys, it uses the Radiosity approach even in rendering (Estes et al. 2004).

There are however, some simulation engines that combine both Radiosity approach and Ray-tracing, the most popular amongst them are:

- Lumen micro, developed by Lighting Technologies in Boulder Colorado (*www.lighting-technologies.com* 2017), formerly called Lumen in 70s. It is considered the first lighting simulation engine (Bryan and Autif 2002). It used to be used only by mainframe computers for artificial lighting, the daylighting features however, was added in 1980. Lumen micro is the successor PC version of Lumen II. It is mostly used for artificial lighting design as it has been recognised as the industry standard in Lighting design communities (Bryan and Autif 2002; Ubbelohde and Humann 1998).

- LIGHTSCAPE visualisation System, sometimes referred to as LVS, but usually as LIGHTSCAPE (Khodulev and Kopylov 1996).

LIGHTSCAPE is a software developed by Lightscape Technologies in San Jose California (Ubbelohde and Humann 1998). Initially it was available in Unix operating to system to be used in high end graphics machines such as Silicon Graphics and Sun work stations before it became available in a PC version for architects and designers. It was used in previous research to evaluate the illuminance level by Ho et al. (2008) in a study to compare the performance of four shading devices with different geometries and physical dimensions, in a classroom environment in Taiwan. Wong and Istiadji (2004) have also used LIGHTSCAPE in their experiment to study the effect of shading devices on daylighting penetration. According to them, LIGHTSCAPE integrates the advantages of the Radiosity method and the Ray-tracing method to configure the illuminance, and enables their application to 3D virtual models to predict daylighting performance that are as accurate as possible. In LIGHTSCAPE, the sky is modelled as a dome with infinite radius placed above the investigated space, so that illuminance level on any point is accounted for in all directions in where the sky is visible. The value of the skylight is set automatically and is based on the orientation, according to the geographic location, date and time defined by the user (Ho et al. 2008; Maamari and Fontoynont 2003; Wong and Istiadji 2004).

On the other hand, most light simulation engines use the Ray-tracing technique, whether it is the forward, or the backward Ray-tracing technique or both. It is not easier and faster than the Radiosity technique (Ho et al. 2008), but it offers advantages for simulating the physical performance of light rays and the material spectral properties for any complex building (Versage et al. 2010). To make it faster, it is commonly combined with a statistical method called Monte-Carlo Technique to reduce the processing time to calculate DC developed by Tregenza (1983). The Ray-tracing is more common to be used for research purposes (Brembilla et al. 2017). Most popular light simulation engines that use Ray-tracing technique are:

- Spectere, developed by Integra in Japan (*www.integra.jp/en* 2007). It uses a bi-directional Ray-tracing technique, but not available in a PC version.
- RADIANCE, which is the most widely used lighting simulation engine. Introduced in 1986 by Greg W Larson as a collaboration between Lawrence Berkely National Laboratory, California Institute of Energy Efficiency, and École polytechnique fédérale de Lausanne (EPFL) in Switzerland (Bryan and Autif 2002). It uses backward Ray-tracing technique (Larson and Shakespear 2003).

RADIANCE engine was first introduced to be used on UNIX operation system work stations in the 80s. Then it was further developed and became available to PC in 1998 (Larson and Shakespear 1998). It works with the Ray-trace backward technique for the precise daylight calculations on which most of the daylighting software tools are based (Larson and Shakespeare 1998; Reinhart and Fitz 2006). It has previously been validated by Mardaljevic (1995), and according to Mardaljevic et al. (2012), RADIANCE is the most rigorously validated lighting simulation system available. It has been proven to be capable of high accurate predictions and it has become a *de facto* standard for researchers worldwide. Some reports have claimed that compared with a number of daylighting software packages, RADIANCE simulations can produce more close prediction to real building measurements (Gugliermeti et al. 2001; Laouadi et al. 2008; Ubbelohde and Humann 1998).

Ubbelohde and Humann (1998) evaluated and compared four major daylighting simulation tools at that time, namely, LIGHTSCAPE, Superlite, RADIANCE, and Lumen Micro. There are also other software that are popular in non-English speaking countries, namely, SPECTER developed by Integra in Japan (Khodulev and Kopylov 1996), GENELUX (Baker et al. 1993) and Optis Light in France (IESNA

1997). These software were ignored in the comparison by Ubbelohde and Humann, claiming that they require graphic work stations, or mainframe computers that are not widely available. They have used a 3D model and a physical model scaled 1:24 of an existing building in San-Francisco. Data were collected from actual lighting conditions in the existing building to be used as a reference point to compare the performance of the simulation packages. The physical model was also tested under artificial sky and real sky. The use of the physical model aimed to compare the software with the most widely used method at that time amongst architects and architecture schools, since it was validated in the 90s (Baker et al. 1993; Benton 1990; Love and Navvab 1991). Despite having limitations pointed by other researchers (Cannon-Brookes 1997). In their conclusion, they rated RADIANCE as the highest for comprehensiveness of accuracy, but not the easiest one to use (at that time). Whereas, LIGHTSCAPE was rated the poorest amongst them, representing significant accuracy problems, although it was ranked with the best user interface (Ubbelohde and Humann 1998).

A similar study in Russia, was conducted by Khodulev and Kopylov (1996) to compare three simulation packages, Specter, LIGHTSCAPE and RADIANCE. It has concluded the same result that RADIANCE being the most accurate engine. Another comparison was conducted by Bryan and Autif (2002) included three of the four previously evaluated software in addition to Form-Z RadioZity. They also concluded that RADIANCE was the most accurate simulation software, although they have just provided a ranking without mentioning accuracy levels between each software.

Estes et al. (2004) have compared the results of RADIANCE with actual data measured in an exciting school. Using a grid of 16 sensors, they took illuminance measurements in foto-candelles fc (an American unit instead of Lux) at 13:00 o'clock on a specific day in the year and compare results with simulating a 3D CAD model in RADIANCE and measuring the illuminance at the same time and day of the year. They have used two types of light meters to record measurements, in order to reduce the probability of meter errors. They found a remarkable agreement in results (Figure 2.32), their results have also agreed with the previous findings, and stated that RADIANCE is among (if not) the most accurate and flexible software in daylight simulation.

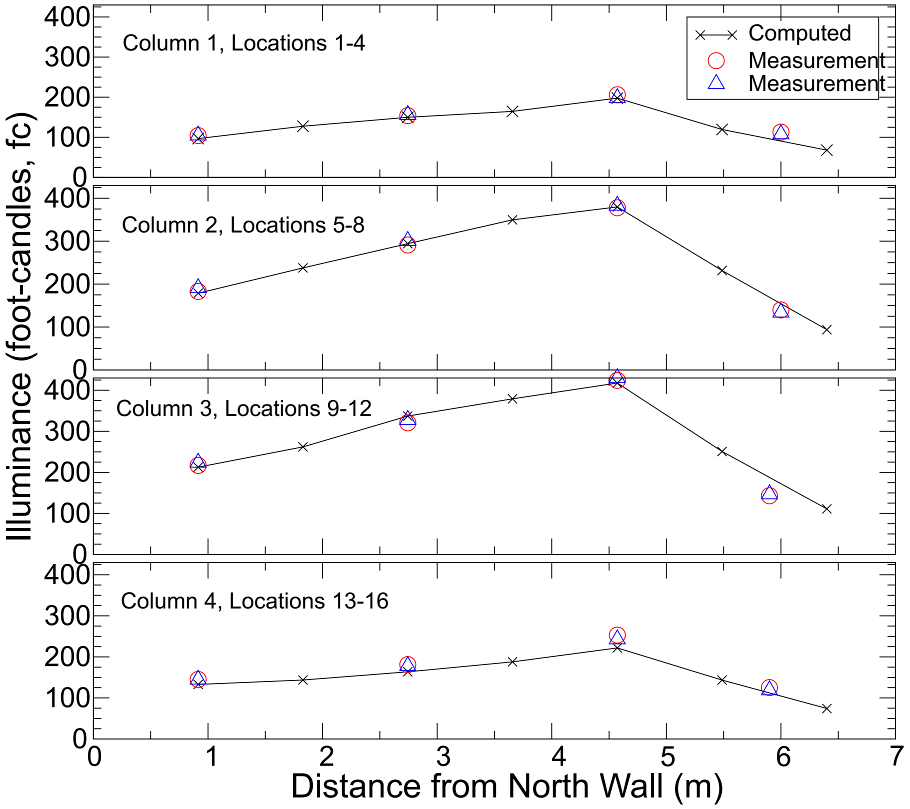


Figure 2.32: Plot of RADIANCE predicted illuminance levels and measured values by Estes et al. (2004) (source: Estes et al. 2004).

Bellia et al. (2000) have compared Lumen micro, Superlite and Di-Light. They found an agreement in results of the three of them. Many other researchers have compared lighting simulation packages (Bryan and Autif 2002; Love 1993; Love and Navvab 1989, 1991; Thanachareonkit et al. 2006). Most of them agreed on the accuracy of RADIANCE amongst all other simulation packages.

Reinhart and Fitz (2006) have conducted a survey on methods of predicting daylight performance in buildings. The survey covered 185 practitioners (Architects and Engineers) from 27 countries. It reveals that 134 participants use computer lighting simulation tool, and 42 simulation tool were mentioned in the survey, each participant could choose one or more software. They gave a total of 342 selections, 176 of them were software using RADIANCE as the simulation engine, that is more than 50% of selections. This advocates that RADIANCE is the choice for the majority of professional lighting simulation users, despite the complexity of it.

In recent years, according to Estes et al. (2004) LIGHTSCAPE was discontinued and transformed to AUTODESK Vis 4, a plug–in integrated with other Auto-cad products. Claiming that stand alone LIGHTSCAPE has low sale volume. SUPERLITE is also no longer under active development, and Lumen Macro is now called Lumen Designer, a full featured CAD system, still more popular for artificial lighting design as it has a big library of luminaire data contributed by hundreds of manufactures. De-Light is now integrated with EnergyPlus to perform lighting simulation (Versage et al. 2010). RADIANCE continued to update and develop, and more software continue to use RADIANCE as the main light simulation engine.

After reviewing most used light simulation engines, it appears that RADIANCE would be the obvious choice to use as a light simulation engine in this research. Therefore, further investigation was directed towards the use of RADIANCE.

Validating RADIANCE

RADIANCE has been the main subject of a number of validation studies, more than any other lighting simulation systems (Ampatzi 2005; Mardaljevic 2004). Not only for daylighting simulation, also in visualisation and renderings (Grynberg 1989; McNamara et al. 2000; Rushmeier et al. 2000). Most of them acknowledged that RADIANCE is the most accurate among all of the commercially available programs for physically based lighting rendering (Ampatzi 2005; Donn 1999).

The BRE-IDMP validation data set is considered as the definitive validation data for any daylight prediction method. It consists of 754 simultaneous measurements of internal and external daylight parameters taking from random 27 days of monitoring in 1992 (Mardaljevic 2004). It was collected by the Building Research Establishment (BRE) as a part of the International Daylight Measurement Programme IDMP, organised by the Commission Internationale de l'Eclairage (CIE) (Mardaljevic 2001, 2004). The major objective of IDMP program was to collect long–duration time series data for a range of daylight parameters including measurements of the actual sky brightness distribution using 15 stations around the globe. One of these stations was located in the BRE headquarter in Garston UK. Simultaneously, the BRE used five experimental rooms with different glazing systems. The sky monitoring sensors for IDMP program were placed on the roof of the BRE experimental rooms (Mardaljevic 2001). Dataset were recorded within seconds of each other. Measurements from these two programs at the BRE location were matched together to produce a data set considered as a benchmark for the validation of lighting simulation programs usually referred to as the BRE-IDMP validation data set.

Mardaljevic (2004) claimed that this data set made it possible to make a true assessment of the accuracy of RADIANCE predictions for internal illuminance levels under a wide range of sky conditions. According to him, testing daylight predictions using the BRE-IDMP data set (Mardaljevic 2001) is arguably the most rigorous validation study of daylight illuminance to date, and it is highly unlikely that actual building façades could be measured and modelled in a simulation with comparable precision to that attained for the benchmark BRE-IDMP validation. He used BRE-IDMP validation data set to validate RADIANCE, using a 3D model of the same test office used by BRE to collect the BRE-IDMP data with a high degree of precision. His results demonstrated a high accuracy for RADIANCE predictions. 66% of predictions were within ±10% of the measured values, and 95% were within ±25%.

RADIANCE has been also validated many times, by comparing simulated results with physical measurements under real sky conditions for existing building, or scale models, under different sky conditions, and using different settings. With clear glass (Mardaljevic 1995, 2004), light shelves (Jarvis and Donn 1997; Mardaljevic 2000b, 2004), Venetian blinds (Reinhart and Walkenhorst 2001), or a translucent glazing (Reinhart and Andersen 2006).

Mardaljevic (1995) used clear single plane glazing with and without light shelves and compared results with RADIANCE. He approved the capability of RADIANCE in modelling indoor daylight under clear and overcast skies. Mardaljevic (2004) used clear glazing under more than 700 sky conditions. He also found that RADIANCE is capable of predicting indoor daylight to a high degree of accuracy for a wide range of sky conditions. Using the same dataset, (Mardaljevic 2000b) combined RADIANCE with the new DC approach CBDM to simulate indoor daylight more efficiently, when he first introduced CBDM as mentioned previously. Reinhart and Walkenhorst (2001) used a full-scale test office to compare measurements with simulated data under more than 10,000 sky conditions in 30 seconds intervals to validate RADIANCE based DC approach combined with the Perez sky model (Perez et al. 1993).

RADIANCE techniques

Since RADIANCE was invented it has provided the back-bone for CBDM development (Brembilla et al. 2017). Originally however, RADIANCE was designed to model illuminances under a single sky conditions at a time (Reinhart and Walkenhorst 2001), that can be time consuming since each calculation could take several minutes to hours (Reinhart and Breton 2009). Several attempts have been made to predict indoor daylight under multiple sky conditions (Reinhart and Herkel 2000). Since then, several RADIANCE-based methods to perform climate base simulation were introduced. With different techniques to describe the sky vault and the contribution from the Sun. RADIANCE uses one of these techniques to analyse solar radiation values from the climate data file. These techniques are (Brembilla et al. 2017):

- Four-Components method
- Two-phase methods

- Three-phase method
- Five-Phase method

A RADIANCE based advanced daylighting analysis tool called DAYSIM can also be used to describe the sky model. DAYSIM was introduced by the National Research Counsel Canada and the Fraunhofer Institute for Solar Energy Systems in Germany (Cantin and Dubois 2011).

Using the same BRE-IDMP validation data set, Mardaljevic (2000a) proved that the Four-Components method have comparable high accuracy to the standard RADIANCE calculation. Brembilla et al. (2017) used the Four-Components method as a benchmark to compare the five techniques mentioned above using a Sensitivity Analysis test. They ran 48 simulations for the same classroom using the five techniques and different metrics. They reported the Mean Bias Deviation (MBD) and Root Mean Square Deviation (RMSD) for all techniques and compared them against the benchmark. They concluded that DAYSIM shows agreement with the benchmark Four-Components technique with lowest deviation than all other techniques, as low as 4.1% according to the used daylight metric. This agreement is considered remarkable knowing that 15% is the limit of typical uncertainty for daylight simulation according to Reinhart and Andersen (2006).

DAYSIM was developed to calculate illuminance and/or luminance time series under varying sky conditions more efficiently (Reinhart and Breton 2009). To reduce calculation time, DAYSIM uses the concept of the DC approach described by (Tregenza and Waters 1983) combined with the Perez all weather sky model described by Perez et al. (1993) (Reinhart and Walkenhorst 2001; Versage et al. 2010). Figure 2.33 displays a flow diagram to explain how DAYSIM works. Once a complete set of DC is calculated for each sensor point, the DC values can be combined with any sky condition in order to determine the amount of daylight that sensor point receive under that particular sky condition (Reinhart and Breton 2009).

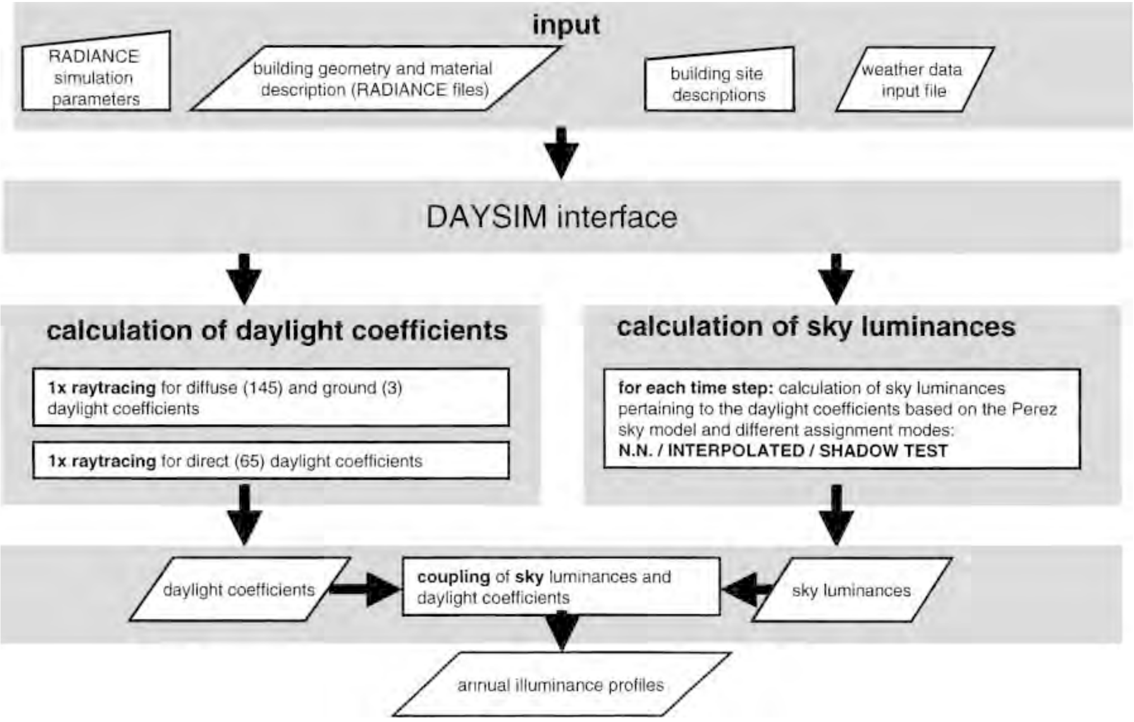


Figure 2.33: Flow diagram of DAYSIM (source: Reinhart and Walkenhorst 2001).

DAYSIM has been validated based on physical measurements (Reinhart and Breton 2009) and also against reality, when Reinhart and Walkenhorst (2001) compared the simulated results with measurements taken in a full-scale test office under more than 10,000 different sky conditions. The DAYSIM predictions showed relative mean bias error ($\text{MBE}_r el$) of <20% and relative root mean square error ($\text{RMSD}_r el$) of <32% (Reinhart and Andersen 2006). Daysim also gave remarkable results when compared with Autodesk 3Ds Max software (Bellia et al. 2015). It also has been shown that DAYSIM outperforms several other dynamic methods in the required simulation time and accuracy (Reinhart and Herkel 2000). It is considered one of the most widespread back-end tools to perform CBDM (Brembilla et al. 2017).

Utilised Radiance simulation parameters

To render using the RADIANCE engine, user should specify the simulation parameters defined by the software engine: ambient bounces, ambient divisions, ambient sampling, ambient resolution and ambient accuracy (Larson and Shakespeare 1998). Different RADIANCE simulation parameters were used in previous research according to the scene size, accuracy required, simulation time. Table 2.3 represents an example of RADIANCE simulation parameters used in a previous study (Reinhart and Breton 2009).

Table 2.3: An example of utilised Radiance parameters used by researchers (source: Reinhart and Breton 2009.

Ambient Bounces	Ambient Division	Ambient Sampling	Ambient Accuracy	Ambient Resolution	Direct Threshold
7	1500	100	0.05	300	0

The selected values of RADIANCE parameters for light simulation in this research are discussed in detail in research methods.

2.5.7 Software tools

Most of light simulation engines discussed above are not used on their own, they usually need a software tool as an interface to the engine. Previous researchers have used different software tools in order to simulate light. However, Most light simulation tools use RADIANCE as the simulation engine. Adeline, which stands for Advanced Day and Electric Lighting New Environment is a product of International Energy Agency IEA. It was developed in the early 90s as an interface that formats data using either RADIANCE or Superlite engines (Erhorne et al. 1995; Ubbelohde and Humann 1998). It was an early attempt to interoperate information from daylight simulation engines directly. It can also provide data for advanced thermal analysis software such as DOE-2, TRSNYS and BLAST (Bryan and Autif 2002). Some software tools are sometimes misrepresented as daylighting programs while they are not, such as DOE-2 and Building Design Advisor. DOE-2 was later inserted into the EnergyPlus program (energy and thermal analysis program) (Versage et al. 2010). The daylight analysis produced by these programs are in support of energy analysis and not adequate to perform daylighting studies (Bryan and Autif 2002).

The most recent software tool for daylight simulation is called DIVA, which stands for Design Iterate Validate Adapt (Jakubiec and Reinhart 2011). It was introduced in 2011 by Jakubiec and Reinhart (ibid.). It is an environmental analysis plug-in for Rhinoceros-3D. Rhinoceros is a 3D Nurbs modelling tool with the capability to create and analyse complex geometry (Mcneel and Associates 2016), often abbreviated as Rhino. DIVA is an environmental analysis plug-in for Rhino that can perform a daylight analysis on architectural models. It is used as an interface for the simulation engines RADIANCE and Daysim (Reinhart and Walkenhorst 2001). Both engines have been previously validated by comparing simulation results with physical measurements (Reinhart and Breton 2009).

Shortly after that, a DIVA component was introduced for a software called Grasshopper (Rutten and McNeel 2012), which is a generic algorithm editor that works as a parametric modelling extension for Rhino. Parametric modelling refers to the automated parameter based generation of 3D elements (Erlendsson 2014). DIVA component for Grasshopper allows the rapid visualisation of daylight from an architectural design model, where users can easily test multiple design variants for daylight performance without manually exporting to multiple software such as MS-office. Both DIVA-for-Rhino and DIVA-for-Grasshopper have been widely used in many recent researches (Hegazy and Attia 2014; Sabry et al. 2014; Wagdy and Fathy 2016).

2.6 Related previous research in similar climates

In this section, previous relative papers that studied or compared shading strategies are analysed and critically discussed. Information from these papers are summarised at the end of this section. These includes: tested parameter(s), used method, location, results and observation.

“The Potentiality of Reflected sunlight through Rawshan screens” by Aljofi (2005)

The earliest paper that investigate properties of Mashrabiya, called Rawshan in the paper. Aljofi (2005) compared the daylight factor distribution of six different shapes of Mashrabiya, using digital light meters placed in a physical model under an artificial sky. He concluded that rounded shapes transmit less light than rectangular shapes and there is no difference between vertical and horizontal screens. He also found that the higher the perforation percentage the more light is transmitted. In the second stage he compared the light oak material with dark oak and found out that the light oak has 17% better performance due to the high reflectivity of the light colour.

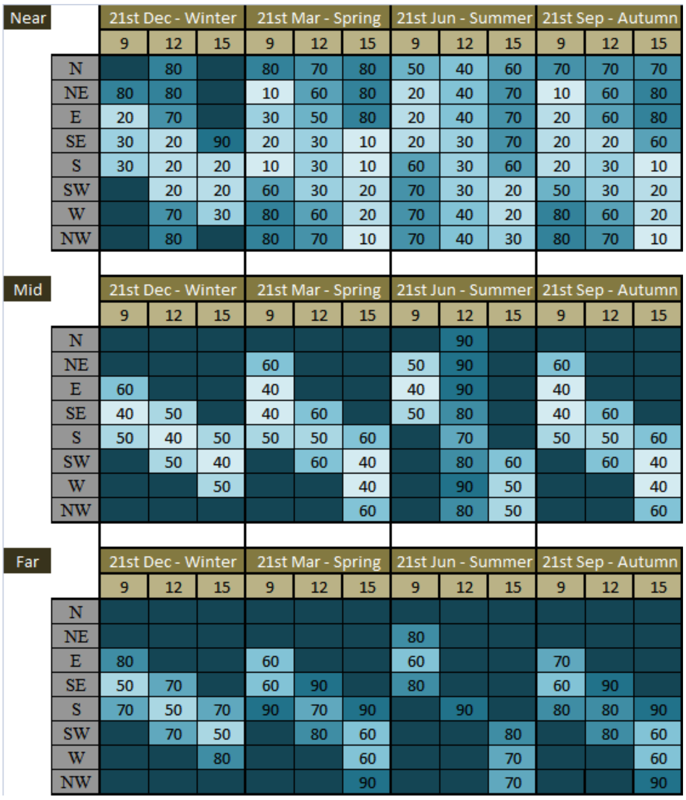
- **Parameters tested:** Geometry shape and colour.
- **Daylight metric:** Daylight factor distribution.
- **Sensor grid:** 7 Sensors spread in the experimental box.
- **Method:** Physical model under natural light, Daylight Factor.
- **Location:** No specific location (overcast-sky).
- **Results and observations:** Rectangular openings provide more daylight that round shapes, Light colour screens provide more daylight than dark colours. Although bigger openings provide more daylight than small openings, all screens have the same thickness so the depth ratio was not considered. This paper showed to the author that light colour screens are preferred to provide higher interior daylight.

“Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions” by Sherif et al. (2010b)

Sherif et al. (2010) tried to find the minimum perforation for achieving a balance between daylight efficiency and visual privacy. They studied a living room in Al-Sadat village in Egypt, the space was simulated by RADIANCE, the space was divided into three zones, near, mid and far zone. Each zone has 84 measuring points. Measurements were recorded for three times a day 09:00, 12:00 and 15:00 for three orientations: north, South and east claiming that the east and west would have the same result since the sun-path is symmetrical. The screen was tested using ten different perforation percentage from 10% to 90% in a 10% intervals.

- **Parameters tested:** Perforation percentage.
- **Studied cases:** 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%.
- **Controlled Parameters:** colour reflectivity 68%, axial rotation 0°, aspect ratio 1:1.
- **Module size:** 5cm.
- **Daylight metric:** Average annual illuminance values.
- **Sensors grid:** 252 points in in a $0.3 \times 0.3m$ grid.
- **Location:** El-Sadat city, Egypt.
- **Space:** Living room.
- **Method:** RADIANCE.
- **Results and observations:** Their experiment resulted of Table 2.4 to indicate a recommended perforation percentage for each case in each zone. This paper showed to the author that zonal division helps analysing average illuminances in a space, and average of each zone can be compared in different cases.

Table 2.4: Recommended perforation percentages according to resulted average illuminance in each zone (source: Sherif et al. 2010b).



Near	21st Dec - Winter			21st Mar - Spring			21st Jun - Summer			21st Sep - Autumn		
	9	12	15	9	12	15	9	12	15	9	12	15
N		80		80	70	80	50	40	60	70	70	70
NE	80	80		10	60	80	20	40	70	10	60	80
E	20	70		30	50	80	20	40	70	20	60	80
SE	30	20	90	20	30	10	20	30	70	20	20	60
S	30	20	20	10	30	10	60	30	60	20	30	10
SW		20	20	60	30	20	70	30	20	50	30	20
W		70	30	80	60	20	70	40	20	80	60	20
NW		80		80	70	10	70	40	30	80	70	10

Mid	21st Dec - Winter			21st Mar - Spring			21st Jun - Summer			21st Sep - Autumn		
	9	12	15	9	12	15	9	12	15	9	12	15
N								90				
NE				60			50	90		60		
E	60			40			40	90		40		
SE	40	50		40	60		50	80		40	60	
S	50	40	50	50	50	60		70		50	50	60
SW		50	40		60	40		80	60		60	40
W			50			40		90	50			40
NW						60		80	50			60

Far	21st Dec - Winter			21st Mar - Spring			21st Jun - Summer			21st Sep - Autumn		
	9	12	15	9	12	15	9	12	15	9	12	15
N												
NE							80					
E	80			60			60			70		
SE	50	70		60	90		80			60	90	
S	70	50	70	90	70	90		90		80	80	90
SW		70	50		80	60			80		80	60
W			80			60			70			60
NW						90			70			90

"Balancing the Energy Savings and Daylighting Performance of External Solar Screens: Evaluation of screen opening proportions" by Sherif et al. (2011)

In this paper Sherif et al. (2011) used depth ratio of 0.75 based on results of a previous study that recommended the best depth ratio to save energy in Kharja city (Sherif et al. 2012c). The perforation percentage of 90% was used based on a previous study in El-Sadat city (Sherif et al. 2010). Then these values were used to test the effect of aspect ratio on the daylighting performance of perforated solar screens in El-Sadat city in Egypt by comparing average illumenance in three zones. Each zone has 84 measuring points.

- **Tested Parameter:** Aspect ratio.
- **Studied cases:** (Horizontal: Vertical) 1:3, 1:6, 1:12, 1:18, 3:1, 6:1, 12:1, 18:1.

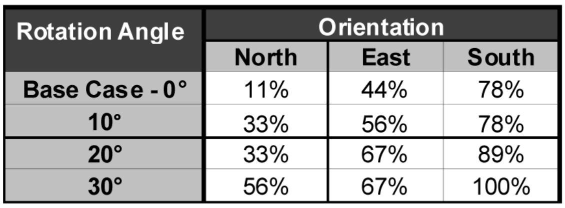
- **Controlled Parameters:** Depth ratio 0.75, Perforation percentage 90%, axial rotation 0°.
- **Daylight metric:** Average illuminance.
- **Sensors grid:** 252 sensors in a $0.3 \times 0.3m$ grid
- **Space:** Living room.
- **Location:** El-Sadat city, Egypt.
- **Method:** RADIANCE.
- **Results and observations:** The daylighting part of this experiment recommends using a horizontal direction openings with aspect ratio of 1:18. However, depth ratio of 0.75 was used to control this experiment based on an experiment that studied the effect of depth ratio on energy consumption (Sherif et al. 2012c) and not related to daylighting. It became apparent through this study that lower depth ratio would improve interior daylight. This paper showed to the author that the option of investigating parameters one at a time and use the result of first study to control the next one in order to reduce cases number and thus simulation time.

"Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies" by Sabry et al. (2011).

Sabry et al. (2011) used RADIANCE to study the impact of the axial rotation of only 10°, 20°, 30°, on the daylight performance in a living room in Kharga city in Egypt. They divided the space to three zones, near, mid and far zone, each zone has 84 measuring points, then the average illuminance in each zone was calculated. Measurements were recorded for three times a day: 09:00; 12:00; and 15:00 for solstices and equinoxes days to cover all seasons: winter; summer; and either autumn or spring, for three orientations: north, south and east, claiming that autumn and spring would give similar results in opposite times due to the symmetry of the sun-path (results of 09:00 and 15:00 on the east = results of 15:00 and 09:00 On the west respectively). Results of each case were compared with a base case where no screen was installed.

- **Tested Parameter:** Axial rotation
- **Studied cases:** 10°, 20°, 30°
- **Controlled parameters:** Perforation 90%, colour reflectivity 68%, depth ratio 0.75, aspect 1:1.
- **Daylight metric:** Average interior illuminance in three zones.
- **Sensors grid:** 252 sensors in a $0.3m \times 0.3m$ grid.
- **Location:** Kharga city, Egypt.
- **Space:** Living room.
- **Method:** RADIANCE.
- **Results and observation:** All studied rotation angles improved average illuminance especially the 30° rotation angle that can be seen in Table 2.5. This paper showed to the author that zonal division helps analysing average illuminances in a space, and average of each zone can be compared in different cases.

Table 2.5: Increase percentage in average illuminances between base case and each rotation angle (source: Sabry et al. 2011).



Rotation Angle	Orientation		
	North	East	South
Base Case - 0°	11%	44%	78%
10°	33%	56%	78%
20°	33%	67%	89%
30°	56%	67%	100%

“The impact of changing solar screen rotation angle and its opening aspect ratios on Daylight Availability in residential desert buildings” by Sherif et al. (2012a)

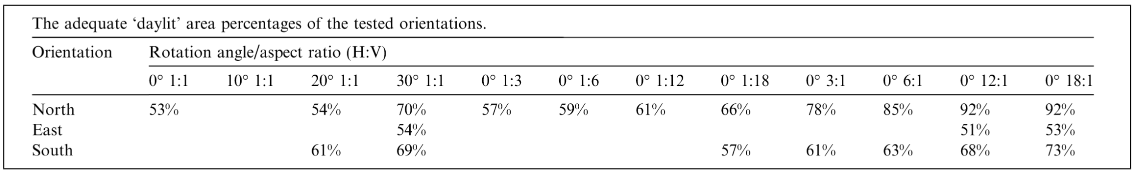
In this paper, Sherif et al. (2012a) studied the effect of screen rotation angle and opening aspect ratio in a window of a living room in Jeddah Saudi Arabia using three stages. In stage-1, they tested three rotation angles 10°, 20°, 30° three times, one for each orientation of north, south and east. Then screens with the best orientation case were studied using eight different aspect ratios were tested for the same three orientations. They then compared the results with a base case with no rotation. Depth ratio was constant on 0.75 based on previous results (Sherif et al. 2012c). Perforation percentage was constant on 90% based on a previous study (Sherif et al. 2010)

For lighting simulation they used DIVA-for-Rhino, the space was divided to three zones each zone has 90 measuring sensors. They used $200lx$ as the minimum illuminance illuminance considered adequate for a living room according to lighting standards. They used DAv metric to analyse the space, and a case achieving 50% or more of total area is considered acceptable.

- **Tested Parameters:** Axial rotation angle and aspect ratio.
- **Studied cases:** Axial rotations 10°, 20° and 30° ; opening aspect ratios: (Horizontal: Vertical) 1:3, 1:6, 1:12, 1:18, 3:1, 6:1, 12:1, 18:1.
- **Controlled Parameters:** Perforation 90%, colour reflectivity 50%, depth ratio 0.75.
- **Module size:** 15cm.
- **Daylight metric:** DAv.
- **Sensors grid:** 270 sensors in a $0.3m \times 0.3m$ grid 1m high.
- **Location:** Jeddah, Saudi Arabia.

- **Space:** Living room.
- **Methods:** Diva for Rhino as an interface of RADIANCE and Daysim.
- **Results and observation:** They presented the final result in Table 2.6, and it shows that 30° and a horizontal direction openings of 18:1 aspect ratio provided the best DAv results. However, there was no combination of different cases, all aspect ratio cases were tested using 0° axial rotation. This paper showed to the author the option of investigating parameters one at a time in order to reduce cases number and thus simulation time.

Table 2.6: Recommended cases of axial rotations and aspect ratios according to resulted DAv (source: Sherif et al. 2012).



The adequate 'daylit' area percentages of the tested orientations.

Orientation	Rotation angle/aspect ratio (H:V)											
	0° 1:1	10° 1:1	20° 1:1	30° 1:1	0° 1:3	0° 1:6	0° 1:12	0° 1:18	0° 3:1	0° 6:1	0° 12:1	0° 18:1
North	53%		54%	70%	57%	59%	61%	66%	78%	85%	92%	92%
East				54%							51%	53%
South			61%	69%				57%	61%	63%	68%	73%

"External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages" by Sherif et al (2012b)

In this study, Sherif et al. (2012b) used the same data from results of their previous paper "Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions" (2010). This time they tested cases of perforation percentages to identify the minimum perforation percentage that provides adequate interior daylight all year round in a living room in Kharga city in Egypt using CBDM modelling and DAv metric.

- **Tested Parameters:** Perforation percentage.
- **Studied cases:** 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%.

- **Controlled Parameters:** Axial rotation angle 0°, colour reflectivity 68%, depth ratio 0.75, aspect ratio 1:1.
- **Module size:** 5cm.
- **Daylight metric:** DAv.
- **Sensors grid:** 252 sensors in a $0.3m \times 0.3m$ grid 1m high.
- **Location:** Kharga, Egypt.
- **Space**: Living room.
- **Method:** CBDM using Diva-for-Rhino as an interface for RADIANCE and Daysim.
- **Results and observation:** Their results showed that 80% and 90% perforation percentages provided acceptable DAv results in the north and south orientations. In the east and west however, using perforated screens have failed to provide acceptable level of DAv, the daylit area covered only up to 24% of total area of the room when 90% perforation percentage is used. It is interesting in this paper that the reason for that might have been using thick screens with depth ratio of 0.75 and less depth ratio would help screens to provide acceptable daylight levels in the studied space for east and west orientations. This paper showed to the author that using DAv metric to evaluate interior daylight is a good option in hot areas where oversupply of daylight can easily occurred.

"External Perforated Solar Screen Parameters and Configurations: Daylighting Performance of Screen Axial Rotation and Opening Proportion in Residential Desert Buildings" by Sabry et al. (2012)

In this paper, Sabry et al. (2012b) tested three cases with different values of aspect ratio and rotation angles based on results of previous results for aspect ratio (Sherif et al. 2011) in El-Sadat, Egypt and rotation angle (Sabry et al. 2011) in Kharga, Egypt. The combined effect of axial rotation and aspect ratio on DAv metric using CBDM modelling in a living room in Jeddah, Saudi Arabia.

- **Tested Parameters:** axial rotation and aspect ratio.
- **Studied cases:** Case A: rotation 30°, aspect ratio 1:1; Case B: rotation 0°, aspect ratio 1:18 ; Case C: rotation 30°, Aspect 1:18
- **Controlled parameters:** Perforation percentage 90%, colour reflectivity 50%, depth ratio 0.75.
- **Module size:** 15cm.
- **Daylight metric:** DAv.
- **Sensors grid:** 270 sensors in a $0.3m \times 0.3m$ grid 1m high.
- **Location:** Jeddah, Saudi Arabia.
- **Space:** Living room.
- **Methods:** Diva for Rhino as an interface of RADIANCE and Daysim.
- **Results and observation:** Results of daylight simulation showed that case B provided the best daylight performance in the north orientation, Case C was recommended for west and east orientations, and both B and C cases were recommended for the south orientation. It is interested in this paper that the final cases number does not reflect the number of variations, more combinations of cases could be studied. This paper showed to the author the option of testing a combination of cases of different parameters instead of testing one at a time.

"Parametric Analysis for Daylight Autonomy and Energy Consumption in Hot Climates" by Hegazy et al. (2013)

Hegazy et al. (2013) used a parametric approach studying 7 different types of shading devices plus a no shading case, and three cases of Window to Wall Ratio WWR and two cases of floor height. the combination of cases resulted in 48 cases. The illuminance threshold was set to $300lx$. The study was done only on a south facing classroom.

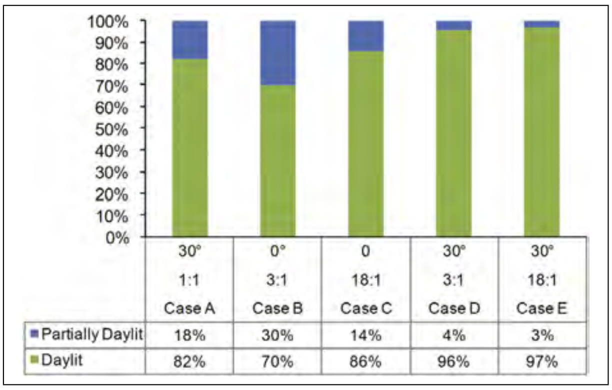
- **Tested Parameter:** WWR (20%, 40% & 60%) Floor height (5m & 12m), comparing 8 cases of different types of windows shading including perforated screens, tinted glaze and a case of no shading .
- **Controlled Parameters:** No information about each shading device.
- **Daylight metric:** Daylight Autonomy DA.
- **Sensors grid:** 120 sensors in a $0.38m \times 0.38m$ grid $0.9m$ high.
- **Space:** Not specified, 5m × 4m box.
- **Location:** Cairo, Egypt.
- **Method:** Diva for Rhino.
- **Results and observation:** What was relative to this research was the cases of perforated screen and tinted glaze. Although using perforated screens or tinted glass with 60% WWR in a high floor provided the best possible DA, all cases of both shading strategies have failed to provide acceptable daylight level of 50% or more of daylit area in the studies space. However, there is no information about the values of perforated screen parameters. This paper showed to the author the option of parametric approach to simulate all combinations of cases and that it takes a long simulation time that it is usually performed for one orientation only.

“Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio” by Sabry et al. (2014)

Sabry et al. (2014) tested combined cases of different aspect ratios and axial rotation angles. Instead of testing the impact of different screen parameters on daylight and thermal performance separately, they decided to test the impact on both performances at the same time using different combined cases. The study aims to find the most effective screen that achieve interior daylight and minimum energy consumption. They used 5 cases for each orientation based on previous results of aspect ratio and axial rotation (Sherif et al. 2012a) in El-Sadat, Egypt. Depth ratio and perforation percentage were constant based on previous results (Sherif et al. 2012c, 2011)

- **Tested Parameter:** Axial rotation and opening aspect ratio.
- **Studied cases:** Case A: 30° & 1:1 aspect, Case B: 0° & 3:1 aspect, Case C: 0° & 18:1 aspect, Case D: 30° & 3:1 aspect, Case E: 30° & 18:1 aspect.
- **Controlled Parameters:** Depth ratio 0.75, perforation 90% and screen reflectance 50%.
- **Module size:** 15cm.
- **Daylight metric:** Daylight Autonomy DA.
- **Sensors grid:** 270 sensors in a $0.3m \times 0.3m$ grid 1m high.
- **Space:** Living room.
- **Location:** Jeddah Saudi Arabia.
- **Method:** RADIANCE + Diva for Rhino.
- **Results and observation:** Their result is displayed in Table 2.34, Case D and E provided highest daylight level in south, east and west orientations, and Case C followed by B provided the highest level of daylight in the northern ori-

entation. It seems like rotated screens increased daylit area in all orientations except in the north orientation. It is interested that the final cases number does not reflect the number of variations, more combinations of cases could be studied. This paper showed to the author the option of testing a combination of cases of different parameters instead of testing one at a time.



	30° 1:1 Case A	0° 3:1 Case B	0 18:1 Case C	30° 3:1 Case D	30° 18:1 Case E
🟦 Partially Daylit	18%	30%	14%	4%	3%
🟩 Daylit	82%	70%	86%	96%	97%

Figure 2.34: Daylit and Partly lit percentages of each case in the south orientation (source: Sabry et al. 2014).

“From romance to performance: assessing the impacts of jali screens on energy saving and daylighting quality of office buildings in Lahore, Pakistan” by Batool and Elzeyadi (2014)

Batool and Elzeyadi (2014) tested the effect of perforation percentage on the performance of perforated screens in an office in Lahore, Pakistan. They conducted the experiment only on west and south orientation. The illuminance threshold was set to 350lx.

- **Tested Parameter:** Perforation percentage.
- **Studied cases:** 30%, 40% and 50% compared with the case with no screen.
- **Controlled Parameters:** Depth ratio 1, other parameters were controled but not specified.
- **Daylight metric:** Spatial Daylight Autonomy sDA and Annual Sunlight Exposure ASE.

- **Sensors grid:** Undefined number in a 3×3 feet grid, 3 feet high.
- **Space:** Office on the second floor.
- **Location:** Lahore, Pakistan.
- **Method:** RADIANCE.
- **Results and observation:** In the south orientation all cases were successful in providing acceptable level of daylight according to the set criteria. Although screens with 30% perforation percentage provided the lowest daylit area, it is still acceptable of more than 50% of the space. In the west orientation the highest studied perforation percentage of 50% was the only case when screens succeeded in providing acceptable daylight. This paper showed to the author an example of testing variations of perforation percentage while controlling other screen's parameters.

"A parametric approach for achieving optimum daylighting performance through solar screens in desert climates" by Wagdy and Fathy (2015)

Wagdy and Fathy (2015) studied the daylight performance of sun louvres in Cairo Egypt. They used a parametric approach to evaluate all possible cases from a combination of five parameters: Screen reflectivity (2 cases 0.35 and 0.8); Louvre counts (8 cases from 3 to 10 louvres); WWR (5 cases from 20% to 60% in 10% intervals); Rotation angle (5 cases from -20% to 20% in a 10% intervals); Depth ratio (4 cases from 0.75 to 1.5 in 0.25 intervals). The total was $2 \times 8 \times 5 \times 5 \times 4 = 1600$ cases. The illuminance threshold was set to $300lx$. The study was done only on south facing classroom.

- **Tested Parameter:** Louvres reflectivity, louvres count, depth ratio, WWR, rotation angle.
- **Studied cases:** Total combination of 1600 cases on south orientation.
- **Controlled Parameters:** Same floor.

- **Daylight metric:** sDA, ASE and DAv.
- **Sensors grid:** 414 sensors in a $0.3 \times 0.3m$ grid $0.9m$ high.
- **Space:** Classroom (5.5m × 7m).
- **Location:** Cairo, Egypt.
- **Method:** Diva component in Grasshopper with a parametric approach.
- **Results and observation:** The optimum configuration out of the studied cases was the case with: reflectivity= 35%, WWR= 60%, Count= 9, Angle= 0° and depth ratio of 1.5. It seems that 80% reflectivity can increase the overlit area in the space. This paper showed to the author the option of parametric approach to simulate all combinations of cases and that it could result in an extremely high number of cases which takes a long simulation time that it is usually performed for one orientation only.

"A parametric approach for achieving optimum daylighting adequacy and energy efficiency by using solar screens" by Wagdy and Fathy (2016)

Similar to their previous study (Wagdy and Fathy 2015), Wagdy and Fathy (2016) studied the daylight performance of sun louvres in Cairo Egypt. In this one however, they used only three parameters for the parametric approach to evaluate all possible cases from a combination of these parameters: WWR (5 cases from 20% to 60% in 10% intervals); Rotation angle (5 cases from -20% to 20% in 10% intervals); Depth ratio (4 cases from 0.75 to 1.5 in 0.25 intervals). The total number of cases was $5 \times 5 \times 4 = 100$ cases. The illuminance threshold was set to $300lx$. The study was done only on a south facing classroom.

- **Tested Parameter:** Depth ratio, WWR, rotation angle.
- **Studied cases:** A total combination of 100 cases.
- **Controlled Parameters:** Louvres reflectivity 80%, Louvres counts 5.

- **Daylight metric:** sDA, ASE and DAv.
- **Sensors grid:** 414 sensors in a $0.3 \times 0.3m$ $0.9m$ high.
- **Space:** Classroom ($7m \times 5.5m$).
- **Location:** Cairo, Egypt.
- **Method:** Diva component in Grasshopper with a parametric approach.
- **Results and observation:** The optimum configuration to provide higher daylit area with lowest overlit area out of the studied cases was the case with: WWR= 40%, Angle= -20° and depth ratio of 1.5. This paper showed to the author the option of a parametric analysis using generic algorithm. Although it has the advantage of providing the best case out of the studied cases, the number of case is reduce to the minimum possible to reduce the extremely long simulation time.

"Multivariable Optimisation for Zero Over-lit Shading Devices in Hot Climate" by Amer and Wagdy (2016)

Amer and Wagdy (2016) used a parametric approach to study the effect of three parameters on the interior daylight in a south facing office in Cairo, Egypt. The parameters were: WWR (18 cases from 5% to 90% in 5% steps); Shading reflectance (3 cases 0.35, 0.5 & 0.8); Shading extrusion (11 cases from 0.0 to $2.5m$ in a $0.25m$ steps). The combination resulted in 585 cases. The illumination target was set to $300lx$. To reduce simulation time, occupied hours cover only working hours of 12 days a year, day 21 of each calendar month in one month steps. The simulation runs continued for 6 consecutive days to be completed.

- **Tested Parameter:** WWR, Shading reflectance ratio and shading excursion.
- **Studied cases:** Total combination of 585 cases on South orientation.
- **Daylight metric:** sDA, ASE and DA.

- **Sensors grid:** 77 sensors in a $0.5\times0.5m$ $0.8m$ high.
- **Space:** Office (6m × 4m).
- **Location:** Cairo, Egypt.
- **Method:** Diva component in Grasshopper.
- **Results and observation:** The optimum case was WWR= 85%, ρ= 80% and shading excursion= $1.7m$. This case occurred in 21 December and displayed in Table 2.35. This paper showed to the author the option of parametric analysis using generic algorithm and how time consuming it is at the moment. It took 6 days to simulate cases in 12 days a year for one orientation.

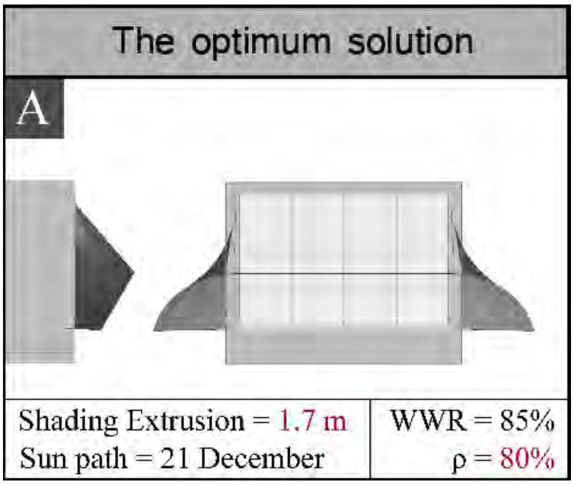


Figure 2.35: Details of the optimum solution of this paper (source: Amer and Wagdy 2016).

2.6.1 Summary of relative daylight simulation research

The review showed that a few past papers have looked into some parameters of Mashrabiya and other shading strategies and their impact on daylight, visual comfort and energy consumption, but mostly for living rooms in residential buildings. The illuminance requirements differ between these two types of spaces, living room to a classroom (Phillips 2000). All studies on living rooms used $200lx$ as the minimum requirement for interior illuminance, whereas in classrooms the minimum requirement is $500lx$ according to light standards. Similarly, the sensor points grid's height for illuminance measurements was 1m as the function in a living-room includes walking, standing and sitting, whereas, in a classroom the measuring sensor points grid should be set slightly above the height of pupils desks as it is the working plane in a classroom. That means an effective value of a parameter of perforated solar screens that achieve successful interior daylight for a living-room might not provide enough daylight levels for a classroom.

Moreover, most classrooms have bigger windows and wider walls than living-rooms, that means a window in a classroom could fenestrate more light even if the WWR was the same as in a living room, The effect of WWR in indoor daylighting have been studied before (Amer and Wagdy 2016; Brotas and Rusovan 2013; Wagdy and Fathy 2015).

Only two papers known to author have studied indoor daylight and evaluate shading strategies in classrooms, they have studied some parameters on the light performance of horizontal louvres in South orientations (Wagdy and Fathy 2015, 2016). They have used a parametric approach by creating a total of 100 and 1600 cases respectively as a combination of all studied variations of the studied parameters, furthermore, all previous studies of the parameters of Mashrabiya were quantitative to investigate the impact of different parameters on daylight, visual comfort and energy performance. No one yet has looked on how parameters of Mashrabiya can affect the privacy function of it using a qualitative study, which is vital to be studied since the main function of Mashrabiya is maintaining privacy through history and in this study.

On the other hand, reviewing these papers have helped the author to understand different methods in daylight simulation to compare the effect of daylight strategies in interior daylight, and different approaches and simulation processes especially to control large number of studied cases.

Table 2.7: Summary of the reviewed relative papers to this study.

Paper	Tested Parapeters	Studied cases	Approach	Controlled Parameters	Daylight Metric	Sensors	Grid	Method	Space	Location
Aljofi 2005	Shape, Colour		One case at a time		DF	7	spread randomly	physical model	Experimental Box	General overcast
Sherif et al. 2010b	Perforation	90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%	One case at a time	Color 68%, aspect 1:1, depth 0.75, perf. 90%	Average illuminance	252	0.3 X 0.3 m	Radiance	Living room	Elsadat city, Egypt
Sherif et al. 2011	Aspect ratio	1:3, 1:6, 1:12, 1:18, 3:1, 6:1, 12:1, 18:1	One case at a time	depth 0.75, perf. 90%	Average illuminance	252	0.3 X 0.3 m	Radiance	Living room	Elsadat city, Egypt
Sabry et al. 2011	Axial rotation	10, 20, 30 degrees	One case at a time	Color 68%, aspect 1:1, depth 0.75, perf. 90%	Average illuminance	252	0.3 X 0.3 m	Radiance	Living room	Kharga city, Egypt
Sherif et al. 2012a	Axial rotation, aspect ratio	10, 20, 30 degrees and 1:3, 1:6, 1:12, 1:18, 3:1, 6:1, 12:1, 18:1	One case at a time, one parameter at a time	Color 50%, depth 0.75, perf. 90%	Dav	270	0.3 X 0.3 m	Radiance and Daysim	Living room	Jeddah, Saudi Arabia
Sherif et al. 2012b	Perforation	90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%	One case at a time	Color 68%, aspect 1:1, depth 0.75, perf. 90%	Dav	252	0.3 X 0.3 m	Diva-for-Rhino	Living room	Kharga city, Egypt
Sabry et al. 2012	Axial rotation, aspect ratio	10, 20, 30 degrees and 1:3, 1:6, 1:12, 1:18, 3:1, 6:1, 12:1, 18:1	random combined cases	Color 50%, depth 0.75, perf. 90%	Dav	270	0.3 X 0.3 m	Diva-for-Rhino	Living room	Jeddah, Saudi Arabia
Hegazy et al. 2013	WWR, floor height	wwr 20%, 40%, 60%; Floor heght 5m, 12m: and 8 shading strategies	all combined cases (84 cases)	NA	DA	120	0.3 X 0.3 m	Diva-for-Rhino	5 X 4m general room	Cairo, Egypt
Sabry et al. 2014	Axial rotation, aspect ratio	Rotation 0, 30 degrees; Aspects 1:1, 3:1, 18:1,	5 Combined cases	Color 50%, depth 0.75, perf. 90%	DA	270	0.3 X 0.3 m	Diva-for-Rhino	Living room	Jeddah, Saudi Arabia
Batool and Elzeyadi 2014	Perforation	30%, 40%, 50%	One case at a time	Depth ratio: 1	sDA, ASE	NA	3 X 3 feet	Radiance	Office on the 2nd floor	Lahore, Pakistan
Wagdy and Fathy 2015	WWR, rotation, reflectance, louver count	Total combination of 1600 cases	Parametric approach	NA	sDA, ASE, Dav	414	0.3 X 0.3 m	Diva-for-Grasshopper	Classroom	Cairo, Egypt
Wagdy and Fathy 2016	WWR, rotation, Depth ratio	Total combination of 100 cases	Parametric approach	Relectance 80%	sDA, ASE, Dav	414	0.3 X 0.3 m	Diva-for-Grasshopper	Classroom	Cairo, Egypt
Amer and Wagdy 2016	WWR, reflectance, depth	Total combination of 585 cases	Parametric approach	NA	sDA, ASE, Dav	77	0.5 X 0.5 m	Diva-for-Grasshopper	Office	Cairo, Egypt

2.7 Summary

The aim of this chapter is to review literature in areas related to this research, it starts by reviewing the aspect of visual privacy in buildings with a discussion on how to evaluate the level of privacy of occupants in buildings by studying factors that affect the view from outside to inside. It also explains the definition of Daylighting and its benefits with a special focus on daylighting in school buildings. It indicates the disadvantages of using daylight in building and how to overcome these disadvantages by using proper shading strategies presenting the Mashrabiya as a possible solution that used to be used traditionally to solve the same problem but without any knowledge of its performance and the effect of its parameters. The Mashrabiya is described in detail in this chapter to get a wide idea about its parameters. The chapter lists the parameters that is selected to be investigated in this research, which can be listed as follows:

- Perforation percentage
- Depth ratio
- Module cell size
- Opening aspect ratio
- axial tilting

The chapter also discusses the methods used before to evaluate and measure daylight in buildings and the types of daylight metrics. The chapter also reviews the difference between digital simulation and physical models and discusses available simulation engines and simulation tools and reviewed most available tools and compared them. Then a special discussion is oriented towards Radiance as it appeared to be the best option to be used as the light simulation engine.

At the end of this chapter, the author reviewed relative previous papers that have evaluated parameters of perforated solar screens and other shading strategies in hot areas. Reviewing these papers have helped to build a better understanding on appropriate methods and techniques to use in this research and to acknowledge what has been done before and what has not.

CHAPTER 3

Methodology

3.1 Introduction

This chapter presents the methods used and the rationale behind the choices made. It discusses the modelling approach for daylight analysis and the visual privacy assessment. A field study was done in summer 2015 to provide background information for the study. Findings of this survey have helped the set up of a base-case of a classroom and its surroundings, that was used both in the daylight analyses and visual privacy assessment.

This chapter also describes the research methods used in this research as well as the work flow of experiments conducted in order to assess the research hypothesis. The daylight measurements methods and metrics are described in detail. The privacy cases and privacy-breaching scenarios are also described, to investigate visual exposure in buildings in an experimental way with human subjects.

3.2 Rationale for methods used

This section lists the outcomes of the literature review, which concluded the nominated methods to be used in this project in evaluating interior daylight levels and in evaluating privacy in buildings through openings. It therefore presents the links to previous work done in the subjects concerned, and the potential for an original contribution to the existing body of knowledge.

3.2.1 Selected shading strategy

The advantages and disadvantages of possible solutions to retrofit existing buildings in order to solve the problem of privacy in existing school buildings were discussed earlier in Chapter 1. Table 1.1 lists these possible solutions and concludes that using perforated solar screens has the potential to satisfy the requirements set for this particularly challenging context. This is in contrast to the other possible solutions identified as it has been successful throughout history in similar contexts, but without knowing the effect of the varieties of each of the screen parameters in maintaining privacy and providing interior daylight. Using Perforated solar screens was also discussed in Chapter 2, Section 2.2, as one of the successful traditional strategies to maintain visual privacy in buildings. Therefore, this research is aimed toward investigating the parameters of perforated solar screens.

3.2.2 Selected parameters to be studied

The parameters of perforated solar screens in relative research were listed, described and reviewed in Chapter 2. Based on that review, the selected parameters to be investigated in this project are:

- Perforation percentage;
- Depth ratio;
- Cell module size;
- Opening aspect ratio, and;
- Axial tilt angle.

To answer the research question of this study, these parameters were tested using daylight simulations, and the configurations that satisfied the criteria set were further tested in relation to providing privacy.

3.2.3 Evaluating indoor daylight

Available methods and options for evaluating interior daylight are discussed and reviewed in Chapter 2, with the conclusions of this discussion presented in Table 3.1. The selected options for each method type are explained in the next subsections.

Table 3.1: Concluded available options to be used in research methods

Method type	**Available options**	
Modelling	Physical models	Virtual models
Daylight metrics	Average illuminances sDA DA$_{Max}$ DAv	DA DA$_{con}$ UDI Daylit area
Criteria for successful cases	+50% of area	+30% of area

Physical models and Virtual models

A comparison between the scaled physical models and virtual models is summarised in Table 3.2. The table lists the advantages and disadvantages of each method and shows that using virtual models have more advantages than using physical models, and the disadvantages of simulating virtual models can now be potentially overcome due to the introduction of high performance computers at low costs and software improvements (simpler and more user-friendly). Therefore, a decision was made for this study to use digital simulation using a virtual model, and the next methodology options are oriented toward a virtual daylight simulation.

Table 3.2: Comparing physical and virtual models.

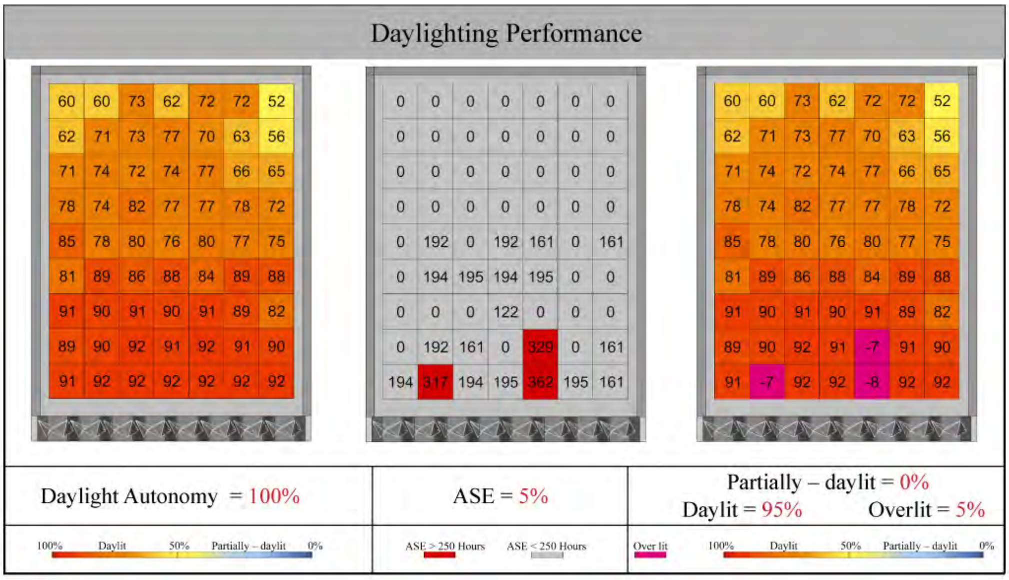
Model type	**Advantages**	**Disadvantages**
Physical Models	Relatively fast Easy for non-experts Needs less preparation Needs less time to extract data	Subject to operational errors Needs special equipment Needs frequent calibration Lamps stability
Virtual models	High accuracy level Flexible Easy to change materials Easy to extract data	Needs more time to extract data Needs powerful computers

Selected daylight metric

After reviewing all available daylight metrics in literature, it appears that DAv represents the results in an easier way to understand when compared with DA and UDI. In order to represent similar information as achieved using DAv, one can represent a result in one chart or figure, while DA_{con} needs to be accompanied with DA_{max}, which means multiple figures to express the same result. This can confuse the non-experts in light simulation. Results of using UDI are also need to be presented in multiple figures, to show at least area within useful range, area less than $100lx$ and area with more than $2000lx$. Therefore, DAv was selected by the author as the best DDPMs option for the context of hot arid climate, since it presents the Overlit areas in the same result. In contrast to DAv, some other metrics do not consider Overlit area (e.g. DA, and Daylit area), can display either useful daylit area or Overlit area (e.g. DA_{con}, ASE), or need to display more graphs to display Overlit area in the result (UDI and sDA) which can be confusing to users that have no previous experience in lighting simulation. In addition, the average illuminance is also used to give a wider idea about daylight in specific times throughout the occupancy time in girls' schools in Saudi Arabia. By using these two metrics, results of daylighting analysis would cover both static and dynamic daylight metrics.

Assessment criteria

The difference between metrics and criteria, and the criteria used in previous relative research, were discussed in Chapter 2. It was indicated that the criteria used for assessing indoor daylight varied according to the activity concerned. In assessing daylight in living rooms, some researchers used daylit area of 30% or more of the total studied space (Sabry et al. 2012b; Sherif et al. 2012a), claiming that not all users in living rooms need the target illuminance to be achieved. Whereas, when daylight was assessed in classrooms, 50% or more daylit area was set as the criteria for successful cases (Wagdy and Fathy 2015, 2016), as well as office spaces (Amer



60	60	73	62	72	72	52
62	71	73	77	70	63	56
71	74	72	74	77	66	65
78	74	82	77	77	78	72
85	78	80	76	80	77	75
81	89	86	88	84	89	88
91	90	91	90	91	89	82
89	90	92	91	92	91	90
91	92	92	92	92	92	92

Daylight Autonomy = 100%

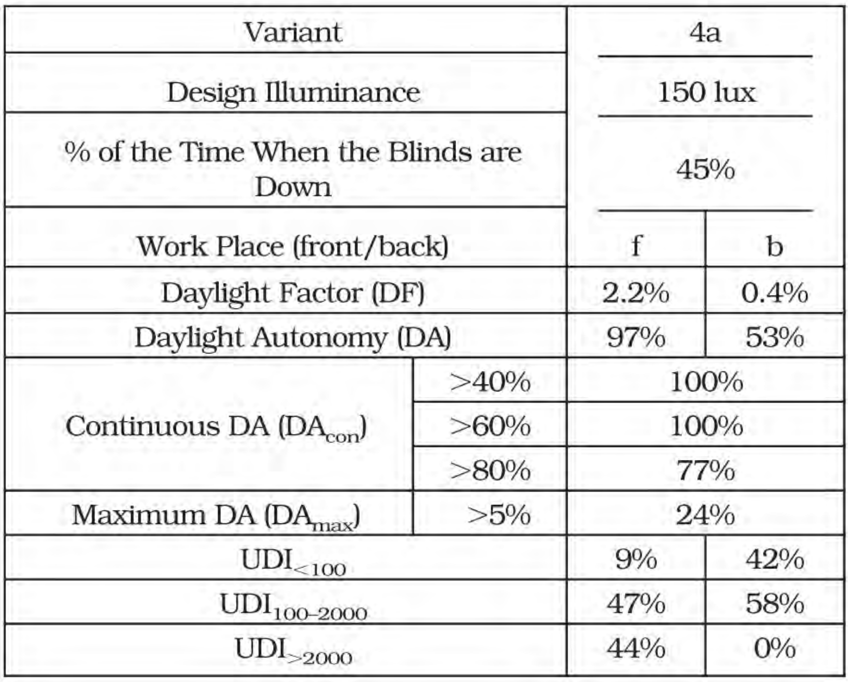
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	192	0	192	161	0	161
0	194	195	194	195	0	0
0	0	0	122	0	0	0
0	192	161	0	329	0	161
194	317	194	195	362	195	161

ASE = 5%

60	60	73	62	72	72	52
62	71	73	77	70	63	56
71	74	72	74	77	66	65
78	74	82	77	77	78	72
85	78	80	76	80	77	75
81	89	86	88	84	89	88
91	90	91	90	91	89	82
89	90	92	91	-7	91	90
91	-7	92	92	-8	92	92

Partially – daylit = 0%
Daylit = 95% Overlit = 5%

Figure 3.1: Comparing DA, ASE and DAv for the same lighting conditions in the same space (source: Elghazi et al. 2014).



Variant		4a	
Design Illuminance		150 lux	
% of the Time When the Blinds are Down		45%	
Work Place (front/back)		f	b
Daylight Factor (DF)		2.2%	0.4%
Daylight Autonomy (DA)		97%	53%
Continuous DA (DA_{con})	>40%	100%	
	>60%	100%	
	>80%	77%	
Maximum DA (DA_{max})	>5%	24%	
$UDI_{<100}$		9%	42%
$UDI_{100–2000}$		47%	58%
$UDI_{>2000}$		44%	0%

Figure 3.2: Reporting results of some daylight metrics for the same situation of the same space (source: Reinhart et al. 2006).

and Wagdy 2016). The same percentage was therefore applied to this study, given the similarities between classrooms and office spaces in lighting provided.

Radiance parameters

The available simulation engines used in light simulation were reviewed in Chapter 2, concluding that Radiance is currently the most reliable engine that has been validated in different situations and compared with actual readings, physical models and other simulation engines. That solidified the decision to use Radiance as the simulation engine in this study. Radiance has several simulation parameters that need tuning from the user. For the purpose of this research, the parameters were set according to common practice in relevant previous studies reviewed in Chapter 2. More detail is provided below along with an explanation of its parameter:

- **Ambient bounces**

  This parameter represents the number of times the light is allowed to hit and bounce from any plane in the simulated scene. The more the light bounces, the more accurate the results are. However, the calculation time is proportionally increased with more bounces especially in complicated scenes and/or complicated geometries. The recommended value according to IES is at least 6, to allow accounting for complicated configuration such as perforated screens (Heschong et al. 2012b) without resulting in a significantly longer simulation time. Moreover, ambient bounces of 6 were also used in previous research (Amer and Wagdy 2016; Sabry et al. 2014). Therefore, ambient bounces are set to 6 in this research.

- **Ambient divisions**

  This parameter determines the number of sample rays sent out from a surface point, and in this research it is set to 1000 as was recommended, to avoid high brightness variation (Reinhart and Wienold 2011). This value was used in previous research when simulating light in similar hot climates (Amer and Wagdy 2016; Hegazy and Attia 2014; Sabry et al. 2014; Sherif et al. 2012a).

- **Ambient sampling**

  This parameter should be greater than zero; it determines the number of extra rays that are sent in sample areas with a high brightness gradient. It is usually set to 20 (Amer and Wagdy 2016; Hegazy and Attia 2014; Sabry et al. 2014; Sherif et al. 2012a), and is therefore set to 20 in this research.

- **Ambient resolution & Ambient accuracy**

  The combination of these two parameters and the maximum scene dimension gives a measure of how fine the luminance distribution is distributed, which can determine the minimum opening in the 3D model according to this formula (Larson and Shakespeare 1998):

  $Min.\ opening = \frac{(Max.\ scene\ dimension \times Ambient\ accuracy)}{Ambient\ resolution}$

  The maximum scene dimension in this research was assumed to be $50m$ since the scene has a ground level $35m$ in length and the classroom is $7m$ wide, Setting the "ambient accuracy" at 0.1 and "ambient resolution" at 300 means that according to the equation, the smallest cell in the simulated perforated screens can be as small as $2cm$ because $\frac{(50m \times 0.1)}{300} = 0.016m$. Therefore, using Ambient accuracy of 0.1 and ambient resolution of 300 would be adequate since the smallest cell size used in the experiments was $2cm$ (which is not less than $0.016m$). Ambient resolution of 300 and ambient accuracy of 0.1 were used in previous research (Amer and Wagdy 2016; Hegazy and Attia 2014; Sabry et al. 2014; Sherif et al. 2012a). These values are selected for the two radiance parameters of this research.

The simulation parameters used for RADIANCE in this research are concluded and presented in Table 3.3.

Table 3.3: Utilised Radiance simulation parameters.

Ambient bounces	Ambient divisions	Ambient smapling	Ambient resolution	Ambient accuracy
6	1000	20	300	0.1

Simulation tool choice for daylighting analysis

The selection criteria for the simulation tool in this study is that it must include using Radiance engine, and the ability to perform parametric analysis in order to reduce the long time needed for light simulation and controlling the exported data. Therefore, the decision was made to use the DIVA-for-Rhino tool as an interface for RADIANCE and DAYSIM that can be controlled to perform parametric analysis using the DIVA-for-Grasshopper plug-in.

Hence, the software tools used for light simulation in this research are as follows:

- "DIVA-for-Rhino" often abbreviated as DIVA. It is an environmental analysis plug-in for Rhino and is used as an interface for the simulation engines Radiance and Daysim (Reinhart and Walkenhorst 2001). It performs daylight analysis on architectural models (Reinhart et al. 2011).
- "Grasshopper" is also used with DIVA in this research to control and increase the work flow of simulation runs and to export results (Lagios et al. 2010). The DIVA component in Grasshopper is used in this study to control DIVA and export results to "Microsoft-EXCEL" in order to generate tables and charts to enable analysis of the results. The DIVA plug-in for Grasshopper is often referred to as DIVA-for-Grasshopper. All of them have been validated based on physical measurements (Reinhart and Breton 2009; Reinhart and Walkenhorst 2001), as discussed in the literature review, Chapter 2.

Selected 3D drawing software

Regarding building the three dimension model, although there are many available 3D modelling software such as 3D studio Max, Maya, Sketchup, Archicad and Revet, Rhinoceros3D is the only 3D modelling software that complies with DIVA and Grasshopper. Therefore, in order to use DIVA and Grasshopper, the author decided to use Rhinoceros3D to build the 3D models. Moreover, all relevant studies discussed in Chapter 2 used Rhinoceros-3D for model drawing when DIVA is used for light simulation.

Selected simulation process

After reviewing previous relevant research that evaluates interior daylight in hot areas in Chapter 2, it appears that the best option to find the optimum configuration of a perforated solar screen is to create a matrix of all possible combinations from the variations of each parameter, and test all options to find an optimum configuration that achieves the best result according to the set criteria. The total number of cases would be the outcome of multiplying the total number of variations for each tested parameter ($9 \times 10 \times 6 \times 10 = 5400$) for each orientation. That would give a large number of simulation runs (more than 20,000 runs), which would require an extremely long time to be simulated. This process referred to as Generic Algorithm or parametric approach. To reduce simulation time, the variation of parameters are kept to minimum to reduce total number of cases and usually when this process is used it is performed for one orientation only such as Hegazy et al. (2013) when they studied a combination of 48 cases on south orientation. Wagdy and Fathy (2015) have also used south orientation for 1,600 cases, and for 100 cases in a different paper (Wagdy and Fathy 2016). Another way to reduce simulation time was to select one day in every month and simulate only 12 days instead of simulating a whole year. This approach was taken by Amer and Wagdy (2016) when they used day 21 of each month to simulate 585 cases on the south orientation. Their total time was still very high, as the simulation runs continued for six consecutive days to completion.

Another option to simulate variations of different cases that appeared in the literature review is to study one parameter at a time. This is done by controlling other parameters by a constant assumed value for each parameter, and then using the the best recommended value of the studied parameter to control that parameter when studying another parameter. For example, Sherif et al. (2010) studied the parameter of perforation percentage and controlled the axial rotation to 0° and aspect ratio of 1:1, resulting in recommending 90% perforation percentage. Then Sabry et al. (2011) studied the parameter of axial rotation and used 90% perforation percentage to control the perforation parameter.

A third option concluded from the literature review was creating a number of selected cases as a combination between two parameters at a time. For example, when Sabry et al. (2012b) investigated axial rotation and opening aspect ratio, they used three cases of a combination between different values of each parameter. They then used other 5 cases for the same parameters in a different study (Sabry et al. 2014). The advantages and disadvantages of these three simulation process are summarised in Table 3.4 as well as previous related research where these options have been used.

Table 3.4: Comparing options for simulation process.

	1. Generic Algorithm (Parametric approach)	**2. Testing random cases from a combination of different parameters**	**3. One parameter at a time**
Advantages:	•Can result in an optimum configuration. •Covers all possible combinations.	•Short simulation time.	•Reasonable simulation time. •Can distinguish successful cases.
Disadvantages:	•Extreme number of cases. •Extremely long simulation time.	•Does not cover all possible combinations. •Limited number of cases.	•Does not result in an optimum configuration.
Previously used in relative research:	Wagdy and Fathy (2015) Amer and Wagdy (2016) Wagdy and Fathy (2016)	Sabry et al. (2012b) Sabry et al. (2014)	Sabry et al. (2010) Sherif et al. (2011) Sabry et al. (2011)

After reviewing the advantages and disadvantages of each simulation process, it appeared that using a generic algorithm in a parametric approach would result in the optimum configuration of all possible combinations of variations of each parameter. The problem in using this approach in this project is that the combination of all cases of different studied parameters would result in a very big number of cases.

For example, using this approach for six cases of each one of 5 parameters would result in $6 \times 6 \times 6 \times 6 \times 6 \times = 7776$ cases for one orientation, and $7776 \times 4 = 31104$. That would give an extremely long simulation time knowing that each run takes about 1–4 hours. However, the hypothesis of this project states that perforated screens are able to solve the problem of maintaining privacy, and at the same time providing acceptable interior daylighting in girls' schools in Saudi Arabia, and one of the objectives of this project is to establish whether using perforated solar screens is able to maintain privacy and simultaneously achieve acceptable interior daylight. That means that it is not necessary to find the optimum configuration of screens. Instead, knowing screen configuration that achieves acceptable interior daylight is enough to fulfil the objective, and achieving acceptable daylight level was explained earlier in this chapter as providing daylit area for 50% or more of the total area of the studied space. Therefore, the author made a decision to use the approach of studying one parameter at a time in steps and to use the result of each parameter in the next step to control the value at the first parameter.

3.2.4 Selected methods to evaluate daylight

All selected methods to be used to simulate and evaluate interior daylight discussed above, are summarised in Table 3.5.

Table 3.5: Selected method for light simulation in this research.

	Selected for light simulation
Daylight metric	DAv and average illuminance
Criteria for DAv	More than 50% is acceptable
Criteria for Illuminance	300lx – 500lx%
Simulation engine	Radiance
Radiance parameters	ab6, ad1000, as20, ar300, aa0.1
Radiance interface	DIVA
Radiance technique	Daysim
3D drawing software	Rhinoceros3D
Simulation process	One parameter at a time

3.2.5 Evaluating visual exposure

In Chapter 2, the author defined not having a visual exposure in buildings through openings as diminishing indoor visibility through openings from outside. Until now there is no software tool that can simulate the ability to view targets because the dynamic range of a human eye cannot be replicated by a simulation tool or a camera. Therefore, testing cases of breaching privacy through window have to be conducted using human subjects. To test these cases, there are different options for methods that can be summarised as follows:

1. Installing the shading strategy in an actual school and testing subjects in real situations.
2. Replicating the cases using a box instead of the window installed under a real sky.
3. Replicating the cases using a box instead of the window installed indoor.
4. Replicating the cases using a box instead of the window installed under an artificial sky.

Each option of these for options has advantages and disadvantages. Installing the tested shading strategy on windows of an existing school in the studied context in Saudi Arabia would give results of a real situation, but it is financially difficult to install shading strategies to all windows in a classroom, and the study might be affected by school times and school days. Since the critical area that needs to be considered the most in maintaining privacy is the area closest to the window, the author believes that a box can replicate this case by placing an object just behind the window, if the shading strategy has successfully maintained privacy for the small area closest to the window, then it is more likely to succeed to maintain privacy for the whole class.

An open box from one side can be used to test different cases of shading strategies by placing screens one by one on the open side to test each case (Figure 3.3).

Thus, using the box to replicate a window in a building with different options to replicate real cases can be tested. One option is to install the box outdoor under real sky; this option has the advantage of high illuminance similar to the real case. However, the unpredictable weather can affect the results and the study might not get approval from ethics committee due to health and safety regulations. The box needs to be easily accessed by the examiner in order to change screens and objects to study different cases; that would be difficult when it is installed in high places to reflect floor height in some cases.

Figure 3.3: A box can resemble a window covered by a solar screen.

Another option is to install the box and the experiment settings in a big studios with mezzanines. Using these settings can replicate the distance and heights but the illuminance would be very low and can not be comparable to daylight. The last option is to install the box and the experimental settings under an artificial sky. Artificial skies have been used as an analogical simulation tool (Dubois et al. 2015). There are two types of artificial skies: hemispherical ones such as sky-domes, and rectangular ones such as mirror boxes (Mangkuto and Siregar 2018). The former type is more reliable but requires a large round space space and high construction cost (Szokolay 2008). The sky-dome has been used in many schools of architecture and laboratories (Bodart et al. 2006; Mardaljevic 2002; Michel et al. 1995). The

Welsh School of Architecture has a sky-dome facility with $8m$ diameter that contains 640 luminaires that can produce up to $8000lx$ on the working plane (*WSA website* 2018) (Figure 3.4).

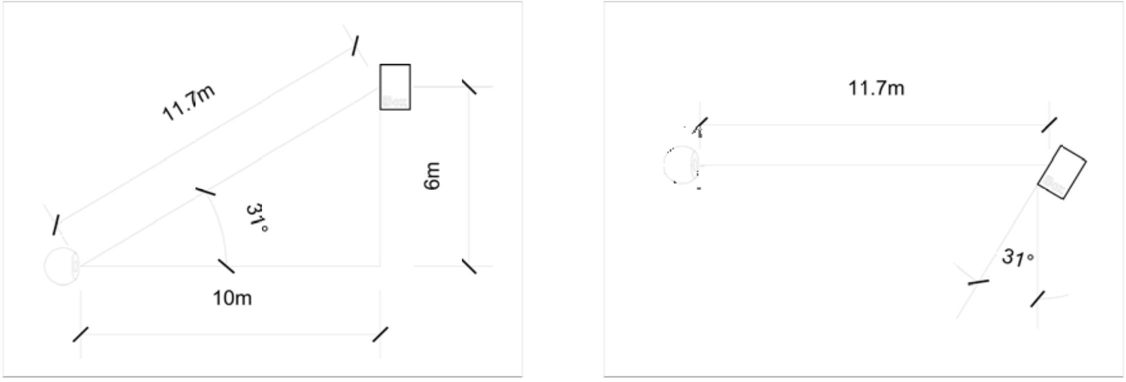
Figure 3.4: The sky-dome facility in the Welsh School of Architecture (source: WSA website 2018).

The option of installing the experiment setting under the sky-dome has advantages of high illuminance and a controlled environment and that it is not affected by weather, however, it does have the problem of limited space. A summary of the advantages and disadvantages of each option are presented in Table 3.6.

Table 3.6: Comparing options to test privacy cases.

Options	**Advantages**	**Disadvantages**
Real situation (In an existing school)	•Tests real cases.	•Needs travelling. •Needs more funds. •Affected by school days.
A box replicating a window under real sky	•Easy to replicate distances. •Real sky gives high illuminance similar to real cases.	•Affected by weather conditions. •Difficult to replicate heights.
A box replicating a window studied indoor	•Heights can be replicated in mezzanines. •Distances can be replicated in big spaces.	•Low illuminance. •Health and safety issues.
A box replicating a window under an artificial sky	•Controlled environment. •High illuminance. •Not affected by weather.	•Limited distance. •Limited heights.

The problem of using the fourth option (installing a box under an artificial sky) can be solved by using the mathematical trigonometric functions. Tilting the box can create the same viewing angle when the box (the window) is on a higher floor after calculating the new distance and the box tilting angle using the mathematical trigonometric functions. For example, if the box in a scenario was 6m high and the observer is 10m away (Figure 3.5), then the viewing angle can be calculated as $Tan\theta = \frac{6}{10} \Rightarrow \theta = Tan^{-1}\frac{6}{10} \Rightarrow \theta \approx 31°$ (Figure 3.5a), and the linear view between the observer's eye and the box can be calculated as the hypotenuse: $\frac{6}{Cos31°} \approx 11.7m$ (Figure 3.5b). This would solve the problem of replicating the height of the window. The other problem is the lack of enough space to replicate the distance, but this can be solved by using mirrors to compensate for distance shortage. Using mirrors in this way is a common practice in optometry testing when a clinic room is not big enough for the recommended distance for the used optometry chart (Jackson and Bailey 2004). Since the disadvantages of the fourth option (using a box under an artificial sky) can be overcome, it appears that it would be the best option to use to evaluate different screens in regard to providing privacy in buildings from outside viewers.



(a) Example of a scenario. (b) A case derived from the scenario.

Figure 3.5: Example of using the mathematical trigonometric functions to derive a case from a scenario by tilting the box and increasing the distance.

To test whether or not a shading strategy has successfully maintained privacy, the author uses testing visibility with human subjects to ask them whether or not the image behind the window could be seen. To do that the author used Kay pictures as explained in Chapter 2. Using the relation between the Kay picture size, visual acuity range and the distance between the picture and the observer, the author is able to calculate the wanted size of picture according to the distance of the observer (keeping the picture at size 4 MAR, which is the size that a low-vision person with visual acuity 6/24 needs to be 6m away to detect a detail that a normal-vision person can detect 24m away). In other words, if a person with normal vision cannot recognise a Kay picture size 4 Mar, then the reason is the solar screen or any tested shading strategy after controlling all other factors. A permission is granted by Kay pictures producers to use them in this study and publish the results; the permission is presented in Appendix F. The exact dimensions of the used pictures can be calculated after knowing the distances of the study cases derived from the collected data of existing schools during the field trip.

In order to accurately test the effect of a shading strategy on the visibility, the author controls the other 10 factors that were concluded from the literature review in Section 2.2. The 11^{th} factor is the shading strategy that will be tested after controlling the other factors. Thus, the main idea of this test is the fact the Kay picture behind the window sized 4 MAR is big enough to be detected and recognised by a person with normal vision , and if an observer was not able to recognise the picture then the reason is the shading strategy applied to the window when controlling all other factors. This test is based on testing the worst case scenarios, if the applied shading strategy was successful in maintaining privacy during the worst case scenarios then it is more likely to succeed in any other case. Therefore, the field work to collect data from schools in Riyadh is vital to conclude these scenarios from the current situation.

3.2.6 Mapping of objectives to methods

In order to meet objective number 1 (to establish whether using perforated solar screens is able to achieve acceptable interior daylight levels), daylight simulation is used to evaluate indoor daylight levels, with different configurations of perforated solar screens. In order to meet objective number 2 (to establish whether using perforated solar screens is able to maintain privacy for occupants), Kay pictures are used to evaluate visibility through perforated screens in a physical experiment by recruited human subjects. In order to meet objective number three (to investigate the parameters of perforated solar screens and evaluate how they affect both the daylight performance and the visual privacy for occupants) a range of parameters are examined to allow comparisons between various configurations of solar screens. In order to meet objective number 4 (to recommend values for each parameter of perforated screens that is able to maintain privacy and achieve an acceptable level of daylight at the same time in classrooms in Saudi Arabia), the research is designed to evaluate indoor daylight and visual privacy of occupants using different values of each parameter of the perforated screens. The recommended values for each parameter are listed at the end of this research in order to achieve this objective.

3.3 Work flow

In order to conduct a daylight simulation and build scenarios of privacy-breaching in girls schools in the studied context, collected data is required to set these methods before starting the experiments. Therefore, a field trip is set as the first step before setting the experiments. The field trip is needed to prepare CBDM variables and to prepare the privacy-breaching scenarios.

To investigate the parameters of perforated solar screens on the aspects of interior daylighting and privacy, a number of experiments are conducted in this research. These experiments are spread in phases and the research is divided into four phases numbered according to the sequence of each phase, details of the phases are explained later in the research methods. Figure 3.6 represents the work flow of the research, starting with the field work to collect data and presenting the sequence of the four phases and their experiments.

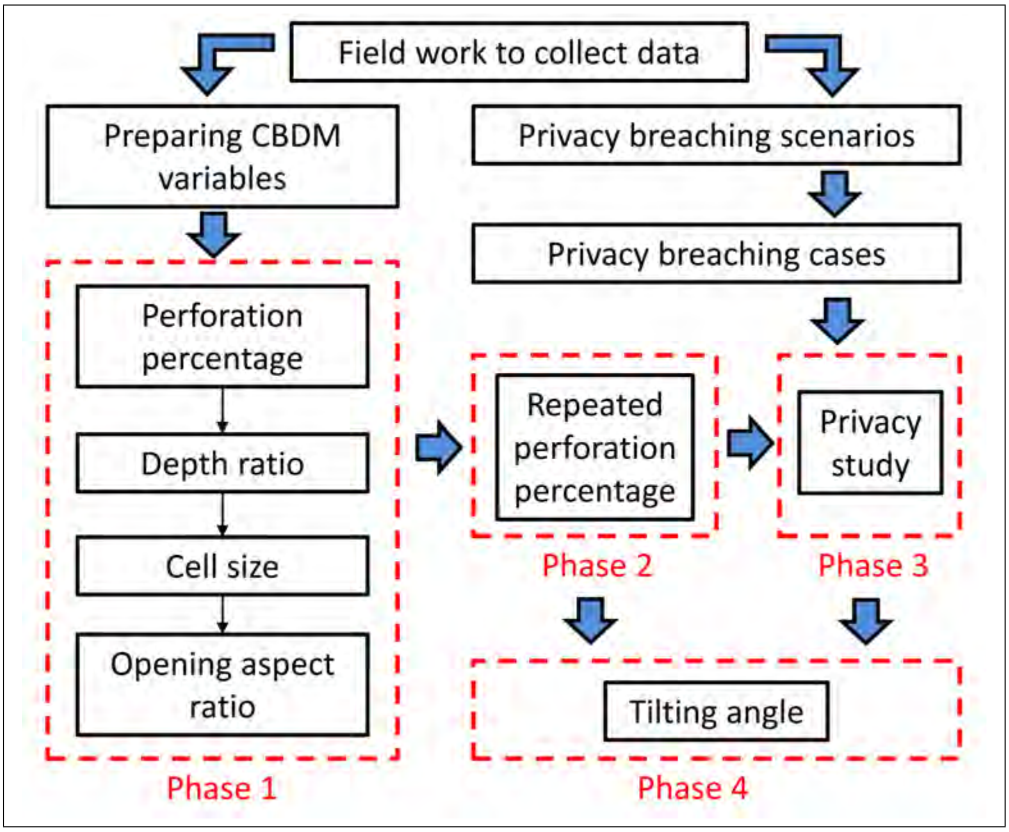


Figure 3.6: Flow chart of research phases and experiments.

3.4 Preparing data to set research methods

It can be seen in Figure 3.6 that the work flow starts with a field trip in order to collect data to build cases of the project.

3.4.1 The field study

The Deputy Minister of Education for buildings was contacted by the author to obtain permissions to access girls' schools during the last two weeks of the summer break in August 2015. Eleven classrooms in four schools were visited to collect data. The four schools were chosen to be spread around Riyadh, Figure 3.7 displays the locations of the schools pinned on Riyadh Map. The number and sizes of windows are measured and dimensions of each class were ascertained. Then 12 measuring points spread in a grid of 3 × 4 in each classroom are used to collect illuminance levels every 15 minutes from 07:30–12:00 noon. A plan presenting the distribution of the

12 measuring points in an average plan is displayed with the measured illuminance levels later in this chapter.

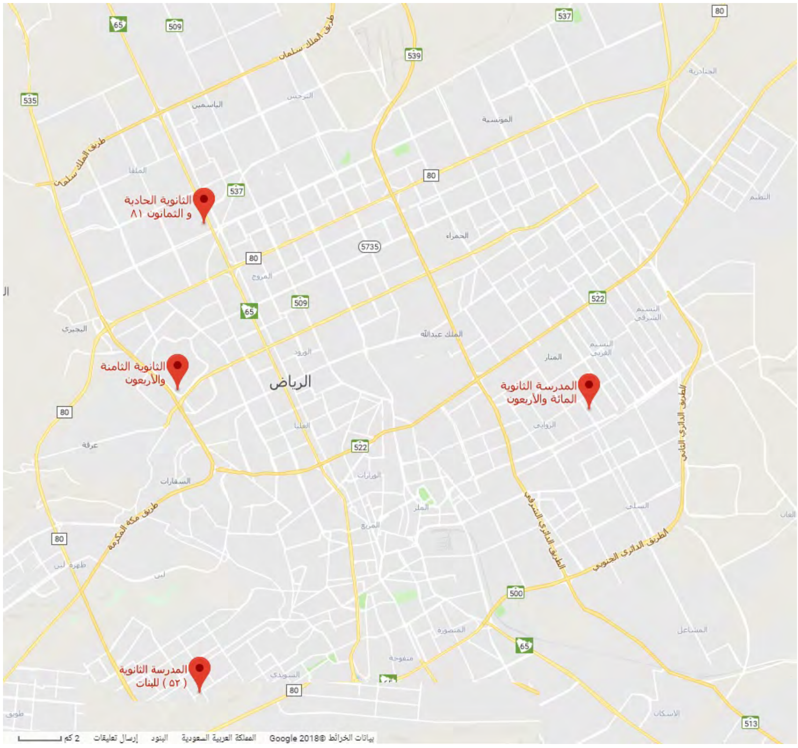


Figure 3.7: Locations of the four schools pinned on Riyadh map (source: Google Maps).

Measuring equipment

To measure illuminance, a Konica-Minolta Chroma Meter CL-200A is used (Figure 3.8a). It has an accuracy of ±2% according to the device manual (CL–200A Catalogue 2018), it can be used to collect data from multi-points, and store data in the device to export them in an MS-excel file. It has been used before in research involving the collection of illuminance in similar experiments (Ho et al. 2008; Sleegers et al. 2013). It is however, acknowledged here that a potential error is present in the results shown , given that the device has not been calibrated since it was bought by the Welsh School of Architecture. This omission was noted in the process of this PhD study but no further action was considered necessary given that it was expected to be negligible, based on the fact that the illuminance levels measured were very low as presented later in Section 3.4.1.

To measure distances and heights, a BOSCH laser meter GLM-50 is used (Figure 3.8b). This device is capable of calculating areas and volumes, and adding/ subtracting distances. It works using a 635-nm semiconductor laser, and it has a measurement range of 0.05–50m with an accuracy of ±1/16 inch, that equals to about ±1.5 millimetre (GLM 50 product Description 2018). It has also been used before in previous research (Ochoa et al. 2014).

(a) Konica-Minolta CL-200A.

(b) BOSCH GLM-50 Laser meter.

Figure 3.8: Measurement equipment used to collect data at the field study.

Collected data

It is observed that most (if not all) windows are covered with black opaque or coloured boards to maintain privacy (Figure 3.9). This confirms the finding in previous research involving schools in Saudi Arabia by Abanomi (2005).

To help in building a base-case model representing the average dimensions and characteristics of classrooms, measurements are taken from the eleven visited classrooms in 4 girls' schools in Riyadh. Classrooms are almost identical inside each school. However, they do vary slightly from one school to another because prototypes were used to build schools in Riyadh as was explained in Chapter 1. Interior dimensions, number of windows, and dimensions are recorded and the average dimensions are calculated and displayed in Table 3.7. The table also shows the final dimensions used to build a base-case which is discussed in the next section.

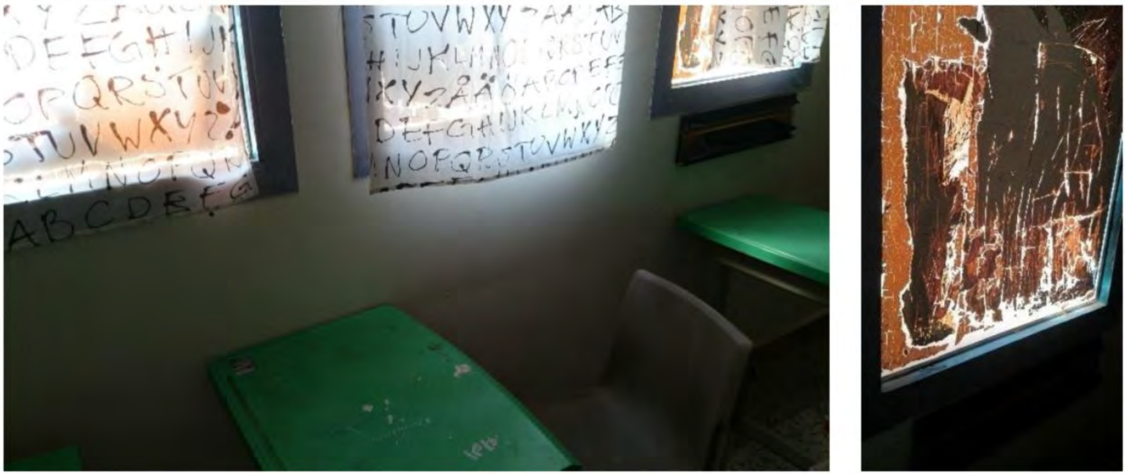
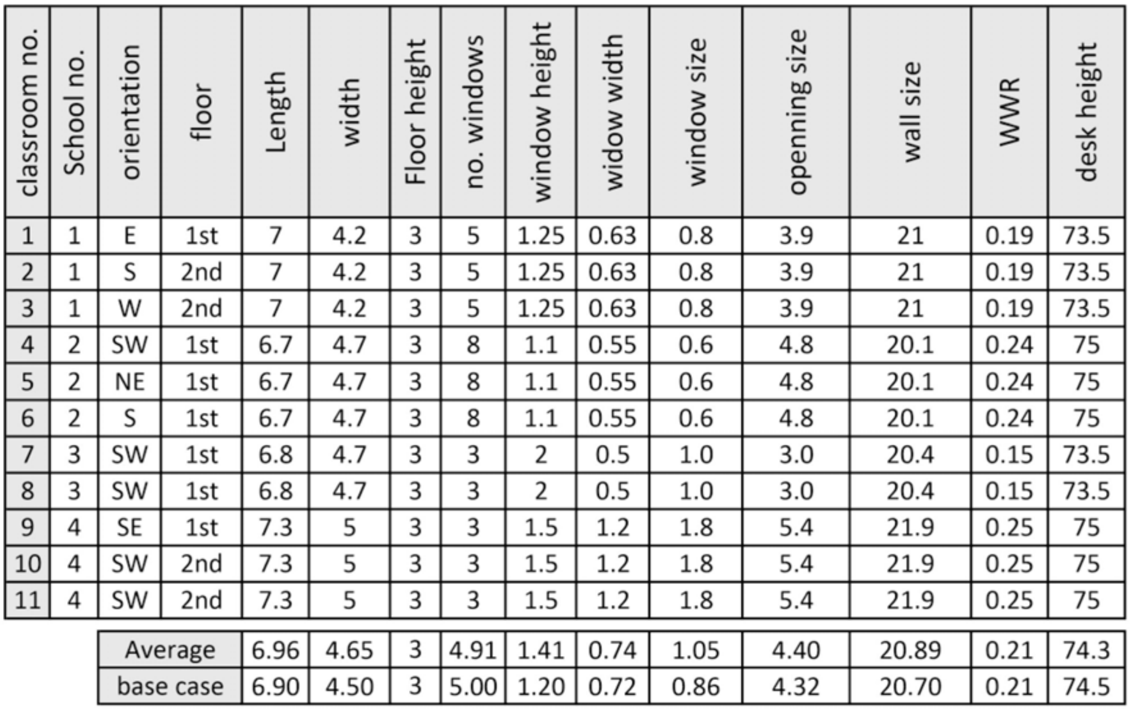


Figure 3.9: Example of using black opaque boards to cover windows to maintain privacy, taken by author during the field visit.

Table 3.7: Average parameters of the surveyed classrooms.



classroom no.	School no.	orientation	floor	Length	width	Floor height	no. windows	window height	widow width	window size	openning size	wall size	WWR	desk height
1	1	E	1st	7	4.2	3	5	1.25	0.63	0.8	3.9	21	0.19	73.5
2	1	S	2nd	7	4.2	3	5	1.25	0.63	0.8	3.9	21	0.19	73.5
3	1	W	2nd	7	4.2	3	5	1.25	0.63	0.8	3.9	21	0.19	73.5
4	2	SW	1st	6.7	4.7	3	8	1.1	0.55	0.6	4.8	20.1	0.24	75
5	2	NE	1st	6.7	4.7	3	8	1.1	0.55	0.6	4.8	20.1	0.24	75
6	2	S	1st	6.7	4.7	3	8	1.1	0.55	0.6	4.8	20.1	0.24	75
7	3	SW	1st	6.8	4.7	3	3	2	0.5	1.0	3.0	20.4	0.15	73.5
8	3	SW	1st	6.8	4.7	3	3	2	0.5	1.0	3.0	20.4	0.15	73.5
9	4	SE	1st	7.3	5	3	3	1.5	1.2	1.8	5.4	21.9	0.25	75
10	4	SW	2nd	7.3	5	3	3	1.5	1.2	1.8	5.4	21.9	0.25	75
11	4	SW	2nd	7.3	5	3	3	1.5	1.2	1.8	5.4	21.9	0.25	75
		Average		6.96	4.65	3	4.91	1.41	0.74	1.05	4.40	20.89	0.21	74.3
		base case		6.90	4.50	3	5.00	1.20	0.72	0.86	4.32	20.70	0.21	74.5

Surfaces reflectance

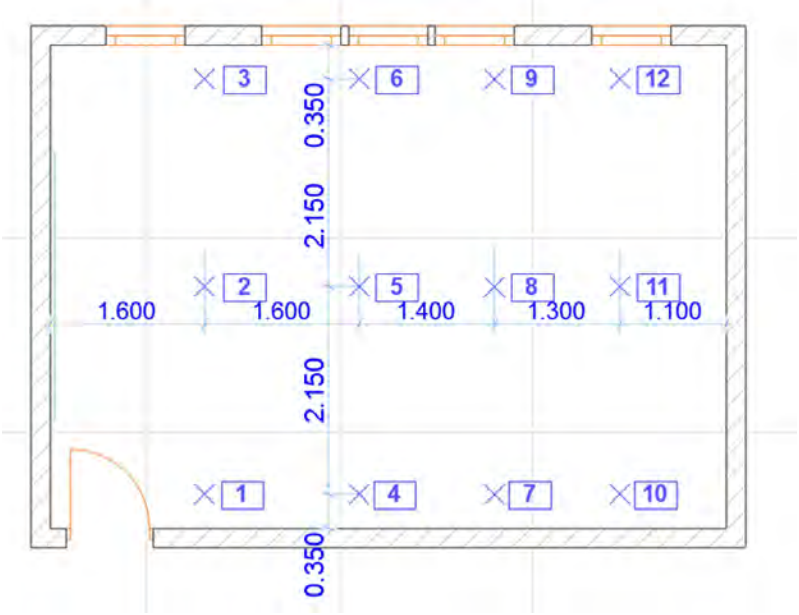
The data collection in this field study has also helped to describe object materials in order to select reflectance ratio for objects in the 3D model to be used in simulation (as this is one of the requirements for conducting a light simulation as discussed in Chapter 2). Object materials are described in Table 3.8. This table is used to assign the appropriate reflectance ratio for each object by comparing these materials with the reflectance ratios in standards and similar related lighting simulation in literature.

Table 3.8: Objects materials description of the field visit.

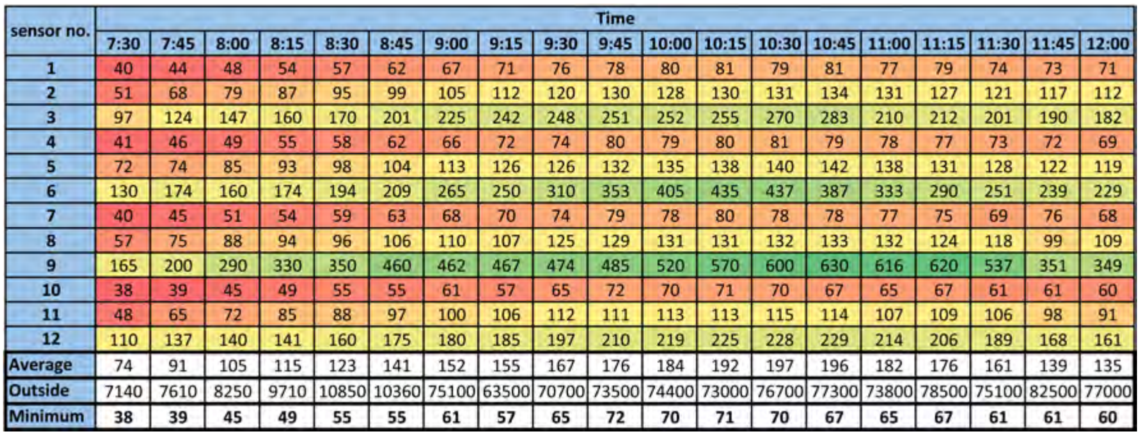
Surface materials description		
Interior walls		Light paint
Ceiling		White paint
Floor		Grey tiles
Furniture		Green desks
White board		High reflective
External Ground		Dark asphalt

Illuminance levels

The collected illuminance data is illustrated in Figure 3.10b. The average interior illuminance was less than $200lx$, which means that electrical lighting is needed to reach the minimum average of $500lx$ in classrooms according to Phillips (2000).Figure 3.10a shows the distribution of the 12 measuring points in an average plan. Only measuring point number nine had more than $500lx$ during less than half of the occupancy time (Figure 3.10b). It appears that the current acts to maintain privacy in girls' schools is affecting the daylight availability very significantly and thus energy consumption in order to provide artificial lighting to meet required lighting levels.



(a) Positions of measuring points



sensor no.	Time																		
	7:30	7:45	8:00	8:15	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00
1	40	44	48	54	57	62	67	71	76	78	80	81	79	81	77	79	74	73	71
2	51	68	79	87	95	99	105	112	120	130	128	130	131	134	131	127	121	117	112
3	97	124	147	160	170	201	225	242	248	251	252	255	270	283	210	212	201	190	182
4	41	46	49	55	58	62	66	72	74	80	79	80	81	79	78	77	73	72	69
5	72	74	85	93	98	104	113	126	126	132	135	138	140	142	138	131	128	122	119
6	130	174	160	174	194	209	265	250	310	353	405	435	437	387	333	290	251	239	229
7	40	45	51	54	59	63	68	70	74	79	78	80	78	78	77	75	69	76	68
8	57	75	88	94	96	106	110	107	125	129	131	131	132	133	132	124	118	99	109
9	165	200	290	330	350	460	462	467	474	485	520	570	600	630	616	620	537	351	349
10	38	39	45	49	55	55	61	57	65	72	70	71	70	67	65	67	61	61	60
11	48	65	72	85	88	97	100	106	112	111	113	113	115	114	107	109	106	98	91
12	110	137	140	141	160	175	180	185	197	210	219	225	228	229	214	206	189	168	161
Average	74	91	105	115	123	141	152	155	167	176	184	192	197	196	182	176	161	139	135
Outside	7140	7610	8250	9710	10850	10360	75100	63500	70700	73500	74400	73000	76700	77300	73800	78500	75100	82500	77000
Minimum	38	39	45	49	55	55	61	57	65	72	70	71	70	67	65	67	61	61	60

(b) Illuminance Levels chart (colour scale: Green= high illuminance, Red= low illuminance)

Figure 3.10: Illuminance levels on 12 measuring points through occupancy hours.

School year

The field study also includes meetings with representatives in the Ministry of Education in order to get information about school-hours, school-days, school-weeks and school-years for public schools. The official week in Saudi Arabia is different than the common week around the world, with the week starting on Sunday and the weekend being Friday and Saturday, and that includes the school week. School year in Saudi Arabia has two terms; it starts on the second week of September until mid-June, and each term has one half term break for a week. There is also a two-week break between terms in mid-January. Saudi Arabia is one of very few countries that do not have a holiday for Christmas and New Year, Instead, there is a public holiday on the last week of Ramadan and Eid Al-Fitr. Eid is an Arabic word meaning Festival, and this Eid is as important for Muslims as Christmas is for Christians (Newall 1989). Usually the Eid holiday occurs within the break between the two terms (*Ministry of Education website* 2015).

School days start at 7:00 and end at 13:30. This school schedule is common in hot arid areas, in an attempt to avoid the high ambient temperatures in the afternoon hours as much as possible. This collected information is used to prepare the time frame which is one of the simulation variables discussed later in this chapter.

School surroundings

Most school buildings in Riyadh are located inside neighbourhoods and surrounded by four streets. The minimum width of streets surrounding school buildings is $15m$ (Figure 3.11). Schools have a boundary wall $3m$ high, with a minimum sit-back of $3m$. The average width of surrounding streets is $10 - -15m$, and there is a $1.1m$ kerb between boundary walls and surrounding streets. The kerb is $20cm$ high. Since Riyadh is in a desert area, usually streets have no tall trees. Hence no trees surrounding schools can obstruct sunlight and view (Figure 3.11), and therefore, external obstructions are ignored when building the 3D model. The exterior of the schools has a sand-beige colour. Figure 3.12 shows an external view of a school building displaying the wall colour and also showing how covering the opening from inside affects the view of the building. The windows on the ground floor are usually uncovered since the surrounding wall is high enough to block the view of them. Collected data regarding school surroundings are important to build the three dimension model of a base-case classroom, which is one of the simulation variables discussed later in this chapter.

Figure 3.11: A satellite image showing streets surrounding a typical girls' high school (source: Google maps 2015).

Figure 3.12: The exterior wall of school buildings showing the effect of blocking windows (taken by author 2015).

3.4.2 Preparing CBDM simulation variables

To conduct daylight simulation using CBDM correctly, there are six variables need to be addressed and prepared as mentioned in Chapter 2. In this section the field work has helped to prepare these variables as follows.

Architectural parameters of the 3D model

Some researchers used Google Sketchup (Brembilla et al. 2016), some have used Rhinoceros (Elghazi et al. 2014; Hegazy and Attia 2014; Sherif et al. 2012a). Any CAD software however, can be used and the file can be exported to the required software for simulation according to the simulation software. The 3D model should include the basic objects in the existing scene (walls, doors and windows) in addition to the daily used furniture (in the case of a classroom: white board, chairs and desks). The model must also have an external ground as reflected and diffused light from the ground could transmit into the building and affect the internal daylighting. Brembilla et al. (2015b) recommends an external ground with linear dimensions at least five times the simulated room main dimension. The 3D model should also consider major external obstructions if they exist in the surrounding e.g. trees and/or other buildings) (Sabry et al. 2010).

For this research, Rhino is selected for its compatibility with DIVA and Grasshopper as explained previously in Section 3.2.3. A three dimensional model of a typical classroom, Figure 3.13 is generated using the average measurements of the visited classrooms in this field study (Table 3.7) and is hereafter called the base-case. One option was to use the maximum possible dimensions to build the model which would provide a worst case scenario that needs more indoor daylight to reach acceptable levels. The author decided however, to use the average dimensions of all measured classrooms instead. The reason for this is that the criterion for accepted interior daylight does not necessary translate to higher daylight levels, as too high daylight levels might cause oversupply of daylight which is associated with glare and excessive heat gain. For example, if the maximum possible dimensions were used in simulation, this might result in screens that provide acceptable daylight for big rooms but too high daylight levels for small rooms. In this, it appears that using average dimensions would be a good approach to find screen configurations that provide acceptable daylight levels for all sizes of classroom. However, as can be seen in Table 3.7, the final base-case dimensions were slightly modified from the average room dimensions to fit in a grid that would provide three equal zones for study. The difference is a maximum of $15cm$ in width, which is less than 4%, and the selected classroom area was $31m^2$, with only $1.3m^2$ difference than the mean classroom size, which is also less than 4%.

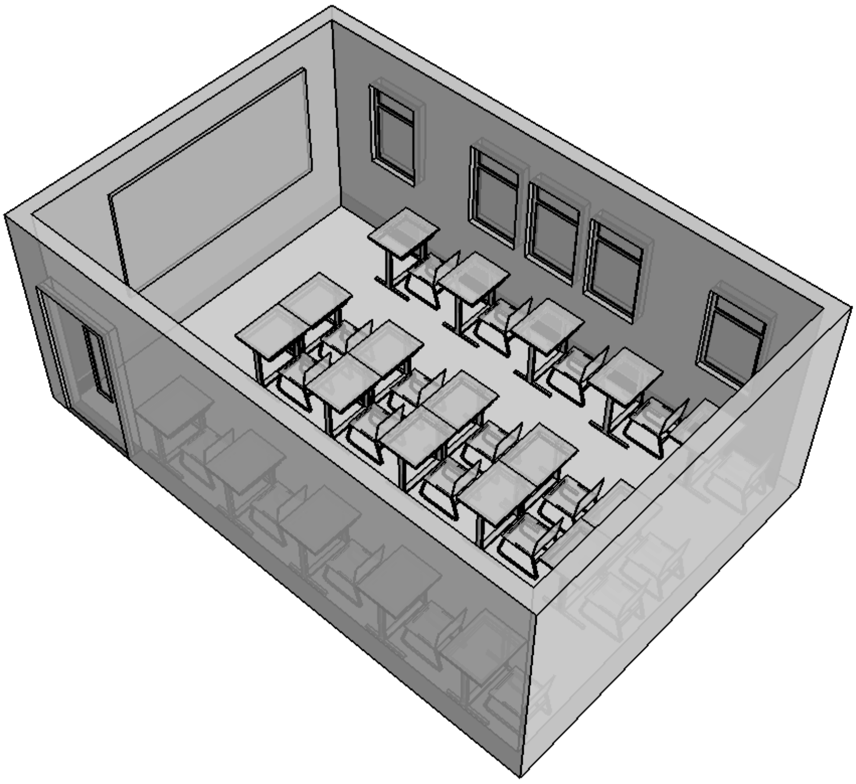
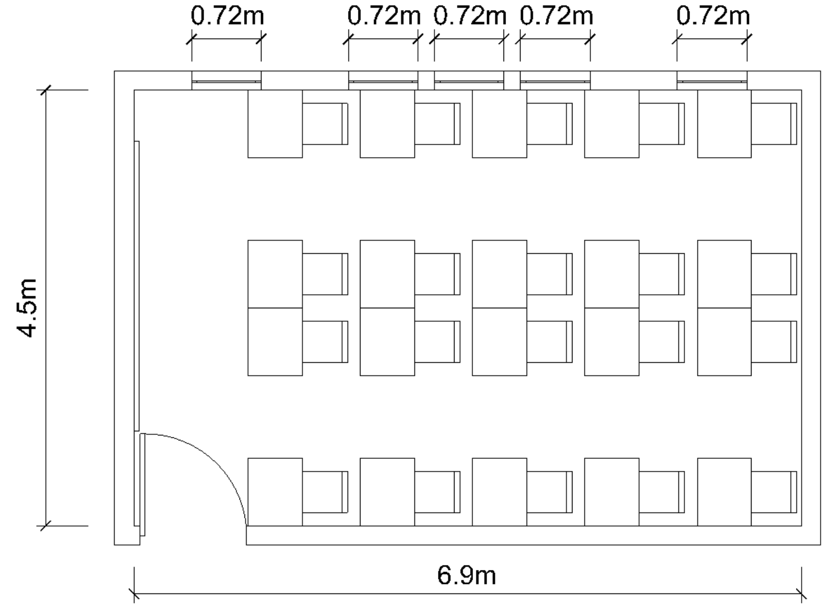


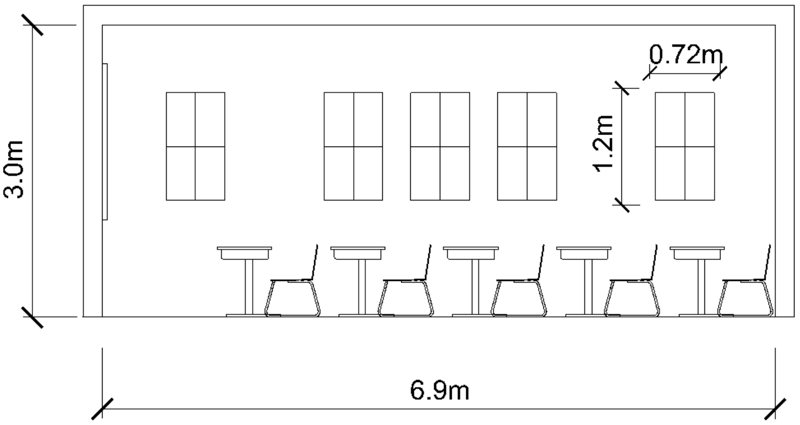
Figure 3.13: Isometric view of the 3D model of the base-case classroom.

Generating a typical classroom is not difficult since most schools were built using prototypes as discussed in Chapter1. The dimension of the classroom is selected to allow dividing the space into three exact size zones. The reason for this zonal division is explained later in this Chapter 2.

The dimension of the generated virtual classroom is $6.90m \times 4.50m$ with a height of $3.0m$ as shown in Figure 3.14a. According to the collected data from the field work, the number of windows vary between classrooms according to the window size (they range between two big windows and eight small windows), but the range of Window to Wall Ratio "WWR" between all visited classrooms is 15%–25% with an average of 21%, the number of windows in the base-case classroom is selected to



(a) Plan view of the base-case classroom showing horizontal dimensions.



(b) Section view of the base-case classroom showing windows and height.

Figure 3.14: 2D drawings of the base-case virtual model of the studied classroom.

be five windows with a 21% WWR. Which is exactly the average WWR with an average number of windows that appeared in three of the visited classrooms. The dimension of each window is chosen to be able to be divided equally by 2, 3, 4, 6, 8 and 10, to explore as many variations as possible of different cell sizes, perforation percentages and different aspect ratios using the same window size for each case. The window dimensions selected for the experimentation is $1,200mm \times 720mm$ in a vertical direction as can be seen in Figure 3.14b and Table 3.7. Although window sizes are slightly different than the average, the window to wall ratio WWR remains the same 21%.

Table 3.9: Architectural parameters of the base-case classroom.

Space Parameters	
Length	$6.9m$
Width	$4.5m$
Height	$3.0m$
Reference plane	$+0.75m$
Windows parameters	
Window to wall ratio WWR	21%
No. of windows	5
Dimension	$1.2m \times 0.72m$
Sill height	$1.15m$
Glass transmission	88%

Table 3.9 provides the architectural parameters of the 3D model of the selected base-case classroom. Schools in Riyadh are designed in such a way that classrooms are located on first and second floors, while the ground floor contains other school facilities and administration offices. Some schools have only two floors but the majority have three floors according to the required size for the neighbourhood in which the school is located. The base-case 3D model is assumed to be on the first floor, and it is modelled with a ground plane extending $35m$ at the side where the wall with openings is located. This size of ground plane was selected according to the recommendation for lighting simulation, to be not less than five times the length of the studied space (Brembilla et al. 2015b) (which in this case is $6.9m$). Therefore, $6.9m \times 5 \approx 35m$.

Reflectance values

To simulate light in space, the simulating engine requires a description of the materials of the object in the 3D model, in a matter of reflectance values and transmission value for transparent and semitransparent objects. There are five ways to assign reflectance values to modelled objects surfaces (Brembilla et al. 2016). These are listed as follows:

1. Using standard reflectance values from reference books.

2. Using reflectance values according to object materials from a material database such as the website www.lighting-materials.com (*Lighting Materials for Simulation* 2017).
3. Using reflectance values through cards with known reflectance as a reference (Society of Light and Lighting 2001).
4. Using calculations from illuminance and luminance measurements (ibid.).
5. Using reflectance values derived from High Dynamic Range (HDR) images (Mardaljevic et al. 2015).

The Illuminating Engineering Society (IES) recommends using actual reflectance values for walls, floors, ceiling and furniture, and if the actual values are unknown, IES recommends using values from an appropriate standard reference. Table 3.10 represents some of the suggested reflectance values, indicating the source of it as one of these references: The IES LM-83-12 (Heschong et al. 2012a); CIBSE application manual 11 on building performance modelling (Chartered Institute of Building Services Engineers 2015); the Society of Light and Lighting (SLL) lighting Guide: LG5 Lighting for Education (Society of Light and Lighting 2011); and the requirements for the Priority Schools Building Programme (PSBP) promoted by the UK Education Funding Agency (EFA) (Education Funding Agency 2014). There are other references which report a list of reflectance values for some materials instead of standard values, namely the Illuminating Engineering Society of North America (IESNA) Handbook (Rea 2000) and the British Standard 8206 Part 2 (Mansfield 2008). However, until submitting this research there was no reference standard for reflectance values in Saudi Arabia. Therefore, the author reviewed previous relevant research conducted in similar climates and building materials, namely, Jeddah in Saudi Arabia, Cairo, Kharja and Sadat cities in Egypt (Sabry et al. 2014, 2012b, 2011, 2010; Sherif et al. 2012a, 2010). Table 3.10 also compares reflectance values recommended by reference books and values used in similar previous research with similar climate and building materials.

Table 3.10: Comparing reflectivity ratios recommended by reference books with ratios used in previous relative daylight simulation studies in similar climates.

	Floor	Walls	Ceiling	Furniture	Solar Screen	External Ground
Ref. books						
IES LM-83-12	0.2	0.5	0.7	0.5	0.5	0.1
CIBSE AM11	0.05–0.3	0.4–0.7	0.7–0.85	–	–	0.05–0.3
SLL LG5	0.2–0.4	0.5–0.8	0.7–0.9	–	–	–
PSBP	0.2	0.5	0.7	–	–	–
Relevant climate						
Jeddah, Saudi Arabia (Sherif et al. 2012a)	0.2	0.5	0.8	0.5	0.5	–
Jeddah, Saudi Arabia (Sabry et al. 2012b)	0.2	0.5	0.8	0.5	0.5	–
Jeddah, Saudi Arabia (Sabry et al. 2014)	0.2	0.5	0.8	–	0.5	–
Sadat, Egypt (Sabry et al. 2010)	0.2	0.6	0.8	0.5	–	0.2
Sadat, Egypt (Sherif et al. 2010)	0.31	0.68	0.857	0.5	0.68	–
Kharja, Egypt (Sabry et al. 2011)	0.317	0.68	0.857	0.5	0.68	–
Kharja, Egypt (Sherif et al. 2012b)	0.317	0.68	0.857	–	0.68	–
Cairo, Egypt (Elghazi et al. 2014)	0.2	0.5	0.8	0.8	–	–
Cairo, Egypt (Amer and Wagdy 2016)	0.2	0.5	0.8	–	–	–
Cairo, Egypt (Hegazy and Attia 2014)	0.2	0.5	0.8	–	–	–
Cairo, Egypt (Hegazy et al. 2013)	0.2	0.5	0.8	–	–	–
Cairo, Egypt (Wagdy and Fathy 2015)	0.2	0.5	0.8	0.5	0.35–0.8	–
Cairo, Egypt (Wagdy and Fathy 2016)	0.2	0.5	0.8	0.5	0.8	–
Sydney, Australia (González and Fiorito 2015)	0.2	0.5	0.8	–	0.9	0.2

The HDR image method was not introduced by the time the surfaces reflectance ratios were selected in this research, and cards nor a luminance meter were not available to use by the author at the field trip. Therefore, the reflectance ratios are selected based on observations of materials at the field study as displayed in Table 3.8 by taking the ratios representing each material from a lighting materials data base (*Lighting Materials for Simulation* 2017), and comparing them with recommended ratios by reference books and ratios used in previous relative studies displayed in Table 3.10. Accordingly, the selected surface reflectance values of objects of the 3D model in this research are presented in Table 3.11 and they are selected as follows:

- Floor reflectivity ratio of 0.2, as it is recommended by three different reference books and was used in 11 previous relevant studies. It represents the grey colour observed at the field study according to lighting materials database.

- Walls reflectivity ratio of 0.5, as it is recommended three different reference books and was used in 10 previous relevant studies. It represents the light colour of walls observed at the field study according to lighting materials database.
- Ceiling reflectivity ratio of 0.8, as it is recommended two different reference books and was used in 11 previous relevant studies. It represents the white colour observed at the field study according to lighting materials database.
- Furniture reflectivity ratio of 0.5, as it is the only ratio recommended by reference books and was used in seven previous relevant studies.
- Solar screens reflectivity ratio of 0.7, as it is recommended by Aljofi (2005) when he studied the effect of colour on screen performance.
- External ground reflectivity ratio of 0.2, as it is the only ratio used in relative studies, and it represents the dark colour observed at the field study according to lighting materials database.
- White board reflectively ratio of 0.9, was not mentioned before, but it reflects the high-reflective white boards observed at the field study, according to the lighting materials database.

Table 3.11: Surface reflectivity ratios of objects materials in the 3D model.

Surface reflectivity ratios						
Floor	Walls	Ceiling	Furniture	Solar Screen	External Ground	White board
0.2	0.5	0.8	0.5	0.7	0.2	0.9

Sensor points grid

In general, one or few points can be chosen to represent an average or a worse-case annual illuminance level such as in corners. That however, cannot quantify how daylight is distributed in the space. Therefore, a grid of points is recommended to perform CBDM simulation (Rogers and Goldman 2006). Until now however, there has been no standard reference specifying the resolution of the grid (the spacing between sensor points) (Brembilla et al. 2015a). In relation to the grid setting, the current Code of Lighting published by the Society of Light and Lighting (SSL), one of the societies of CIBSE, recommends using a square spacing grid with a height equal to the working plane height, and a minimum boundary between the grid and walls of $0.5m$ (Raynham 2012). This boundary however, could be less than $0.5m$ in cases where a task is performed within the boundary area itself.

The total grid area should have a length to width ratio between 2 and 0.5. The SSL code (ibid.) also gives an equation to specify the maximum spacing size:

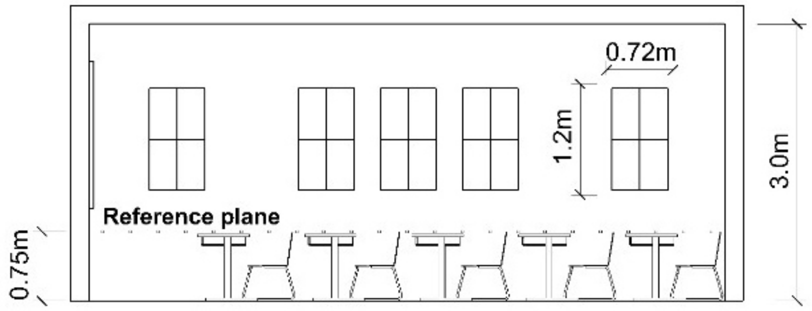
$$p = 0.2 \times 5^{logd} \tag{3.1}$$

where P is the maximum spacing and should not be more than $10m$, and d is the longest dimension of the studied area (ibid.). Brembilla et al. (2015a) have tested four grid resolutions: $0.1m$, $0.25m$, $0.5m$ and $1m$. They recommend using a grid resolution of at least $0.5m$. Nabil and Mardaljevic (2005) believe that a typical grid resolution would be $0.5m \times 0.5m$ depending on the space; the smaller the grid the more distributed. In the U.S however, the Illuminating Engineering Society IES recommends a grid resolution of $0.3m \times 0.3m$ to improve accuracy of simulation (Heschong et al. 2012b).

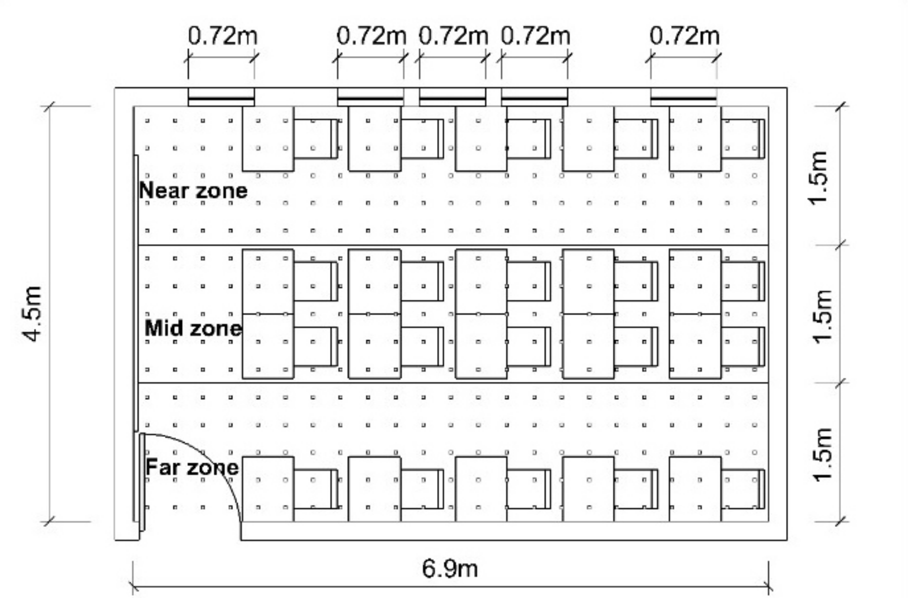
A grid with $0.3m \times 0.3m$ resolution was used in many similar projects simulating daylight in buildings (Sabry et al. 2012a, 2014, 2012b; Sherif et al. 2012a,b, 2011; Wagdy and Fathy 2015, 2016). A grid with $0.25m \times 0.25m$ resolution with a boundary of the room walls of $0.5m$ was also used before (Brembilla et al. 2017, 2015b).

The maximum spacing of the grid of measuring sensors in this research is calculated using Equation: 3.1.

$0.2 \times 5^{log6.9} \approx 0.77$, therefore, maximum spacing is $0.77m$. However, closer spacing provides more accuracy to the simulation as recommended by Nabil and Mardaljevic (2005). A sensors grid with spacing of $0.3m \times 0.3m$ is selected for this study as it is recommended by IES (Heschong et al. 2012b) and used before in similar research. The reference plane (sensors grid) was slightly above the working plane as recommended by the SSL code of lighting. The working plane in this research was the top of students desks. The average desk height according to the field study is $74.3cm$ (Figure 3.7), therefore, the height of the sensors grid is $75cm$, which makes it just above the average desk height and not less than the highest desk found. The grid is also divided into three zones according to the distance from the window: Near Zone, Mid Zone and Far Zone. This zonal division has been used before in similar light simulation projects (Sherif et al. 2010, 2012b) and also in energy simulation (Sherif et al. 2011). Different cases can be compared according to the average data of each zone. Figure 3.15b represents the zonal division and the measuring sensors grid positions and spacing on a base-case plan, and Figure 3.15a displays the height of the sensor grid.



(a) Base-case section showing height of sensors grid.



(b) Base-case plan showing zones and grid spacing.

Figure 3.15: Position and spacing of sensors grid in the base-case classroom.

Target illuminance

The target illuminance threshold can be taken directly from an appropriate standard reference, such as *The IESNA lighting handbook: reference & application* (Rea 2000), *British Standard BS 8206-2 Lighting for Buildings-Part 2: Code of Practice for Daylighting* (Mansfield 2008), and *Daylighting in Architecture, A European Reference Book* (Baker et al. 1993).

The standard adequate illuminance for a reading and/or writing task is $500lx$ (Phillips 2000). However, it is very difficult to depend on daylight solely to achieve this level without causing glare, and the aim was to reduce the use of artificial light as much as possible. Therefore, the illuminance threshold is set to $300lx$. Wagdy and Fathy (2015, 2016) have also used the $300lx$ illuminance threshold instead of $500lx$ when they tested indoor daylighting in classrooms.

Time frame

The time frame used in simulation could be either the daylit hours for a whole year, or the occupied hours in one year. The former is useful in residential buildings and any building that is occupied all day (this was used before in daylight simulation concerning domestic spaces). The latter is used for simulation of office buildings and schools, etc. where a time frame is set according to the weekly schedule excluding weekends and holidays. This was also used before (Reinhart et al. 2006) and sometimes referred to as occupancy schedules.

The occupancy schedule in this research is created using a typical school year in Saudi Arabia, one of the collected data of the field study in Section 3.4.1. School terms, holidays and school-day times were used to create an occupancy schedule as follows: each term has 18 weeks with one week half term break and two weeks between the two terms; the academic year ends with a 12 weeks summer break. School days have seven hours. Thus, the total number of school days is 180 days in 36 weeks, with a total of 1080 hours. The occupancy schedule file for simulation is generated in a Micro-soft Excel file. In this file, each hour of the year is given a value number of either 0 or 1, where the value of 1 represents an occupied hour.

Weather data file

During CBDM modelling, the simulation engine needs an annual weather data set to define the external luminance conditions that characterise the location while corresponding to each hour of the time frame. To use a climate data file in daylighting simulation, the file should contain two parameters: global horizontal irradiance, and either diffuse horizontal irradiance, diffuse horizontal illuminance or direct normal irradiance (Mardaljevic et al. 2012). These luminance conditions are calculated by converting the global and diffuse irradiances values in the weather file into illuminances using a luminance efficacy model (Jakubiec and Reinhart 2011). Then these illuminance values are used to generate a luminous distribution, in order to model a sky dome and finally simulate indoor daylight levels on each sensor point (Mardaljevic 2000).

There are several weather data sets that contain annual data needed for dynamic light simulation (Bellia et al. 2015b; Iversen et al. 2013). The most widespread amongst them are: the Design Reference Year (DRY) (Jensen and Lund 1995); the Satel–Light (Ebrahimpour and Maerefat 2010); the Test Reference Year (TRY) (Commission of the European Community 1985); and the International Weather for Energy Calculations (IWEC) weather file (Iversen et al. 2013). There are also more weather data sets but not freely available nor widespread, such as Solar-GIS (Solar-GIS 2010); Weather Source (Weather-Source 2017); and Weather-Bank (WeatherBank-INC. 2010). The DRY file contains data to describe climate conditions for 12 typical months compiled from at least 15 years of recorded data from a weather station (Jensen and Lund 1995; Watkins et al. 2013). The Satel-Light was developed for Europe as a "European Database of Daylight and Solar Radiation" using satellite measurements for five years from 1996 to 2000 (Ebrahimpour and Maerefat 2010). The Meteonorm data set consists of data collected by 8,325 meteorological stations around the globe. Data for irradiance were deduced from two historical sets 1981–1990 and 1991–2010 (Meteonorm Handbook 2015). The TRY weather file is generated by selecting one typical year out of the historical set. This year is selected by excluding years containing months with highest average high and low temperatures (Crawley 1998).

The IWEC weather file has annual data as a Typical Meteorological Year (TMY). The TMY file is created using a method called sandia method, developed by Sandia National Laboratories (Hall et al. 1978). It is an empirical approach that selects individual months from different years from the period of records (Marion and Urban 1995). For instance, in a case that contains 20 years of data, all 20^th Januaries are examined and the one considered the most typical is chosen to be included in the TMY. All other 11 months are treated in the same manner, then the 12 chosen months form a complete typical year. The TMY continued to develop to TMY2 (ibid.) and TMY3 (Wilcox and Marion 2008) in order to include more data and to cover more recent years (Crawley et al. 1999; Petrakis et al. 1998; Wilcox and Marion 2008). The website of Energy Plus thermal simulation program (Crawley et al. 2001) (a courtesy of the US Department of Energy) contains freely available IWEC files for over 2100 locations (EnergyPlus 2014). The effect of the choice of the weather file was studied before by some researchers (Bellia et al. 2015a,b; Bhandari et al. 2012; Crawley 1998; Iversen 2011; Monteoliva et al. 2017).

The location of analysis in this research is Riyadh (Latitude 24.7, Longitude 46.80 at 612m above sea level). The hot weather in Riyadh was described earlier in Chapter 1. The external illuminance in such a climate can reach up to 100,000lx in summer (Alshaibani 2015). Accordingly, the simulated sky condition is set as “clear sky with sun” as this is the typical sky in such climate. The weather data file for Riyadh used for simulation is an IWEC file. The weather file is obtained from the website of Energy Plus thermal simulation program (EnergyPlus 2014). The IWEC weather data contains a generated typical year TMY, which contains 12 Typical Meteorological Months (TMM) selected from recorded data for at least 23 years (Hall et al. 1978). The data to produce the TMM and TMY for Riyadh was recorded in King Khalid Airport in Riyadh (Al-Maayouf 2005), which is the closest weather station to the urban areas of Riyadh where most schools are located.

Selected CBDM variables

This section aims to prepare the CBDM variables to conduct daylight simulation correctly. Collected data from field work were used to select dimensions to build a three dimentional model for the base-case, describe materials, select a time frame and select a height for sensor grids. The field study helped in preparing the CBDM variables as well as describing the school surroundings to conclude the privacy-breaching scenarios used to evaluate privacy in schools. The summary of selected CBDM variables for conducting daylight simulation in this research is presented in Table 3.12.

Table 3.12: Summary of CBDM variables.

Selected CBDM variables for simulation	
Variable	**Selected Value**
3D model	Displayed in Figure 3.13 with parameters in Table 3.9.
Reflectance ratios	Displayed in Table 3.11.
Sensor grid	0.3×0.3m grid, 0.75m height, displayed in Figure 3.15.
Target illuminance	300lx
Time frame	1080 hours in 180 days in 36 weeks a year.
Weather data file	IWEC file contains TMY for Riyadh obtained from Energy Plus website (EnergyPlus 2014).

3.4.3 Privacy-breaching scenarios

After defining maintaining privacy as diminishing visibility between the viewer outside and the building interior behind openings in Chapter 2, the author found it essential to study the scenarios of breaching privacy in girls' schools in order to study privacy in buildings by examining also the influence of the schools' surroundings. After analysing the school surroundings during the field work and the dimensions of a typical school building in Section 3.4.1, the author concluded three worst case scenarios to breach privacy of occupants in school buildings. Worst case scenarios have the minimum possible distance between viewer and schools openings; all viewers are assumed to be 1.8m high (the author acknowledges this limitation and agree that using a range of heights would have been better to account for many heights).

The diagram in Figure 3.16 represents a layout of the smallest boundary street and the closest neighbouring building found at the field study according to school buildings regulations in Riyadh. The diagram also represents the following worst case scenarios for privacy-breaching by viewers around schools:

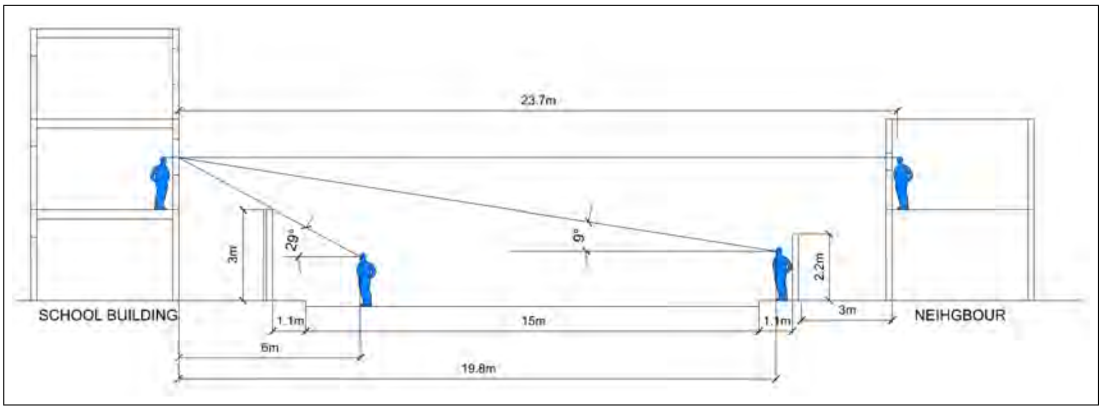


Figure 3.16: Cases of an average actual school building.

1. A viewer on one of the streets surrounding the school. In this scenario the viewer is the closest possible to the opening of concern; that is $6m$ away from the first floor window. Any closer distance would cause the boundary wall to cover the view of the opening (Figure 3.16). The height difference between the viewer's eye and the target is $3.3m$. Although the viewer here is the closest to the opening, they have to tilt their head a high angle of about 29° degrees in order to view the target. The mathematical trigonometric functions explained in Section 3.2.5 and Figure 3.5a are used to calculate this angle, $Tan\theta = \frac{330}{600} \Rightarrow \theta = Tan^{-1}\frac{330}{600} \Rightarrow \theta \approx 29^\circ$ (Figure 3.17). The figure also shows that the viewer has a straight view to the window; this view has a linear length of $6.86m$, also calculated also using mathematical trigonometric functions: $\frac{330}{Cos29^\circ} \approx 686cm$.

2. A viewer on the kerb across the street surrounding the school. In this scenario, the viewer is $19.8m$ away from the school building. The height difference between the viewer's eye and the target is $3.1m$. It differs in this scenario compared to the first scenario because of the kerb height difference. Thus, viewers need to tilt their heads about 9° degrees in order to keep the target in their central vision. Mathematical trigonometric functions were used to calculate this angle, $Tan\theta = \frac{310}{1980} \Rightarrow \theta = Tan^{-1}\frac{310}{1980} \Rightarrow \theta \approx 9^\circ$ (Figure 3.18).

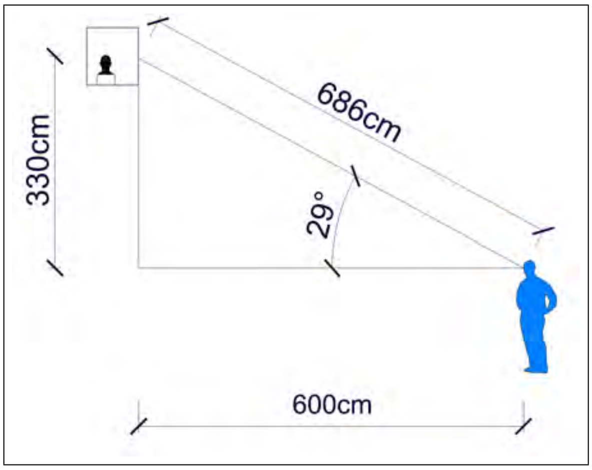


Figure 3.17: First scenario: $6m$ away with 29° angle.

The same figure also shows that the viewer has a straight view to the window at the first floor; this view has a linear length of $20.04m$, also calculated using mathematical trigonometric functions:$\frac{310}{Cos9^{\circ}} \approx 2004cm$

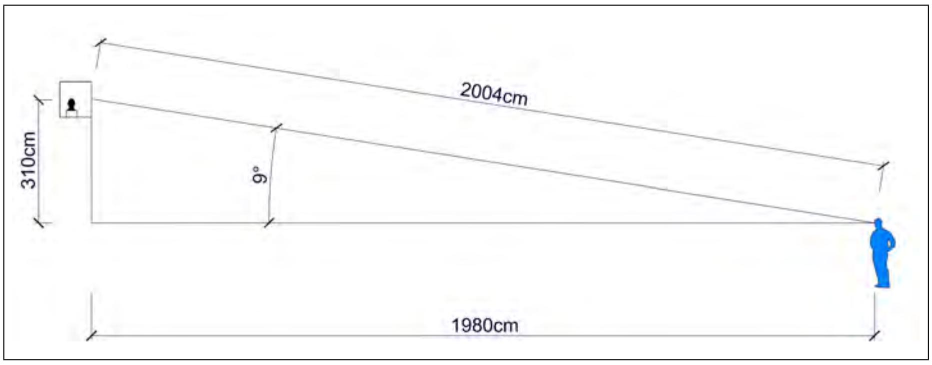


Figure 3.18: Second scenario: $19.8m$ away with 9° angle.

3. A viewer from the first floor of a neighbour across the street surrounding the school. In this scenario, the viewer is $23.7m$ away from the first floor window (Figure 3.19). Although the viewer in this scenario is more than $20m$ away, they have a direct angle of viewing which reduces the effect of viewing angle and eye movement as discussed before in Chapter 2.

Figure 3.19: Third scenario: 23.7m away with 0° angle.

3.4.4 Building the privacy-breaching cases

The three worst privacy breach scenarios inside schools are discussed above and presented in Figure 3.16. These three scenarios are then replicated to three cases for the experimental study using the method explained in Figure 3.5 to diminish the need for installing the box in high places. The third scenario was easy to replicate as an experiment since it was a straight view without any tilting angle (Figures 3.19 and 3.22), whereas for the other two scenarios, the box must be tilted and the distance between the observer and the screen adjusted, in order to compensate for the angle caused by the height of the windows on the first floor (Figure 3.17 and 3.18).

Using simple mathematical trigonometric functions to derive the angle and distance corrections explained in Figure 3.5b, in case-1 the box is tilted for 29° and the distance is 6.84m instead of 6m (Fig: 3.22), whereas the box in the second case was tilted 9° and the distance is 20.04m instead of 19.80m (Figure 3.21). Each case is tested with each subject. How these cases are used to test privacy through perforated screens with subjects is discussed in detail in the research methods to evaluate privacy in Section 3.5.5.

Figure 3.20: Case-1 of privacy-breaching.

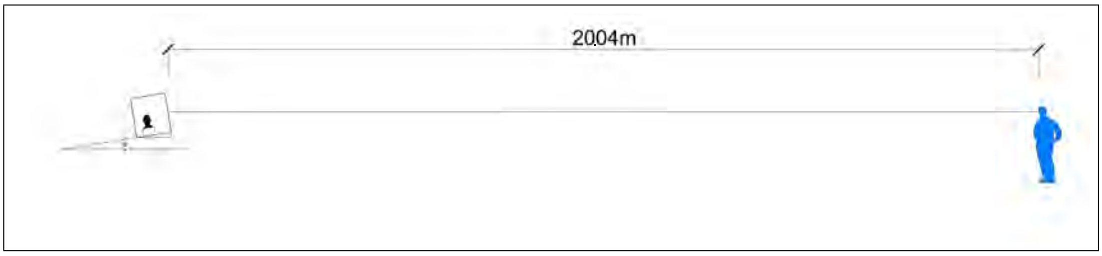


Figure 3.21: Case-2 of privacy-breaching.

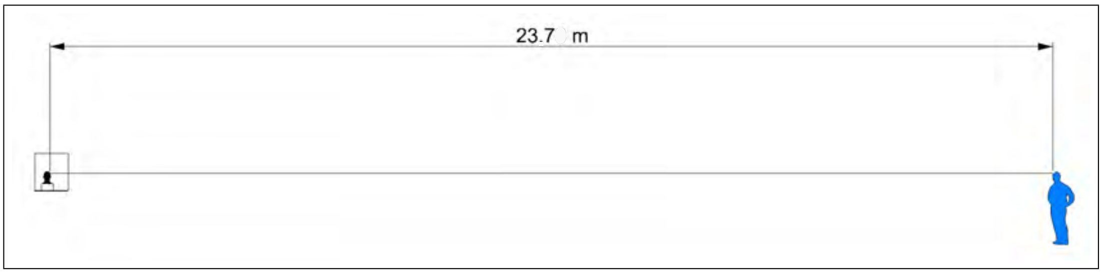


Figure 3.22: Case-3 of privacy-breaching.

Controlling the factors affecting privacy level

After concluding the privacy-breaching scenarios from the field study and replicating them into experimental cases, it is now important to control the factors discussed in Section 2.2.5. There are eleven factors affecting the visibility between a viewer outside and the interior of a building through openings; one of these factors is the shading strategy. When testing the effect of using solar screens on visual exposure, the other ten factors need to be controlled to the worst case scenario in order to confirm to one part of the research hypothesis (that a shading strategy can maintain privacy in buildings). Factors are therefore controlled as follows:

1. **The distance between the eye of the viewer and the target.**

   The distance is controlled for each case according to the reflected scenario. The distance of cases represented the worst case privacy-breaching scenarios. Therefore, if privacy was maintained in the studied distances, then it is likely to be maintained in any longer distance for each scenario.

2. **Glass reflectivity and transmission.**

   To avoid affecting the result, perforated screens are tested without the use of glass. If privacy could be maintained without glass, then the privacy level is likely to be higher when using glass as the glass reflectivity can reduce visibility as discussed in Chapter 2.

3. **Viewing angle.**

   To control this factor, all subjects are seated at the same position directly in front of the solar screen. An office chair with adjustable height was used, and the eye level was marked on a vertical pole beside the chair (Figure 3.23). The chair height is adjustable for each subject, and subjects are asked by the assistant to keep their back straight to maintain the appropriate eye level, in order to make sure the eye level of all subjects is the same (thus the same viewing straight angle). During the experiment, the assistant should make sure that subjects keep their back straight and remind them that they are allowed them to have a break at any time for comfort.

Figure 3.23: Controlling eye level for all subjects.

4. **Luminance of the background of the target inside the building.**

   The background of the Kay pictures images is white, which provides the most contrast with the target. All images are printed with an A1 plotter using the same paper roll to make sure that all images have backgrounds with the same white level. If subjects are unable to see the high contrast target, they are more likely not to see other targets with lower contrast.

5. **Eye movement.**

   One of the advantages of doing that and also tilting the box and changing the distance accordingly (Figure 3.5) instead of using a higher floor (e.g. a mezzanine) is making sure that human subjects are using their central vision instead of their peripheral vision because it would be difficult to control the head tilting of subjects when looking at a higher target. Using their peripheral vision might affect the results because it provides less image rendering quality than their central vision. Moreover, the eye bone and different facial features of subjects might affect the visual field of the eye. Therefore, head tilting of the subjects might affect the visual acuity. Controlling the eye level of subjects as discussed above, would provide the most accurate visual information for subjects (Figure 3.23).

6. **Illuminance contrast between outside and inside.**

   In the context of this project, in order to control the factor of pupil size for all subjects, the environment is controlled to create the same contrast between inside and outside using the same contrast as the studied classroom.

   To eliminate the effect of illuminance contrast factor, the DF is used to calibrate the illuminance difference between outdoor and classroom interior, and the illuminance difference between under the sky-dome and box interior. DF for the studied class is simulated using DIVA-for-Rhino for every case of screen. Then, using a multi-point light meter, one sensor is placed inside the box exactly at the position of the sensor when simulating the DF for the virtual classroom. The lighting settings are changed until similar DF is achieved for the studied cases of different screens. DF ratio between indoor and outdoor illuminances is calculated under an overcast sky (Moon and Spencer 1942; Rockcastle and Andersen 2013) which would provide the lowest possible outdoor illuminance. The illuminance contrast between outside and inside the classroom would be higher under a clear sky, whereas in overcast skies, the contrast will be lower, hence visual privacy is likely to be more compromised than in a clear sky scenario. Therefore, using DF would provide the worst case scenario for the illuminance contrast. The used actual DF percentages to control this factor are displayed later in the relative experiment in Chapter 4.

7. **Luminance of the wall surrounding the opening.**

   The outside of the box has a beige colour (Figure 3.3), which is similar to the exterior wall of schools in Saudi Arabia, according to the conducted field trip by author (Figure 3.12) and also in a previous field trip by Abanomi (2005) (Figure 3.24).

Figure 3.24: The exterior wall of schools (source: Abanomi 2005).

8. **Movement of the target**

   According to what was discussed in the related optometry principles in Chapter 2, the moving target is more difficult to detect and recognise by human eye. That means that the worst case scenario is viewing a static target. Therefore, the target image in this experiment is a still image (Kay pictures). If visual privacy is maintained for a still image, it would be more likely to be also maintained for a moving target.

9. **Visual acuity of the viewer**

   To make sure the differences in visual acuity performance of human subjects has no effect on the experiment, all participants are subject to a visual acuity test before the experiment. A Snellen chart (Figure 3.25b) is placed 6m away from subjects and they are asked to read the letters, especially line number nine which reflects normal vision as discussed in Chapter 2. Results of any subject with visual acuity results below normal vision standards are excluded from the final results.

(a) Testing visual acuity of subjects before the experiment.

(b) Snellen visual acuity test. Reproduced by author.

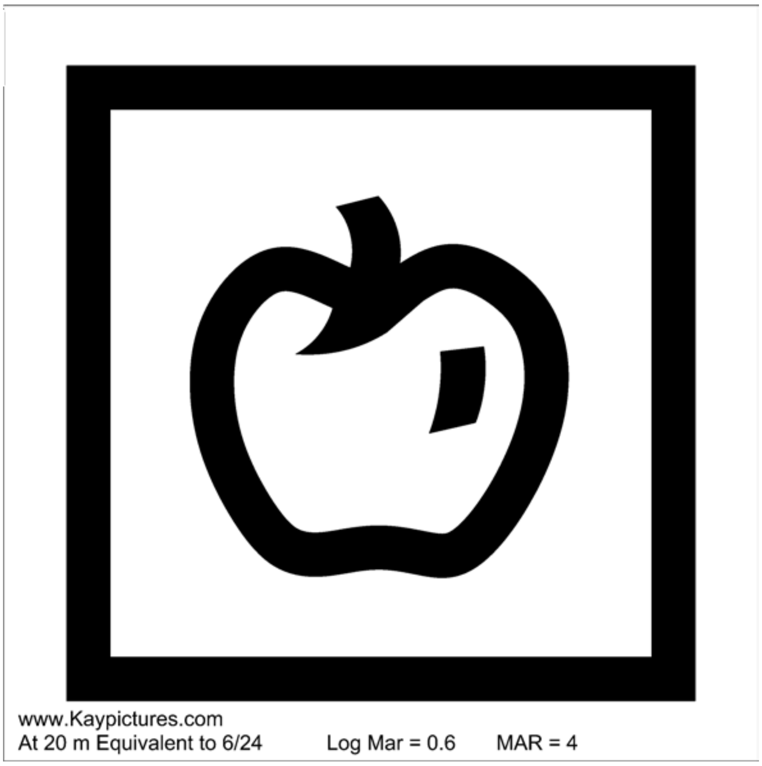
Figure 3.25: Using Snellen visual acuity test to make sure that all participants have normal visual acuity.

10. **Size of the target**

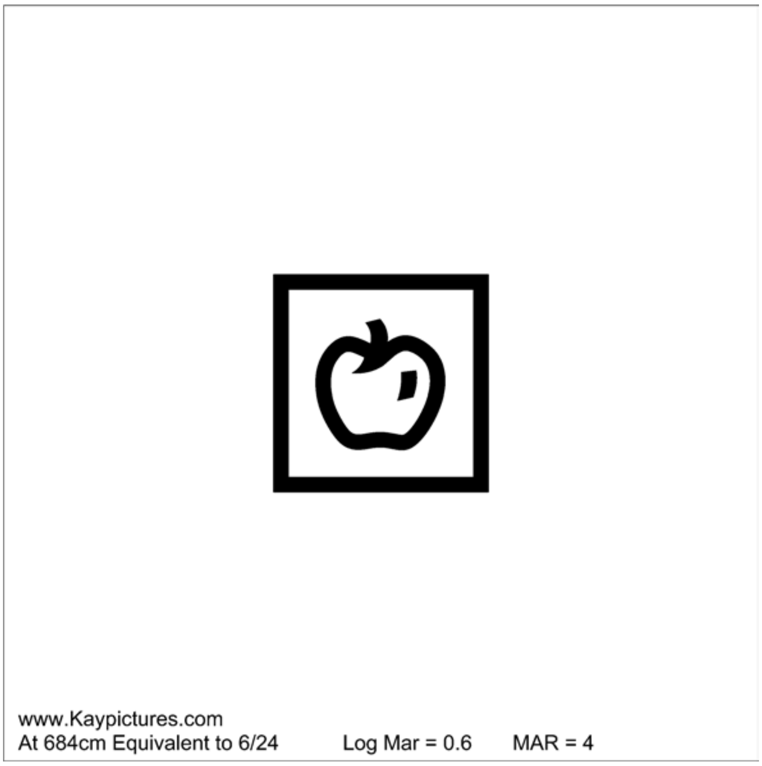
    Each target requires a minimum distance in order to be detectable, and this is one of the main principles in all visual acuity charts used by optometrists. According to the distances of the privacy-breaching cases in Figures 3.20, 3.21 and 3.22, the size of the Kay pictures images are reproduced with size 4 MAR that requires the human eye to be at least 6m away, for someone with low visual acuity to detect any image. That would mean that a participant with a normal vision acuity would very easily detect and recognise the same image from 6m away. If an image that big was not able to be detected by a human with normal vision, then it would be the result of the perforated solar screen since all other factors were controlled. As explained in Chapter 2, visual chart size including Kay pictures can be calibrated according to the distance between the chart and the observer, using equation: $\text{Tan}\theta = \frac{X}{L}$ where L is the distance between target and observer and X is the height of the stroke of each picture. Thus, two sets of Kay pictures are produced ,adopting the same principles to be used with the required distances according to the privacy cases in Figures: 3.20, 3.21 and 3.22. One set with a stroke size of $7.96mm$ to be used with $6.86m$ in case-1, and a set with $23.72mm$ stroke size to be used with 20m distance and more (case-1 and case-2). Figure 3.26 represents the proportion of size different between the two sets, scaled to 1:4.

11. **Shading strategies.**

    The last factor affecting the visibility of occupants from outside is the use of an external solar screen in front of openings. This is the focus of this phase. Since all other factors were controlled, not being able to see an image behind a perforated solar screen means that the screen succeeded in maintaining privacy if the image can be seen easily without a solar screen.



(a) a Kay-Picture image used in case 1 & 2 (scale 1:4).



(b) a Kay-Picture image used in case 3 (scale 1:4).

Figure 3.26: Size difference between a Kay Picture image used for case 1 & 2, and case 3, scaled to 1:4 (reproduced by author).

3.5 Research methods

After selecting the methodology following the outcomes of the literature review and preparing all data needed to conduct the research according to the work flow presented in Figure 3.6, this section explains the experiments and phases of the research, and explains how daylight and privacy are evaluated in these phases after using the data collected from the field study.

3.5.1 Phases

In the first phase, the effect of the first four parameters on daylight performance of solar screens is tested one at a time according to the selected simulation process discussed in Table 3.4. The tested parameters in this phase are: perforation percentage; depth ratio; cell module size ; and opening aspect ratio. When testing a parameter, all other parameters are fixed based on the results of previous experiments. When no previous result was available, for example, when testing the perforation percentage, other parameters are controlled based upon assumptions derived based on previous similar research. Then when testing the depth ratio, the recommended values of the previous experiment (perforation percentage) is used to control that parameter.

Since there is no logical sequence to test the parameters in phase one, the author decided to start with the most parameters that have been studied before. Although it was in different contexts, it would give a starting point to set the values of the controlled parameters. Hence, phase one is performed with the following sequence: perforation percentage, depth ratio, cell size and then aspect ratio.

In order to review whether the selected sequence has an effect on the result, the author in phase two has repeats the first experiment (Perforation percentage) using the recommended values of the results of phase one to test the effect of perforation percentage again. Finding an agreement between the results of testing the effect of perforation percentage in phase one and in phase two, would prove that the selected sequence of experiment has no effect on the final result.

The last parameter (Axial tilt angle of the screen) is tested in the third and the fourth phases. Theoretically, axial tilting is the most important parameter to reduce visibility through perforated screens even without affecting the daylight performance of the screen, in fact, upper horizontal axial tilting would be expected to allow more indoor daylight as the screen would have a bigger sky view avoiding obstructions of surrounding buildings. Therefore, this parameter is tested in a different way than the other parameters. Screen configuration based on the results of the first two phases are used to produce different cases of screens for the privacy experiment. Then the effect of the tilt angle of screens is tested in phase three to find out the recommended angle that provides privacy.

Then in phase four, Instead of testing a range of values of axial tilting, only the recommended angle values resulted in phase three (The sucessful angles that maintain privacy) are used to test the daylight performance of the perforated solar screens. At the end of this phase, the daylight simulation results of tilted screens is compared with the results of vertical screens and the case of windows without screens.

3.5.2 Generating the screens

To use screens with different configuration according to the studied parameter in daylight simulation, screens are generated as 3D models in Rhino. The most appropriate way to generate different versions of a screen according to the value of each parameter is to use parametric modelling. Parametric modelling refers to the automated parameter based generation of 3D elements (Erlendsson 2014). "Grasshopper-3D" developed by David Rutten at Mcneel and Associates (Rutten and McNeel 2012), is a generic algorithm editor allowing the user to perform parametric modelling extension for Rhino. By using Grasshopper, screens can be automatically drawn based on the author's defined algorithms and can be altered by changing parameters within the algorithm according to the required resulting object. Figure 3.27 displays the components used to build the algorithms in order to generate all the screens. The used components are grouped, named and organised to make it easier to the non-expert to understand what have been done in the Grasshopper canvas to generate the screens. Only the values of the parameter of tilt angle in phase 4 are done manually by the author in Rhino.

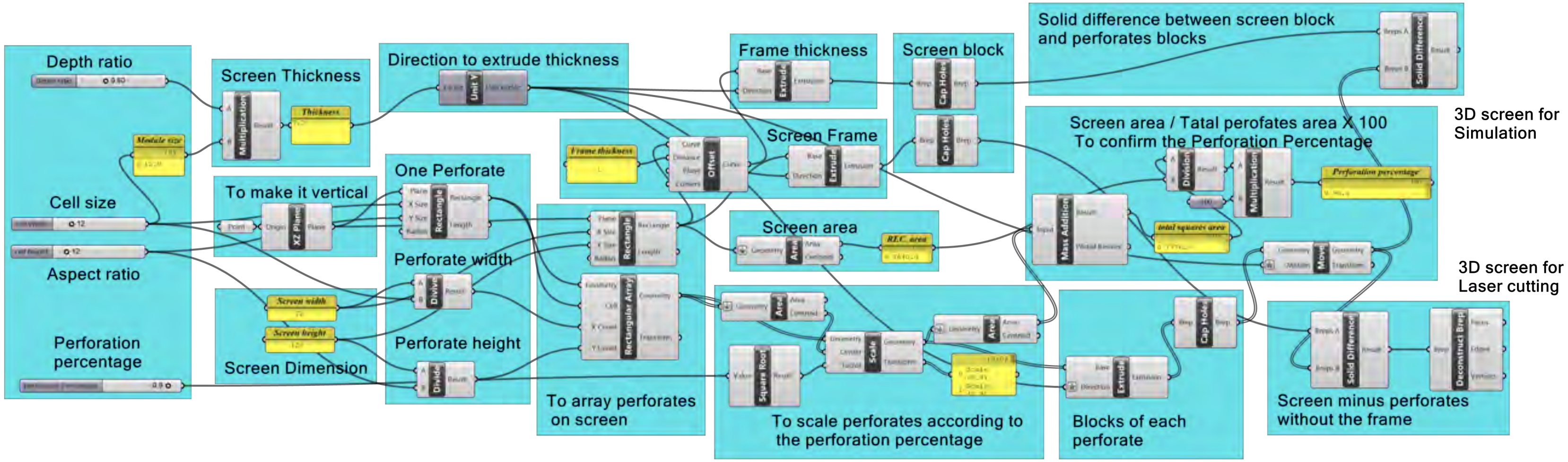


Figure 3.27: Screen-shot of the Grasshopper canvas created to generate screens by controlling values of each parameter.

3.5.3 Daylight performance

Phase one, two and four involve testing the daylight performance of perforated solar screens. Based on the Literature review outcomes, two metrics of evaluating daylight in buildings are used in this research. One static and one dynamic: Average illuminance distribution on the working plane; and the DAv respectively. Studying the illuminance levels would provide information for the best parameter values for a specific time and day in the year. Whilst the DAv allows for covering the set occupancy time and gives more information about the daylight performance for the whole year.

Illuminance levels

For each case of each parameter in the phases mentioned, the illuminance levels are simulated on each sensor point at the reference plane. The average illuminance is calculated for each zone. Measurements higher than $5000lx$ are excluded from the rest of the analysis, including these points would bias the average values although they stand for less than 0.5% of the measuring points, this approach was used previously by Sherif et al. (2012b).

The measurement are recorded three times a day, for four typical days, namely the summer and winter solstices and the autumn and spring equinoxes. The selected simulated times are 07:00, 10:00 and 13:00, to cover a school day in Saudi Arabia, from 6:30 to 13:30 as mentioned previously. The simulation is also repeated for each of the main orientations (N, E, W and S). This method was used before in similar relevant studies (Sabry et al. 2011; Sherif et al. 2012b), they however, have used 09:00 12:00 and 15:00 in only three days a year in three orientations: summer and winter solstices and either autumn or spring equinoxes, given that the day length of autumn and spring equinoxes are equal and the sun path is symmetrical. Therefore, the result of 09:00 and 15:00 in the West would be the same as the result of 15:00 and 09:00 on the East respectively (Sherif et al. 2010). This was not applicable in this project since the selected simulated hours are 07:00, 10:00 and 13:00 to cover the school day, thus, not symmetrical between East and West. Although there would be slight difference in results for schools oriented different that direct main orientation, it is unlikely to find a building in Riyadh that is not oriented to the main orientations. The reason for that is that Riyadh has a gridiron plan which can be seen in Riyadh map in Figure 3.7.

Dynamic Daylight Metrics

Cases of each studied parameter are simulated to study how they affect the annual daylight performance using the DDPMs. These metrics evaluate daylighting performance based on time series of illuminance or luminance levels within a space. These time series cover the occupancy hours in a calendar year and are based on external, annual solar radiation data for the building site. As mentioned before, Daylight Availability DAv is selected to be the dynamic daylight metric used in daylight simulation for this study as explained in Section 3.2.

The result of DAv metrics provides a percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone, and then categorise the space according to that into three criteria: ‘Daylit area’, ‘Partly Daylit area’ and Overlit. Daylit area is the area receiving adequate daylight for at least half of the occupancy time, whereas, areas that fail to achieve the required threshold are considered as Partly lit areas. Overlit areas however, are defined as those areas receiving ten times or more of the adequate daylight for at least 5% of the occupancy time (Reinhart and Wienold 2011).

Simulating the cases

Selecting the simulation process as simulating and studying one parameter at a time was discussed in Section 3.2.4. That section also discussed the selected software tools as Diva-for-Rhino and Grasshopper to control DIVA more efficiently and to export data to Microsoft-Excel. The script to perform the daylight simulation and export data is written in Grasshopper and can be seen as a Grasshopper canvas showing the used components in Figure 3.28.

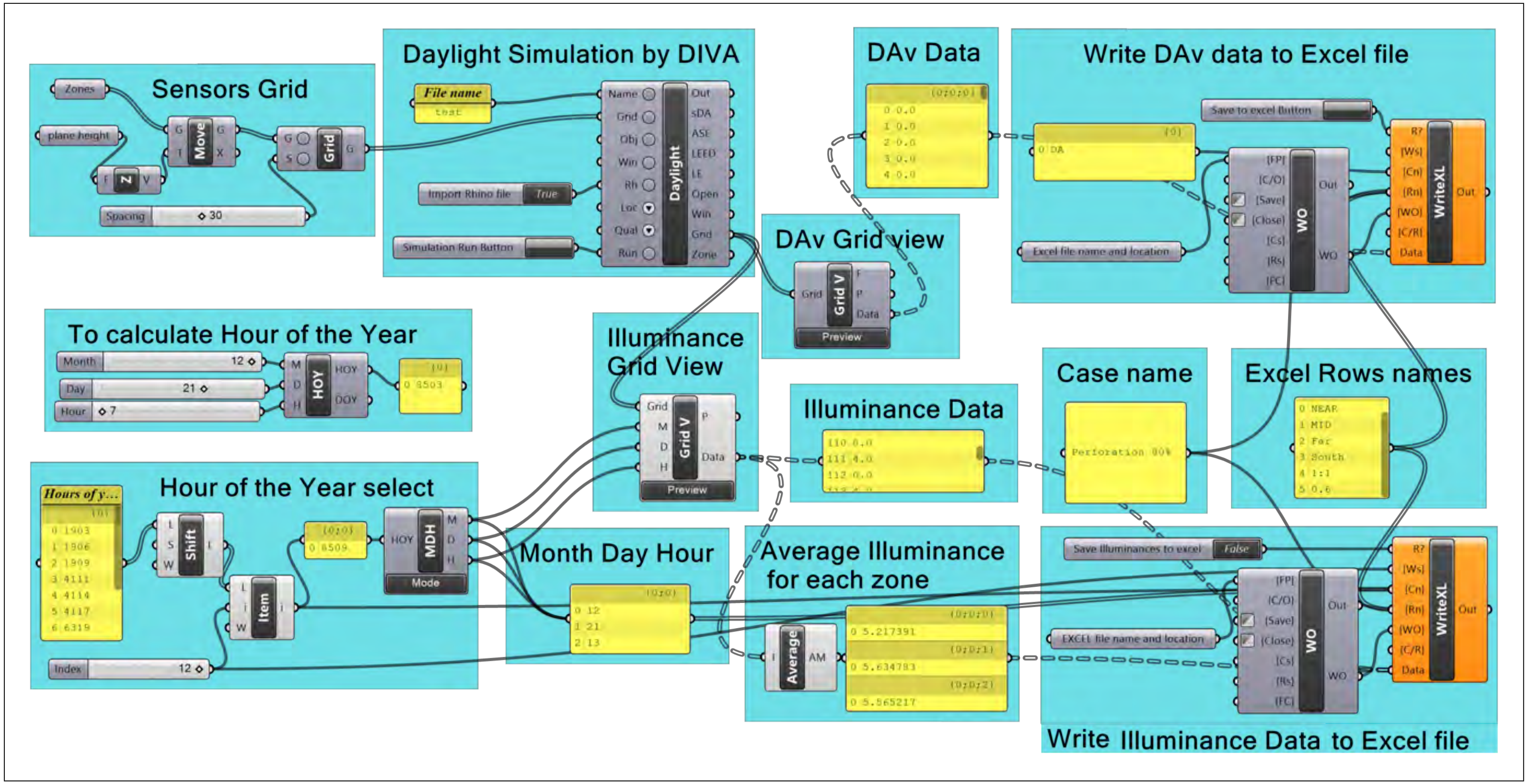


Figure 3.28: Screen-shot of the Grasshopper canvas created to perform daylight simulation using DIVA.

3.5.4 Presenting results of daylight simulation

The results of experiments related to daylight simulation are represented in charts and tables. The results of average illuminance experiments for each studied parameter are represented in tables, one table for each orientation. Each table is listing a matrix of average illuminance values covering the following:

- Average illuminance values for each zone of the three zones: (Near, Mid and Far), named according to the distance from the wall with openings, zonal division was explained in Section 3.4.2 and displayed in Figure 3.15.
- Average illuminance values for each specific time (7:00, 10:00 and 13:00) of summer and winter solstices and the autumn and spring equinoxes.
- Average illuminance values for each case of the studies cases of that parameter (e.g. perforation percentage has 9 cases: 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10%)

The cells of the average illuminance values table are highlighted to show the results easily. Black cells represent results that have illuminance levels more than $1000lx$, grey cells represents results that have illuminance between $500lx$ and $999lx$, finally, light grey cells represents results that have illuminance between $300lx$ and $499lx$. These ranges aimed to ease comparisons between different timings and zones. Results parameters that showed significant different between each variation, have helped also to produce tables to indicate recommended values for the tested parameter.

The results of DAv experiments for each studied parameter are represented in charts and tables. The simulation results give each sensor point on the grid (of the 345 sensor points) a value of DAv from 0%–100%, this percentage is calculated using this equation:

$$DAv = \frac{Occupied\ time\ achieving\ the\ target\ illuminance\ (300lx)}{Total\ occupied\ time} \times 100$$

Each sensor point then would have a value of DAv, then it is represented on the plan of the classroom as a grid of squares, one square for each sensor points in order to show the distribution of DAv on the plan. Each square is coloured according to its DAv value using a coloured scale that ranges from Blue (0%) to Red (100%). Squares with magenta colour indicate the 'Overlit' areas, which have received received at least 3000lx (10 times the target illuminance threshold) for at least 5% of the occupancy time. Figure 3.29 is an example of a grid of DAv to explain how the grid is resulted out of the values of each sensor point and the colour scale. When studying each parameter, a table for each orientation illustrates a DAv grid for each studied case. In order to simplify comparisons between results of each orientation, all grids in all tables are superimposed on the classroom plans where windows are always on the upper side of the grid regardless of the studied façade orientation in that table.

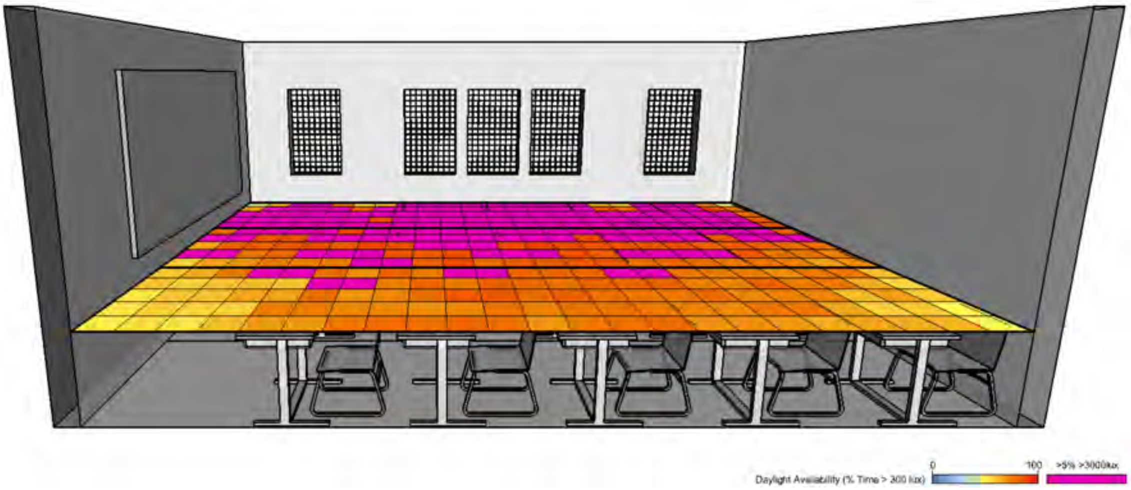


Figure 3.29: An example of the analysis grid resulted from the simulation for Daylight Availability.

The total area of Overlit squares is then calculated, and total area of squares that failed to achieve at least 50% DAv is calculated and considered as 'Partly lit area', and total area of squares that achieve 50% or more DAv without being categorised as 'Overlit area' is calculated and considered as 'Daylit area', in other words Daylit area is all the remain areas that were not categorised as neither Overlit or Partlylit areas because the total has to be 100% (Table 3.13).

Table 3.13: Representing DAv resulted areas in a graph.

Area	**Description**
Overlit	Receiving $3000lx$ or more for at least 5% of occupied time
Partly lit	Receiving $300lx$ or less for less than 50% of occupied time
Daylit	All remain areas

These data is then illustrated in bar charts. Four charts for every parameter, one for each one of the four main orientations. In every chart, the studied cases of that parameter on that orientation is compared, the case providing the biggest 'Daylit area' would give the best value for that parameter.

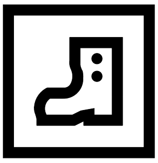
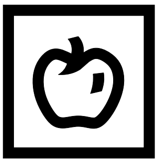
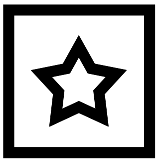
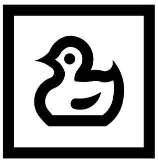
All of daylight simulation experiments in this research are presented using the same methods discussed above. A copy of the method of representing results of daylight simulation is attached in Appendix H printed in an A3 sheet so that readers can unfold it when needed and use it to interpret any daylight simulation results in this research.

3.5.5 Privacy study

3.5.6 Methods

The general methodology of this phase, is building a physical model to test the use of solar screen with recruited subjects. The physical model consisted of a box with one open side covered by a perforated screen. Human subjects are used to test whether the image hidden behind the screen can be identified or not by subjects. The box was able to be tilted to represent the viewing angle of each one of the privacy breaching scenarios discussed in Section 3.4.3 (Figures 3.17, 3.18 & 3.19). Position of subjects, distance form the box and box tilting angle was set according to the three scenarios of breaching privacy, and each scenario is tested three times using three perforated screens. Different Kay picture images are placed inside the box one at a time. Subjects are asked to identify the Kay picture hidden behind screens one at a time. Six different Kay pictures are used and each picture is assigned with an image number. Table 3.14 represents the image number for each Kay picture, and the possible names that subjects might call it. A picture would be reported as identified by subjects when the subjects call a proper name of the viewed image. The size of Kay pictures is calibrated and changed in this experiment according to the distance between subjects and pictures to be equivalent to size 24/6 as explained in Section 3.4.4. A permission from the producers of Kay pictures is obtained by the author to use them and calibrate their sizes as required. A copy of the permission is attached in Appendix F.

Table 3.14: Images, possible names and assigned numbers to each one of the used Kay Pictures in the experiment.

1	2	3	4	5	6
					
Boot Shoe	Car Vehicle Truck	House building Home	Apple Cherry	Star	Duck Bird Chick

Recruiting subjects

This part of the research is looking at establishing satisfaction of privacy requirements considering the worst case privacy breach scenarios. Therefore, the recruitment deliberately looks for people who are sensitive to these privacy requirements. That means recruiting Muslims or/and citizens of a Middle eastern country. This does not impose any ethical risks, on the contrary it is expected that volunteers would happily contribute to the research and understand that no risks are present. Other subjects from a Western background are also recruited to enable comparison of the results and check whether cultural background has an effect on the results.

Subjects are recruited using inviting posters that disseminates information regarding the study are distributed across Cardiff University buildings, and messages in social groups and societies (e.g. Saudi Student Society in the Student Union of Cardiff University). Subjects age target is between 18–39 years. This range is selected to cover mostly subjects that are parents and simultaneously young enough to ensure good visual acuity. The effect of age, gender as well as the effect of the subjects being parents are analysed against the results of the experiment. 28 subjects are finally recruited, 14 male and 14 females. Participation in this study is entirely voluntary, and the participants have the right to withdraw from the study at any time without giving a reason. Since most potential subjects are PhD candidates in the Welsh School of Architecture, the author is keen that all PhD candidates do not see any of the Kay picture images prior to the experiment as exposing the images to subjects before the experiment would affect detecting the images as subjects might use the imagination from their memory when trying to guess the image. For the same reason, no subjects from the Optometry school or optometrists are recruited in this experiment as they might be familiar with Kay pictures. Participated subjects are asked not to discuss the images they have seen during the experiment with others, especially if their colleagues and families are possible subjects.

Health and safety considerations

Prior to conducting the experiment, the researcher considered the likelihood of any risks associated with the planned study and listed how to control them and all actions needed to avoid them. These data were filled in a risk assessment form and was approved by the health and safety officer at Welsh School of Architecture where the experiment is taking place. Hence, the experiment met the requirements of Cardiff University's health and safety policies. A copy of the risk assessment form is attached in Appendix B.

Subjects are informed by the examiner or his assistant about the safety procedures in case of emergency and the direction of the nearest emergency exit and the nearest facilities. They are also informed that they can ask for a break any time during the experiment, they are also provided with a bottle of water and informed that they can drink between sessions.

Ethics considerations

An ethical request was submitted to the ethics committee in the Welsh School of Architecture, and approval was granted prior to commencing the experiments. A copy of the approved application is provided in Appendix C.

To comply with the "Prevent Duty" requirement, which aims to prevent anyone being drawn into terrorism, all recruited subjects from outside the Welsh School of Architecture are asked to bring a photo identification card and are required to sign in and sign out with their names recording the time entering and exiting the building respectively. The examiner checks their identification cards and signs them in with their full names. This information however, is not related to the questionnaire. This sign in and sign out of the building and a record of the exact timings is kept entirely for security reasons in a password protected file with the signed consent forms. Any other information provided by subjects are anonymous and held confidentially and used only for this academic research. Collected data from subjects will not be kept after the degree is awarded and it will be erased. To comply with ethics requirements, eyes of subjects who their photos appeared in this thesis were covered so they cannot be recognised.

Construction the box and screens

Perforated screens are constructed in the FabLab facility in WSA (*the Digital Fabrication Lab* 2018) using a laser cutter machine FB–700 (Figure 3.30) which has a resolution of 0.025mm and a minimum spacing of 1mm between any two cuts to prevent material burning (*www.cct–uk.com* 2018).

To control the light level behind the studied screens, a box is constructed with one open side, which is the method selected in Section 3.2.5. The open side is

(a) Laser cutter FB–700, source: (*www.cct–uk.com* 2018).

(b) Cutting perforated screens in the laser cutter in the FabLab of WSA.

Figure 3.30: Laser cutter used to produce physical models of perforated solar screens.

able to be covered with an interchangeable perforated solar screens. Each screen is able to be easily replaced by another one to reduce total time of experiment, which would reduce the effect of fatigue on subjects. The box is constructed using timber beams cut in the workshop of the Welsh School of Architecture with the help of a professional craftsman experienced in model making. His supervision in constructing the model is one of the requirements for the health and safety risk assessment form discussed in Section 3.5.6.

To simplify moving and changing the tilt angle of the box, the box is attached to a tilting table with four wheels with brakes. The table is a typical drafting table used by students at the Welsh School of Architecture. It is not totally vertical when folded, therefore, the researcher attached a piece of timber to make it vertical with 90° degree (Figure 3.31b). The ability for the table to be folded from horizontal to vertical allows the examiner to control the rotation angle of the box which can reflect one of the three experimental cases that resemble the three scenarios of breaching privacy shown in Figures 3.17, 3.18 & 3.19, discussed in Section 3.4.4.

Another tilting mechanism is constructed on the box itself, using a piano hinge to allow the rotation of the perforated solar screen only. It is used to test the effect

(a) The box installed on the fold-able table.

(b) Correcting the vertical angle of the table.

Figure 3.31: Attaching the box on a tilting drafting table and correcting its angle when folded.

of the screen's tilting angle on privacy as one of the parameters of perforated solar screens which is the aim of the experiment of phase three discussed in Section 3.5.1. In order to simplify recording the tilt angles, a transparent compass is attached on the side of the box to give a reading of the rotation of the screen angle during the experiments. The compass is also produced using the laser cutter from a rhino file prepared by the examiner (Figure 3.32). The author acknowledges that there might be +-1 degree error due to the manual recording of the tilt angle, however, the worst case scenario was used to control all other factors which would to reduce the effect of errors.

When the screen is tilted, the void underneath would definitely be allowing subjects to see what is inside the box as well as allowing light to emit inside, which would alter the controlled illuminance contrast. Therefore, a piece of blackout fabric is used to cover that area. It is sewed and stitched according to the size of the box to cover around the screen when it is tilted. That would block the view of the subject and also allow controlling the light level inside the box as controlled by the examiner. The attached blackout fabric can be seen in Figure 3.33.

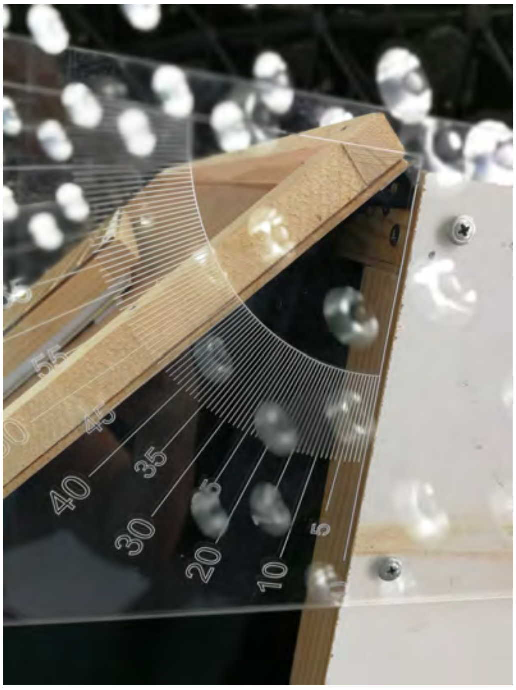


Figure 3.32: The transparent compass used to report tilt angles.

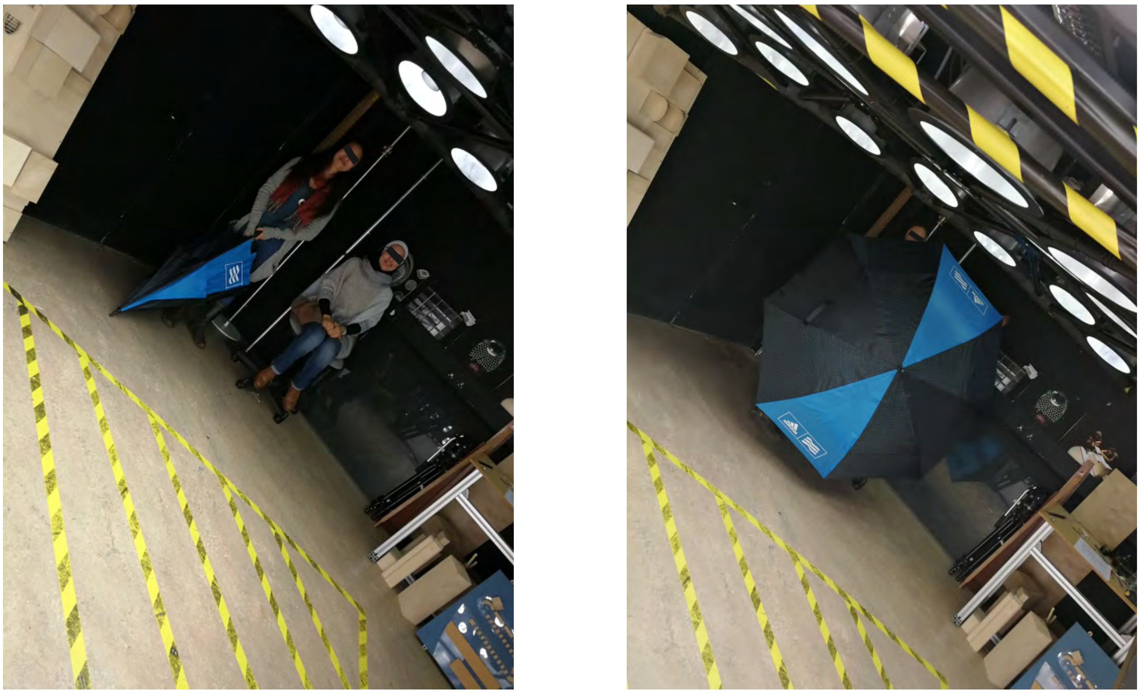
(a) Starting point from 90°.

(b) Recording the angle.

Figure 3.33: Using the compass to record rotation angles.

The human subjects in this experiment are recruited to test three screens in the three cases, which gives a total of nine stages. For each case, the subject sets on a chair at a specific distance away from the screen according to each case's privacy scenario, cases are explained in Section 3.4.3, and Figures 3.17, 3.18 & 3.19.

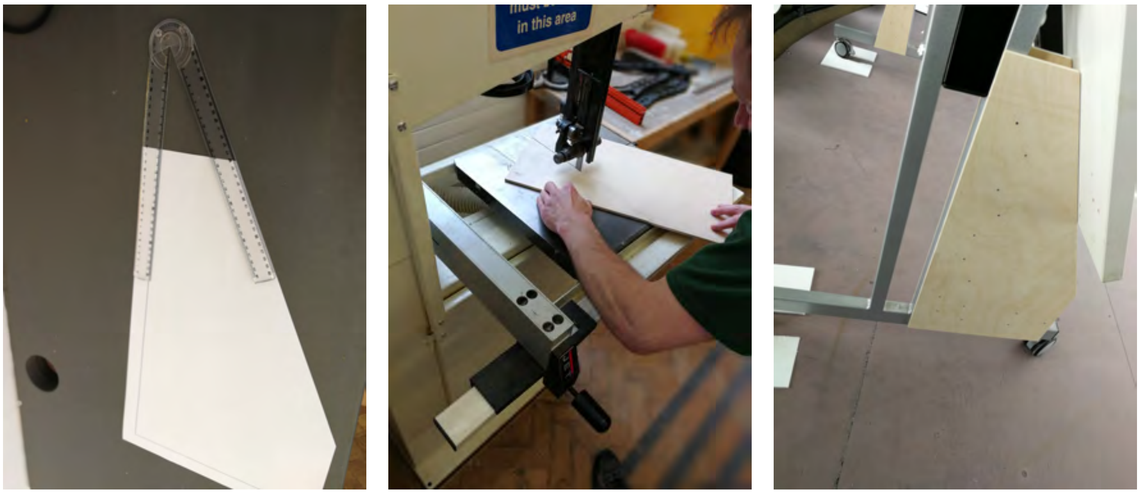
One by one, subjects are asked to declare whether they are able to recognise the image behind the screen. Starting from a 90° angle where it is impossible to view anything through the opening (Figure 3.33a). The examiner starts to rotate the screen slowly until the subjects ask him to stop, as they wished to make a guess about the image behind the screen. Subjects are able to make any number of guesses until the image is recognised, and then this tilting angle of the screen is recorded by the examiner (Figure 3.33). These steps are repeated for every screen in every case with each subject. When changing screens and images, the assistant has to make sure that subjects do not have any view to any of the images by placing a big dark umbrella in front of them (Figure 3.34).


(a) The assistant holding the umbrella.

(b) The subject is covered.

Figure 3.34: Blocking the view of the subject with a large umbrella during the transition between each case during the experiment.

in order to reduce the total time for experiment, the transition between cases is designed to be as smooth and fast as possible. Two pieces of timber are cut by the examiner to represent the required angle to tilt the box to replicate each case (Figure 3.35), and either one of them is able to be positioned easily between the bottom of the table plain and table legs. To make the transition from one case to



(a) Measuring the angle. (b) Construction. (c) Attached under table.

Figure 3.35: Controlling the tilt angle of the table for each case.

another, the examiner or his assistant positions the required piece or removed it according to the required case. Figure 3.35c displays an example of the piece that is used to represent the 29° in case-1 (Figure 3.20).

Environment

This experiment took place under the Sky-Dome, which is an artificial sky facility in the Welsh School of Architecture. It contains 640 luminaires (Philips CL 4500K) mounted within an open geodesic framework. It can produce up to $7,000lx$ (*WSA website* 2018) (Figure 3.4). As explained in Section 3.4.4, in order to control the illuminance contrast between inside the box and outdoor, the sky-dome output is set to achieve the same DF when using the same screen configuration for each studied screen the DF used to control the illuminance contrast is assigned later in the Research chapter (Chapter 4).

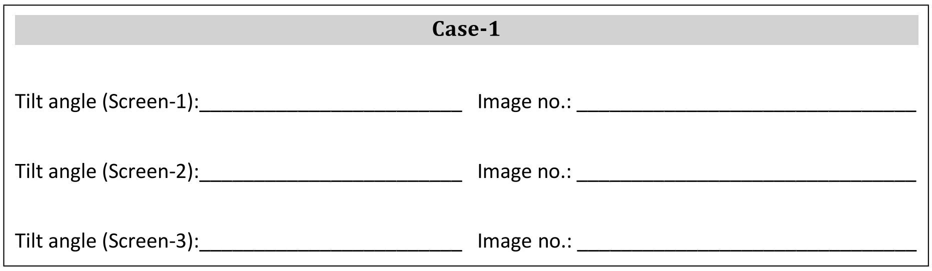
The Sky-Dome is required to be used by other architecture students during the period of the experimentation and therefore, sometimes it is necessary to remove the box to allow other students to work on their projects. Therefore, foam boards are cut as a mask and fixed on the floor to mark the exact position of the table wheels (Figure 3.36). The ease of movement and control position is one of the main reasons to attach the box on a table with wheels. A mirror is used in some cases to compensate for distance shortages when the space is not wide enough to replicate the privacy breach scenarios, this is a typical practice in optometry testing (Jackson and Bailey 2004).

Figure 3.36: Masks on the floor to mark wheels positioning.

The questionnaire

The data collection sheet has two parts, the first part is to be completed by the subjects and contains questions about their backgrounds, gender, age group and number of children. Details of the number of children is also given in this part regarding their gender and whether they are in school age or not. All of these data are compared at the end to see if they have any effect on the results.

The second part of the sheet is to be completed by the examiner. At first, the result of the visual acuity test is recorded. Then using responses form subjects, the angles of screen rotation that allowed visibility is recorded by the examiner for each tested screen in each privacy case. The three privacy cases were explained in Section 3.4.4. The image number of the Kay picture used for each test is also recorded to see if there is an effect by the image used on the result. The assigned image numbers to each Kay picture are displayed in Table 3.14. The questionnaire used to collect data from subjects and report responses of subjects is included in Appendix E. As an example, a part of the questionnaire is displayed in Figure 3.37.



Case-1

Tilt angle (Screen-1):________________________ Image no.: _______________________________

Tilt angle (Screen-2):________________________ Image no.: _______________________________

Tilt angle (Screen-3):________________________ Image no.: _______________________________

Figure 3.37: Part of the data sheet collecting data from answers of subjects.

3.5.7 Summary

This chapter started with discussing the literature review outcomes and listing the options of methods to conduct the research. The options are analysed to select the appropriate methods to achieve the research aim and objectives. Then the work flow of the research is presented explaining the field work to collect required data to prepare CBDM variables and to prepare privacy breaching scenarios.

The work flow also explains the phases and experiments of the research. The research methods of the research is also explained including the used metrics to simulate and analyse indoor daylight which is used in all indoor daylight experiments in this research, and how the results of daylight simulation are presented. Research methods include also details and experimental settings of the privacy study.

CHAPTER 4

Research

4.1 Introduction

This chapter presents the experiments of this research spread over four phases as explained in the work flow of the research in Figure 3.6. A virtual simulation method is used for three phases, one, two and four, whereas in phase three an experiment with a human subject is used to assess the visibility of objects behind screens and thus the privacy aspect of screens. The results of daylight simulations are presented according to the results presenting methods (explained in Section 3.5.4).

Phase one contains four experiments for the following parameters: perforation percentages, depth ratio, cell size and opening aspect ratio. Parameters are studied one at a time according to the selected simulation process identified in Chapter 3. Phase two aims to check whether or not the selected sequence of experiments has an effect on the result, by repeating experiments on the perforation percentage using the results of phase one. In phase three, the results of phase two are used to create three screens and test the effect of the tilting angle of screens providing privacy for the occupants of buildings viewed through screened windows. In phase four, the results and recommended screen tilt angles are used in a virtual daylight simulation to test the interior daylight levels when using the screens that maintained privacy. At the end, the result of the last experiment is compared with the results of vertical screens that achieved acceptable interior daylight levels without tilting, as well as the base case with windows without any solar screens.

4.2 Phase one: The effect of four parameters on indoor daylight

Four parameters of perforated solar screens are tested in this phase, facing the four main orientations, using daylight simulation methods reporting the average illuminance and the DAv metrics as explained in Chapter 3. Parameters are tested one at a time in this order: perforation percentage, depth ratio, cell module size and aspect ratio. The results of testing each parameter are displayed in tables and charts. The result of studying each parameter is used to control successive parameters until the last experiment in this phase is reached. At the end, the recommended values of all of the four parameters are represented in a table as the final result of this phase.

4.2.1 The effect of perforation percentage

The objective of this experiment is to define the recommended perforation percentages for perforated solar screens in order to enhance interior daylighting for the main orientations in the context of schools in hot arid areas. Creating a method that can be used to study perforated screens in any location. Previous studies have already investigated the effect of different values of perforation percentage on the performance of perforated solar screens on daylight in living rooms of residential spaces; Sherif et al. (2012b) have studied the effect on indoor daylight levels and on energy load (Sherif et al. 2010). However, results are expected to be different for educational spaces, due to different illuminance requirements, different window to wall ratio, space size, dimensions and hours of occupancy when compared with residential spaces.

Variation of the parameter

Each perforated screen has a perforation percentage. To explain the perforation percentage, a screen is divided in a module grid, and the perforation percentage is calculated considering the module grid and the size of a perforation. It represents the percentage of the size of each perforation to the cell module size. For example, Figure 4.1 presents an example of two screens with different perforation percentages, 90% in the left screen, 50% in the screen shown on the right, but having the same module grid, thus, the same cell module size ($6cm \times 6cm$). The parameter of perforation percentage is tested in a range of cases from 10% to 90% in 10% intervals; results are juxtaposed against those of a case of a window where no screens are used.

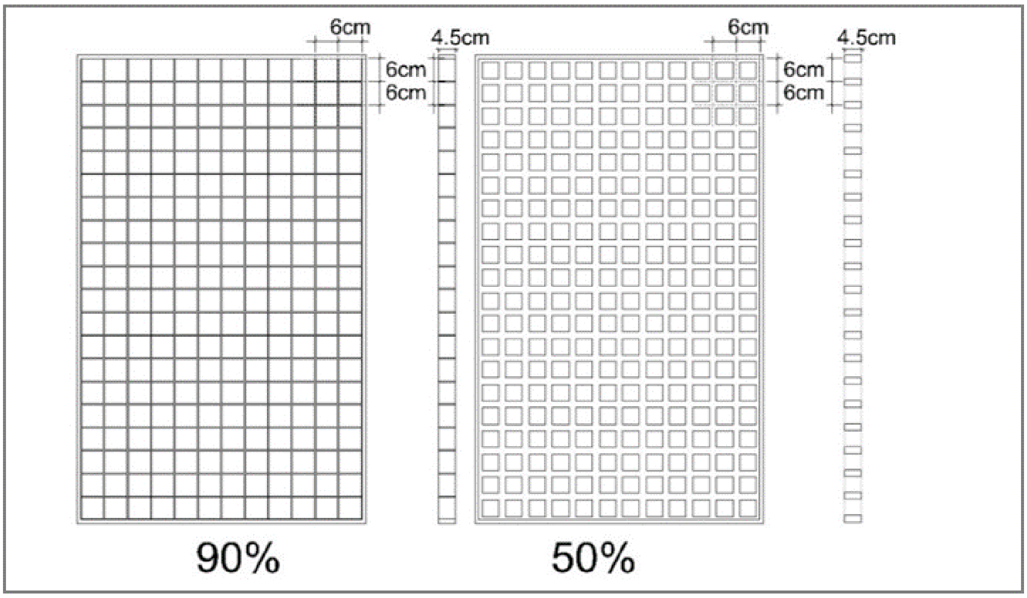


Figure 4.1: Elevations and sections of examples of 50% perforation percentage on the right and 90% perforation percentage on the left.

Controlled parameters

To study the effect of perforation percentage, all other parameters are controlled; Table 4.1 presents the controlled screen parameters. Values of depth ratio are controlled to 0.75 according to results of previous publications in similar climates (Sherif et al. 2011), and was also used to control depth ratio by Sabry et al. (2014). Cell module size is controlled using 6*cm* as a starting point since it has not been studied before; the 6*cm* is used as a module as it gives flexibility for further investigation of aspect ratio. The opening aspect ratio is controlled using 1:1 aspect ratio (square cells) as a starting point. Previous research of a similar nature started with square cells to control aspect ratio when testing parameters of perforated solar screens (Chi et al. 2017; Sabry et al. 2011; Sherif et al. 2012b).

Table 4.1: Values of all parameters when testing perforation percentage.

	Controlled screen parameters		
Orientation	Depth ratio	Aspect ratio	cell module size
south	0.75	1:1	$6cm$
east	0.75	1:1	$6cm$
north	0.75	1:1	$6cm$
east	0.75	1:1	$6cm$

4.2.2 Results

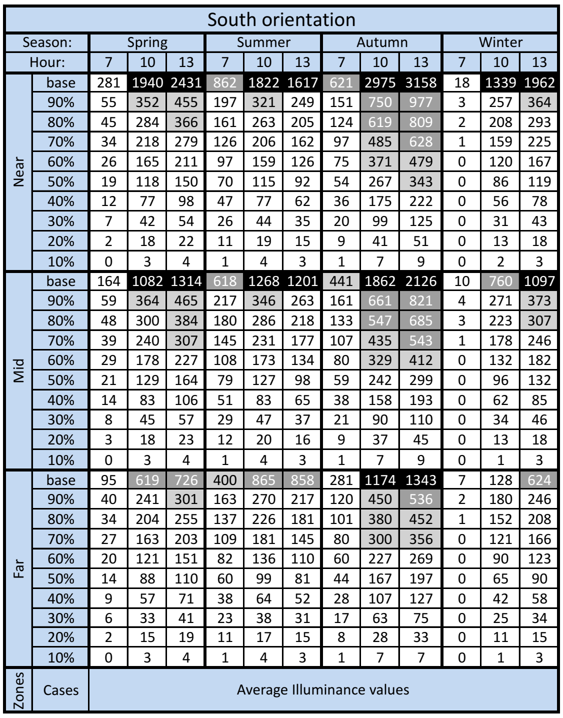
The results of the two daylight metrics: average illuminance and Daylight Availability are displayed and discussed for each of the four main orientations.

Average illuminance levels

The results of simulating average illuminance levels are presented in Table 4.2. In the majority of cases, the average illuminance levels in the Mid zones increase dramatically and become even higher than in the Near zones with the use of solar screens compared with base cases with no screen, because the solar screens are able to reduce the high illuminance values on the Near zones which could improve the distribution. In some extreme cases, average illuminance levels in the Mid zone are almost double the levels in the Near zone especially in spring and winter in all orientations, which means that screens are able to emit daylight deeper into the space. The only exception to that is at 10:00 in autumn in the east orientation where the average illuiminance in the Near zone remains higher that average illuminance in the Mid zone, however, this is only one case out of 50 cases and the increase is only about 3%.

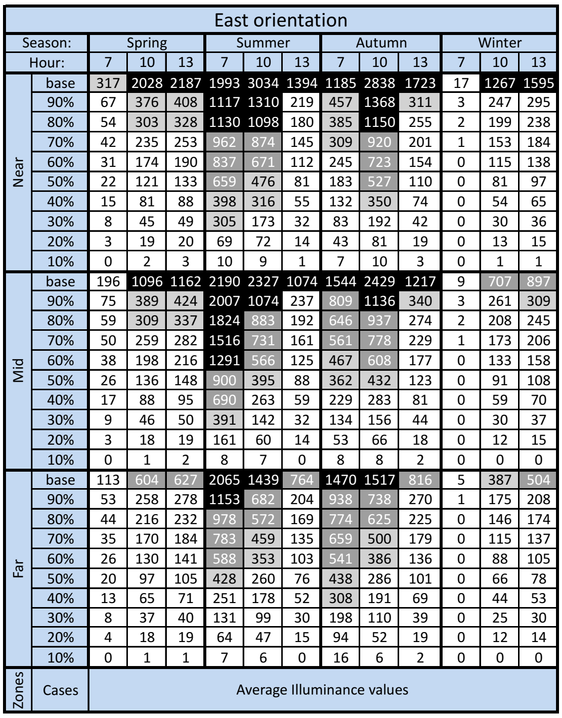
Results also show that using perforated screens in most cases succeeds in reducing the high illuminance values that could supply discomfort glare (above $1000lx$) into an acceptable level (300–$500lx$) especially in Near and Mid zones, except in winter and early hours of spring in all orientations. In the later cases, using perfo-

Table 4.2: Average illuminance (lx) for perforation percentage cases in the three zones of each orientation (black cells, $\geq 1000lx$; grey cells, between $500lx$ and $999lx$; light grey between $300lx$ and $499lx$).



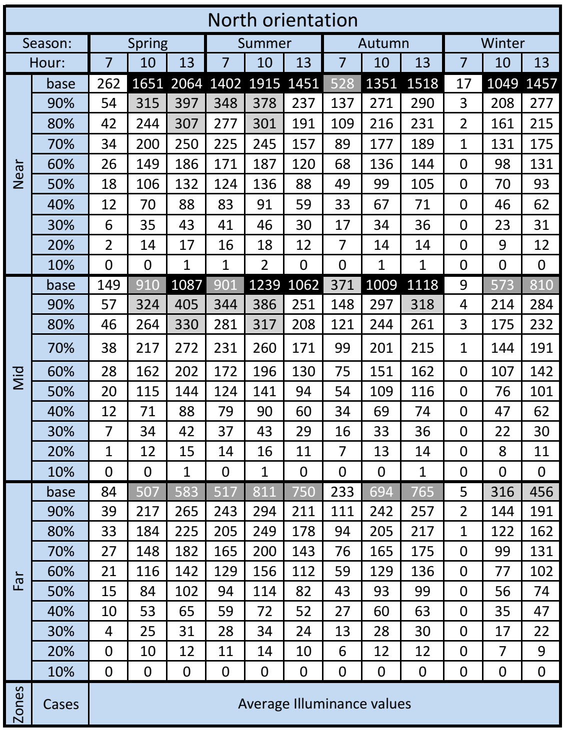
South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	90%	55	352	455	197	321	249	151	750	977	3	257	364
	80%	45	284	366	161	263	205	124	619	809	2	208	293
	70%	34	218	279	126	206	162	97	485	628	1	159	225
	60%	26	165	211	97	159	126	75	371	479	0	120	167
	50%	19	118	150	70	115	92	54	267	343	0	86	119
	40%	12	77	98	47	77	62	36	175	222	0	56	78
	30%	7	42	54	26	44	35	20	99	125	0	31	43
	20%	2	18	22	11	19	15	9	41	51	0	13	18
	10%	0	3	4	1	4	3	1	7	9	0	2	3
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	90%	59	364	465	217	346	263	161	661	821	4	271	373
	80%	48	300	384	180	286	218	133	547	685	3	223	307
	70%	39	240	307	145	231	177	107	435	543	1	178	246
	60%	29	178	227	108	173	134	80	329	412	0	132	182
	50%	21	129	164	79	127	98	59	242	299	0	96	132
	40%	14	83	106	51	83	65	38	158	193	0	62	85
	30%	8	45	57	29	47	37	21	90	110	0	34	46
	20%	3	18	23	12	20	16	9	37	45	0	13	18
	10%	0	3	4	1	4	3	1	7	9	0	1	3
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	90%	40	241	301	163	270	217	120	450	536	2	180	246
	80%	34	204	255	137	226	181	101	380	452	1	152	208
	70%	27	163	203	109	181	145	80	300	356	0	121	166
	60%	20	121	151	82	136	110	60	227	269	0	90	123
	50%	14	88	110	60	99	81	44	167	197	0	65	90
	40%	9	57	71	38	64	52	28	107	127	0	42	58
	30%	6	33	41	23	38	31	17	63	75	0	25	34
	20%	2	15	19	11	17	15	8	28	33	0	11	15
	10%	0	3	4	1	4	3	1	7	7	0	1	3
Zones	Cases	Average Illuminance values											

(a) South orientation.



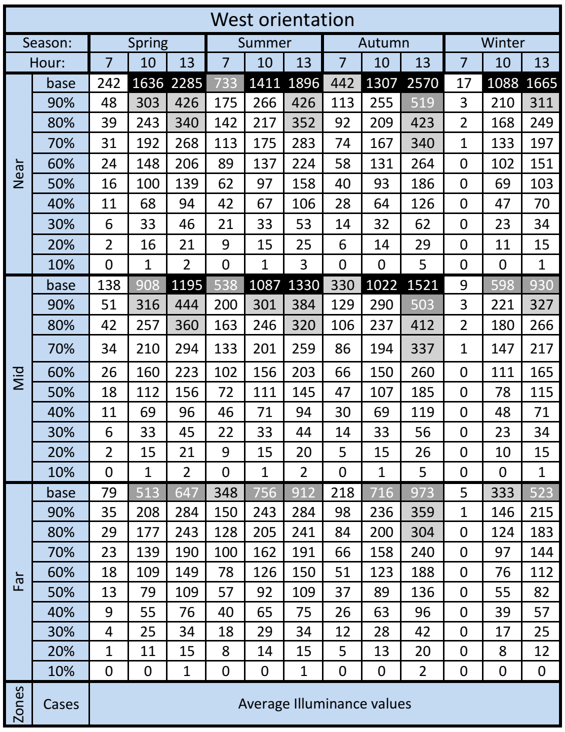
East orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	317	2028	2187	1993	3034	1394	1185	2838	1723	17	1267	1595
	90%	67	376	408	1117	1310	219	457	1368	311	3	247	295
	80%	54	303	328	1130	1098	180	385	1150	255	2	199	238
	70%	42	235	253	962	874	145	309	920	201	1	153	184
	60%	31	174	190	837	671	112	245	723	154	0	115	138
	50%	22	121	133	659	476	81	183	527	110	0	81	97
	40%	15	81	88	398	316	55	132	350	74	0	54	65
	30%	8	45	49	305	173	32	83	192	42	0	30	36
	20%	3	19	20	69	72	14	43	81	19	0	13	15
	10%	0	2	3	10	9	1	7	10	3	0	1	1
Mid	base	196	1096	1162	2190	2327	1074	1544	2429	1217	9	707	897
	90%	75	389	424	2007	1074	237	809	1136	340	3	261	309
	80%	59	309	337	1824	883	192	646	937	274	2	208	245
	70%	50	259	282	1516	731	161	561	778	229	1	173	206
	60%	38	198	216	1291	566	125	467	608	177	0	133	158
	50%	26	136	148	900	395	88	362	432	123	0	91	108
	40%	17	88	95	690	263	59	229	283	81	0	59	70
	30%	9	46	50	391	142	32	134	156	44	0	30	37
	20%	3	18	19	161	60	14	53	66	18	0	12	15
	10%	0	1	2	8	7	0	8	8	2	0	0	0
Far	base	113	604	627	2065	1439	764	1470	1517	816	5	387	504
	90%	53	258	278	1153	682	204	938	738	270	1	175	208
	80%	44	216	232	978	572	169	774	625	225	0	146	174
	70%	35	170	184	783	459	135	659	500	179	0	115	137
	60%	26	130	141	588	353	103	541	386	136	0	88	105
	50%	20	97	105	428	260	76	438	286	101	0	66	78
	40%	13	65	71	251	178	52	308	191	69	0	44	53
	30%	8	37	40	131	99	30	198	110	39	0	25	30
	20%	4	18	19	64	47	15	94	52	19	0	12	14
	10%	0	1	1	7	6	0	16	6	2	0	0	0
Zones	Cases	Average Illuminance values											

(b) East orientation.



North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	90%	54	315	397	348	378	237	137	271	290	3	208	277
	80%	42	244	307	277	301	191	109	216	231	2	161	215
	70%	34	200	250	225	245	157	89	177	189	1	131	175
	60%	26	149	186	171	187	120	68	136	144	0	98	131
	50%	18	106	132	124	136	88	49	99	105	0	70	93
	40%	12	70	88	83	91	59	33	67	71	0	46	62
	30%	6	35	43	41	46	30	17	34	36	0	23	31
	20%	2	14	17	16	18	12	7	14	14	0	9	12
	10%	0	0	1	1	2	0	0	1	1	0	0	0
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	90%	57	324	405	344	386	251	148	297	318	4	214	284
	80%	46	264	330	281	317	208	121	244	261	3	175	232
	70%	38	217	272	231	260	171	99	201	215	1	144	191
	60%	28	162	202	172	196	130	75	151	162	0	107	142
	50%	20	115	144	124	141	94	54	109	116	0	76	101
	40%	12	71	88	79	90	60	34	69	74	0	47	62
	30%	7	34	42	37	43	29	16	33	36	0	22	30
	20%	1	12	15	14	16	11	7	13	14	0	8	11
	10%	0	0	1	0	1	0	0	0	1	0	0	0
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	90%	39	217	265	243	294	211	111	242	257	2	144	191
	80%	33	184	225	205	249	178	94	205	217	1	122	162
	70%	27	148	182	165	200	143	76	165	175	0	99	131
	60%	21	116	142	129	156	112	59	129	136	0	77	102
	50%	15	84	102	94	114	82	43	93	99	0	56	74
	40%	10	53	65	59	72	52	27	60	63	0	35	47
	30%	4	25	31	28	34	24	13	28	30	0	17	22
	20%	0	10	12	11	14	10	6	12	12	0	7	9
	10%	0	0	0	0	0	0	0	0	0	0	0	0
Zones	Cases	Average Illuminance values											

(c) North orientation.



West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	90%	48	303	426	175	266	426	113	255	519	3	210	311
	80%	39	243	340	142	217	352	92	209	423	2	168	249
	70%	31	192	268	113	175	283	74	167	340	1	133	197
	60%	24	148	206	89	137	224	58	131	264	0	102	151
	50%	16	100	139	62	97	158	40	93	186	0	69	103
	40%	11	68	94	42	67	106	28	64	126	0	47	70
	30%	6	33	46	21	33	53	14	32	62	0	23	34
	20%	2	16	21	9	15	25	6	14	29	0	11	15
	10%	0	1	2	0	1	3	0	0	5	0	0	1
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	90%	51	316	444	200	301	384	129	290	503	3	221	327
	80%	42	257	360	163	246	320	106	237	412	2	180	266
	70%	34	210	294	133	201	259	86	194	337	1	147	217
	60%	26	160	223	102	156	203	66	150	260	0	111	165
	50%	18	112	156	72	111	145	47	107	185	0	78	115
	40%	11	69	96	46	71	94	30	69	119	0	48	71
	30%	6	33	45	22	33	44	14	33	56	0	23	34
	20%	2	15	21	9	15	20	5	15	26	0	10	15
	10%	0	1	2	0	1	2	0	1	5	0	0	1
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	90%	35	208	284	150	243	284	98	236	359	1	146	215
	80%	29	177	243	128	205	241	84	200	304	0	124	183
	70%	23	139	190	100	162	191	66	158	240	0	97	144
	60%	18	109	149	78	126	150	51	123	188	0	76	112
	50%	13	79	109	57	92	109	37	89	136	0	55	82
	40%	9	55	76	40	65	75	26	63	96	0	39	57
	30%	4	25	34	18	29	34	12	28	42	0	17	25
	20%	1	11	15	8	14	15	5	13	20	0	8	12
	10%	0	0	1	0	0	1	0	0	2	0	0	0
Zones	Cases	Average Illuminance values											

(d) West orientation.

rated screens reduces the illuminance to below $300lx$ (Table 4.2). Illuminance levels however, are very low in the Far zone in most of the cases when using perforated screens, except for east and south orientation in autumn and summer, and afternoon in autumn for east orientation.

Daylight distribution and spatial distribution of illuminance are also improved in the Far zone. Although illuminance levels do not become higher than levels of the Near zone, the ratio between illuminance in Far and Near zones is improved with the use of perforated screens when compared with the same ratio in cases of windows without screens. To understand this more clearly, results tables are used to calculate a ratio between illuminance in zones when using perforated screens compared with the same ratio of the same zones when no screen is attached, using Equation 4.1:

$$Ratio = \frac{F_{(lx)}}{N_{(lx)}} \times 100 \;\; or \;\; \frac{M_{(lx)}}{N_{(lx)}} \times 100 \tag{4.1}$$

Where: $M_{(lx)}$ is the average illuminance in the Mid zone of the required case in the hour of interest, $N_{(lx)}$ is the average illuminance in the Near zone of the same case in the same hour and $F_{(lx)}$ is the illuminance in the Far zone of the same case in the same hour. This ratio is called the spatial distribution ratio hereafter.

To compare this ratio between cases in order to confirm how spatial daylight distribution is improved in the Far and Mid zones, equation: 4.1 is used for each average illuminance level of each simulated hour to create Tables 4.3 and 4.4. These tables aim to compare results of 90% perforation percentage and results for a window with no screen for south and east cases, and north and west cases respectively using the spatial distribution ratio. Tables display the difference between the ratio of each case in bold font. If the difference is in minus (red cells) then the spatial distribution ratio with no screen is higher.

Table 4.3: Comparing spatial distribution ratio between zones with and without using perforated screens of 90% perforation percentage in south and east orientations (red cells represent where that the ratio without screen was higher than when using screens).

		South orientation												East orientation											
		Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	58	56	54	72	70	74	71	63	67	56	57	56	62	54	53	110	77	77	130	86	71	56	56	56
	90% screen	106	103	102	110	108	106	107	88	84	128	105	103	111	103	104	180	82	108	177	83	109	112	106	105
	difference	**47**	**48**	**48**	**39**	**38**	**31**	**36**	**26**	**17**	**72**	**48**	**47**	**49**	**49**	**51**	**70**	**5**	**31**	**47**	**-3**	**39**	**55**	**50**	**48**
Far / Near x100	noscreen	34	32	30	46	47	53	45	39	43	37	10	32	36	30	29	104	47	55	124	53	47	32	31	32
	90% screen	72	68	66	83	84	87	79	60	55	63	70	68	78	69	68	103	52	93	205	54	87	41	71	70
	difference	**38**	**37**	**36**	**36**	**36**	**34**	**34**	**21**	**12**	**27**	**60**	**36**	**43**	**39**	**39**	**-1**	**5**	**38**	**81**	**1**	**39**	**9**	**40**	**39**

Table 4.4: Comparing spatial distribution ratio between zones with and without using perforated screens of 90% perforation percentage in north and west orientations.

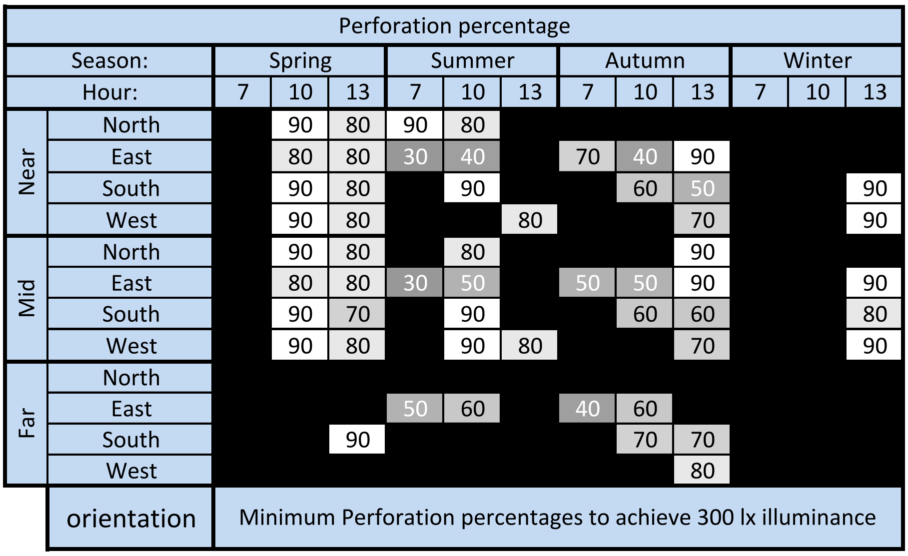
		West orientation												North orientation											
		Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	57	56	52	73	77	70	75	78	59	53	55	56	57	55	53	64	65	73	70	75	74	53	55	56
	90% screen	106	104	104	114	113	90	114	114	97	114	105	105	105	103	102	99	102	106	108	110	110	116	103	102
	difference	**49**	**49**	**52**	**41**	**36**	**20**	**39**	**36**	**38**	**61**	**50**	**49**	**48**	**48**	**49**	**35**	**38**	**33**	**37**	**35**	**36**	**63**	**49**	**47**
Far / Near x100	noscreen	32	31	28	47	54	48	49	55	38	32	31	31	32	31	28	37	42	52	44	51	50	29	30	31
	90% screen	71	69	67	86	91	67	87	92	69	45	69	69	72	69	67	70	78	89	81	90	89	57	69	69
	difference	**39**	**37**	**38**	**38**	**38**	**18**	**38**	**38**	**31**	**14**	**39**	**38**	**40**	**38**	**38**	**33**	**36**	**37**	**37**	**38**	**38**	**28**	**39**	**38**

Results show that the spatial distribution ratio between Mid and Near zones is notably increased with the use of screens in all cases except one at 10:00 in autumn (highlighted in red). Similar results are found also between the Far and Near zones; the ratio increases in all cases except one at 07:00 in summer in the east. that is only 2 cases out of 48 which is remarkable.

It is also noticed that using perforated screens on the north and west orientations reduces the illuminance sharply since the direct sunlight on these orientations is minimal due to the latitude of the location, during the occupancy hours concerned here (afternoon hours are excluded from this analysis). Even when using higher perforation percentages, 90% perforation also reduces illuminance sharply in west and north orientations (Tables 4.2c & 4.2d). This gives an indication that testing other parameters is essential in pursuing the provision of better better daylighting with the use of perforated solar screens.

Illuminance values also helped to produce Table 4.5 that indicates the minimum recommended perforation percentages to be used as a tool to help architects to decide the perforation percentage required according to the orientation and times of use for school classrooms in spaces with similar areas and dimensions at similar contexts. Although this table can only be used when other parameters are controlled by using the same values used in this experiment (e.g. Depth ratio of 0.75), the method developed in this research can be used to produce similar tables for any context in any location.

Table 4.5: Minimum recommended perforation percentages to achieve the target illuminance (300lx) in all studied cases and zones for specific times throughout the year. (black cells represent cases that 300lx cannot be achieved with daylight alone, lighter cells represent higher perforation percentages.)



Perforation percentage													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	North	■	90	80	90	80	■	■	■	■	■	■	■
	East	■	80	80	30	40	■	70	40	90	■	■	■
	South	■	90	80	■	90	■	■	60	50	■	■	90
	West	■	90	80	■	■	80	■	■	70	■	■	90
Mid	North	■	90	80	■	80	■	■	■	90	■	■	■
	East	■	80	80	30	50	■	50	50	90	■	■	90
	South	■	90	70	■	90	■	■	60	60	■	■	80
	West	■	90	80	■	90	80	■	■	70	■	■	90
Far	North	■	■	■	■	■	■	■	■	■	■	■	■
	East	■	■	■	50	60	■	40	60	■	■	■	■
	South	■	■	90	■	■	■	■	70	70	■	■	■
	West	■	■	■	■	■	■	■	■	80	■	■	■
	orientation	Minimum Perforation percentages to achieve 300 lx illuminance											

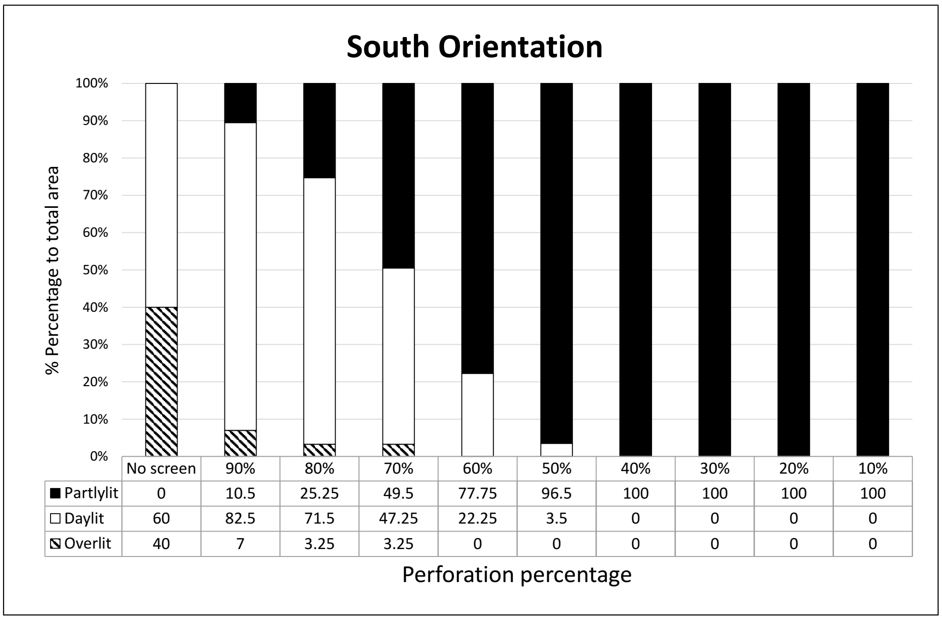
The table is also useful for zoning and controlling mechanisms for artificial lighting installations as it indicates the hours and zones that daylight illuminance is not sufficient when using perforated screens with associated parameter values, thus, artificial light is needed. For example: 7:00 in spring and winter for all zones of all orientations; 10:00 in winter in all zones of all orientations; and most cases in the Far zone, which can indicate that additional artificial lighting fixtures are needed also at Far zones than at other zones.

Results also show that some cases provide average illuminance of more than 2000lx without knowing if the area is considered as Overlit or Daylit, which explains the necessity for the next stage of the research. Further investigation is required to clearly understand the situation, using CBDM simulation and analysing data using Daylight Availability metric, one of the Dynamic Daylight Performance Metrics (DDPMs).

Daylight Availability

The results of the light simulating using DAv in this experiment, are presented in Tables 4.6, 4.7, 4.8 & 4.9 and Figures 4.2, 4.3, 4.4 & 4.5.

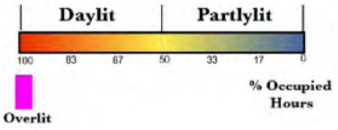
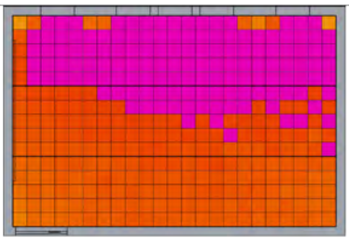
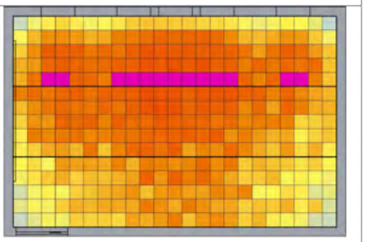
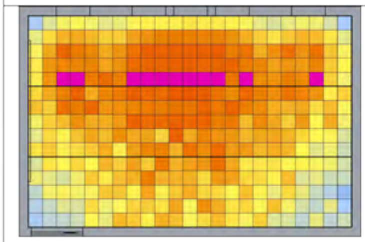
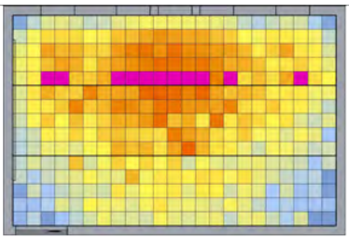
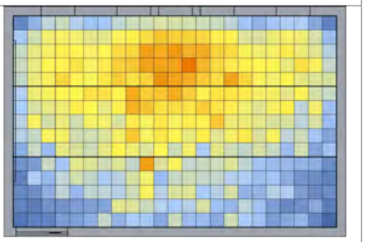
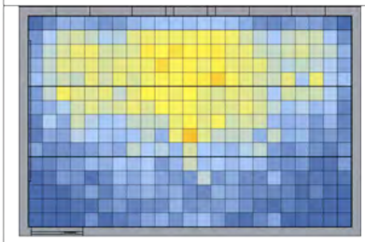
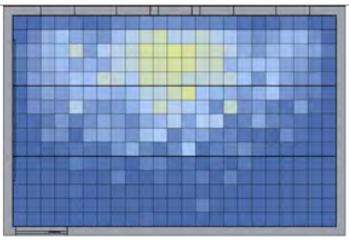
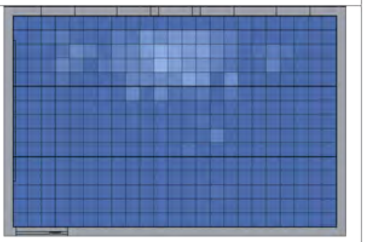
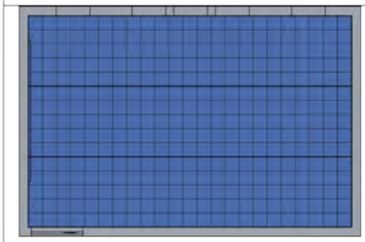
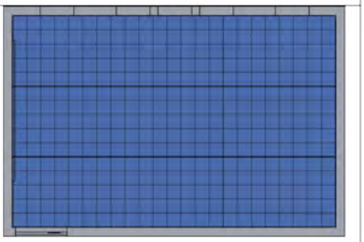
In the south orientation, a 90% perforation percentage achieves better Daylight Availability than other perforation percentages, and an 80% perforation percentage also achieves an acceptable result of a 71.5% Daylit area of the total area (Figure 4.2) and (Table 4.6).



	No screen	90%	80%	70%	60%	50%	40%	30%	20%	10%
■ Partlylit	0	10.5	25.25	49.5	77.75	96.5	100	100	100	100
□ Daylit	60	82.5	71.5	47.25	22.25	3.5	0	0	0	0
▨ Overlit	40	7	3.25	3.25	0	0	0	0	0	0

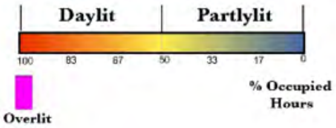
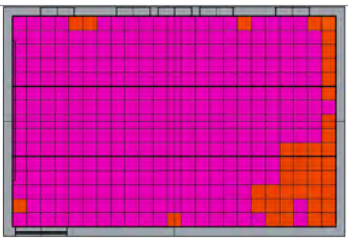
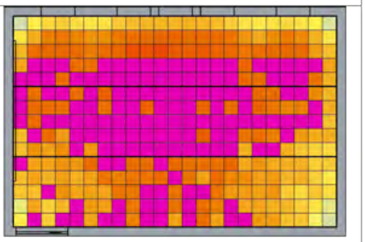
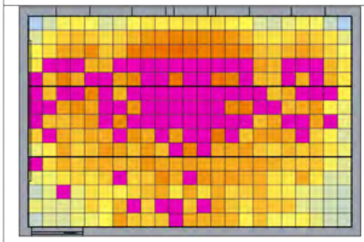
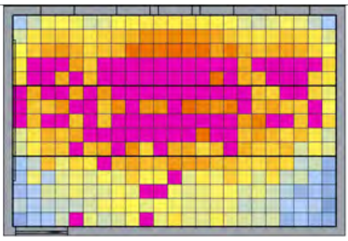
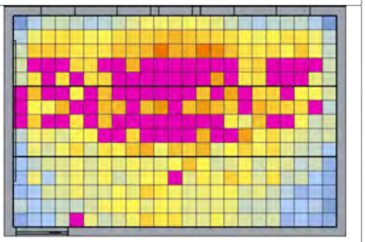
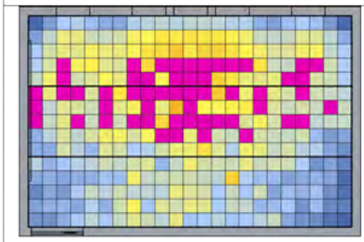
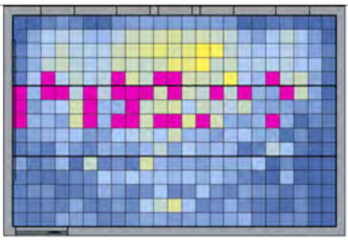
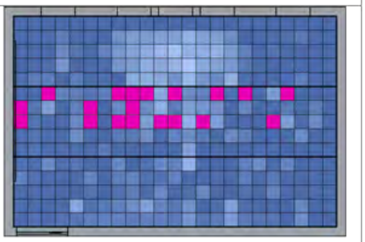
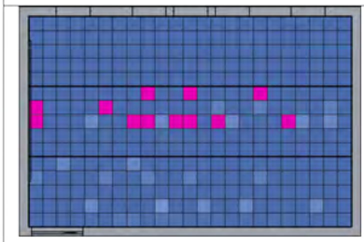
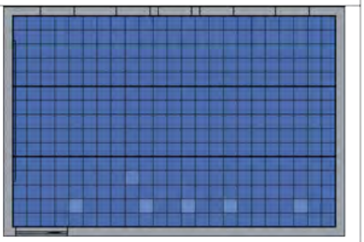
Figure 4.2: DAv of perforation percentage cases for the south orientation.

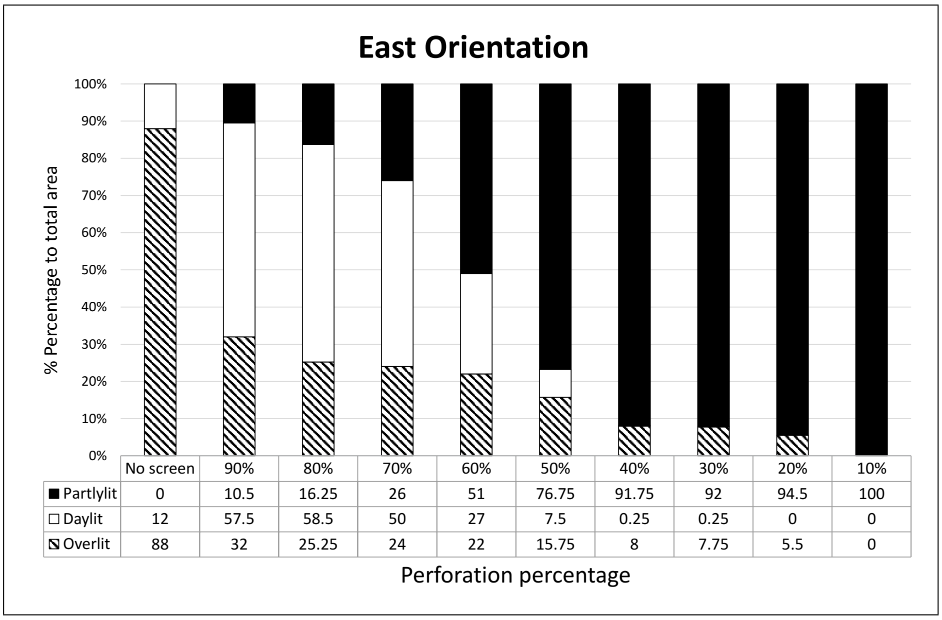
Table 4.6: Distribution of DAv on the classroom plan for the south orientation with different perforation percentages (windows are located on the top side of the plan).

South Orientation		
Perforation percentage	No screen	90%
		
80%	70%	60%
		
50%	40%	30%
		
20%	10%	
		

For the east orientation, an 80% perforation percentage achieves more Daylit area than any other perforation percentages in the east orientation; 90% & 70% perforation percentages also provide acceptable Daylit area of more than 50% of the total area (Figure 4.3 and Table 4.7). Results show a linear increase of the Partlylit area and decrease of the Overlit area for south and east orientations, when decreasing the perforation percentage (Figures 4.2 & 4.3).

Table 4.7: Distribution of DAv on the classroom plan for the east orientation with different perforation percentages (windows are located on the top side of the plan).

<table>
<tr><th colspan="3">East Orientation</th></tr>
<tr><td>Perforation percentage</td><td>No screen</td><td>90%</td></tr>
<tr><td>
</td><td></td><td></td></tr>
<tr><td>80%</td><td>70%</td><td>60%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>50%</td><td>40%</td><td>30%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>20%</td><td>10%</td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

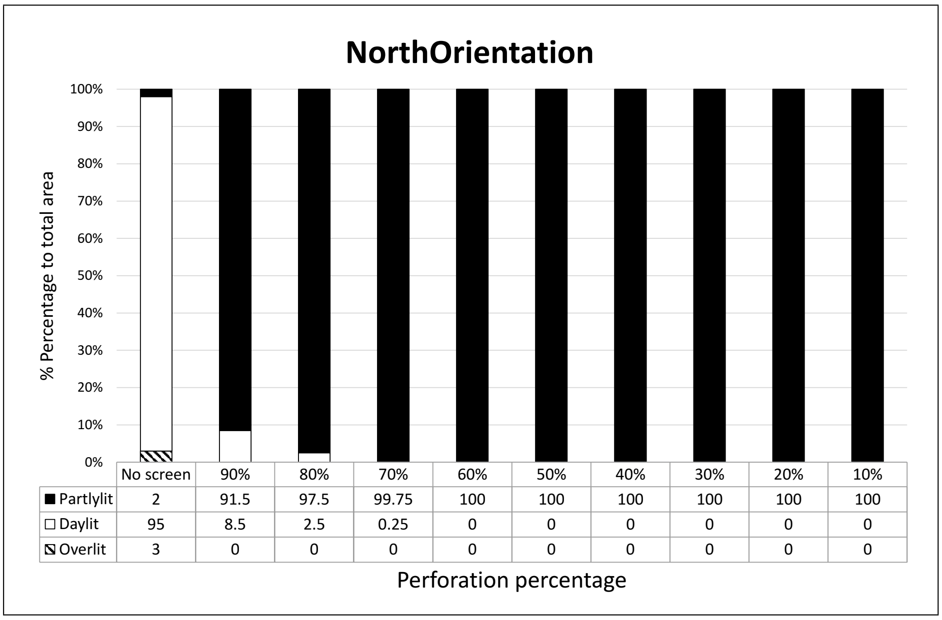


	No screen	90%	80%	70%	60%	50%	40%	30%	20%	10%
■ Partlylit	0	10.5	16.25	26	51	76.75	91.75	92	94.5	100
□ Daylit	12	57.5	58.5	50	27	7.5	0.25	0.25	0	0
▧ Overlit	88	32	25.25	24	22	15.75	8	7.75	5.5	0

Figure 4.3: DAv of perforation percentage cases for the east orientation.

Similar to the previous stage and for the same reasons, results also show that using perforated screens on the west and north orientations reduce the Daylit area to unacceptable levels to less than 50% of the total area, which is problematic and does not meet the criteria. Even with the use of the highest perforation percentage (90%) the daylit area is still as low as 8.5% in north and 12.5% in east as shown in Figure 4.4 and Figure 4.5 respectively.

In general, it appears that Overlit area is reduced in all orientations with the use of solar screens, which means using solar screens would reduce direct sunlight penetration and potential discomfort glare accordingly.



	No screen	90%	80%	70%	60%	50%	40%	30%	20%	10%
■ Partlylit	2	91.5	97.5	99.75	100	100	100	100	100	100
□ Daylit	95	8.5	2.5	0.25	0	0	0	0	0	0
▨ Overlit	3	0	0	0	0	0	0	0	0	0

Figure 4.4: DAv of perforation percentage cases for the north orientation.

Table 4.8: Distribution of DAv on the classroom plan for the north orientation with different perforation percentages (windows are located on the top side of the plan).

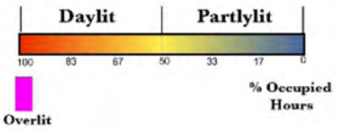
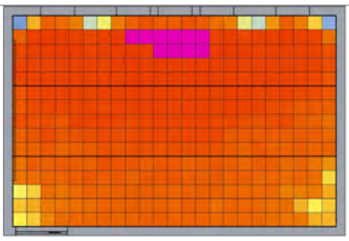
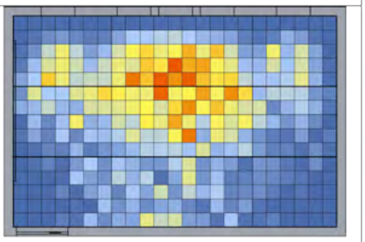
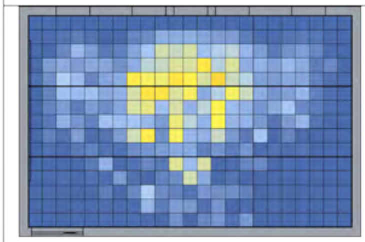
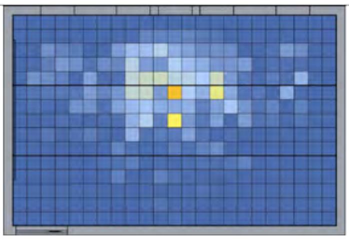
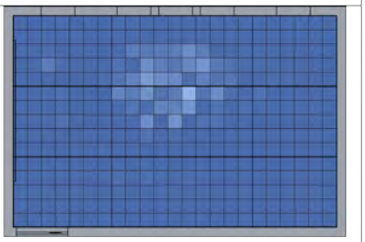
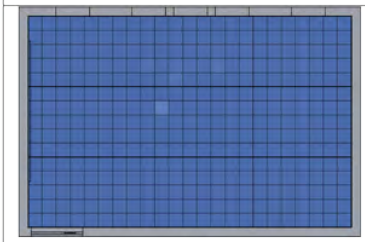
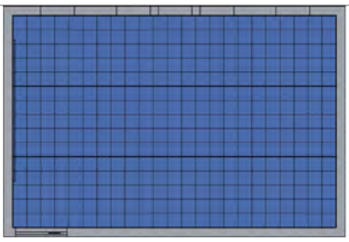
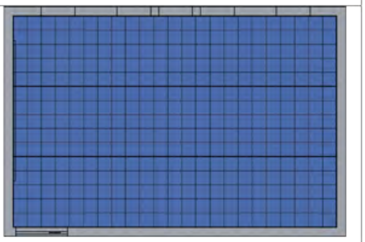
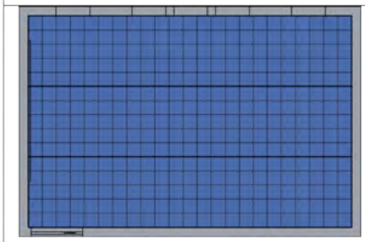
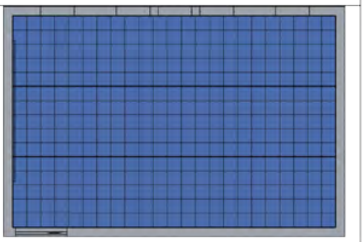
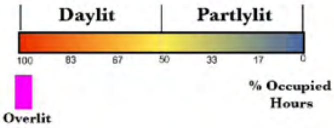
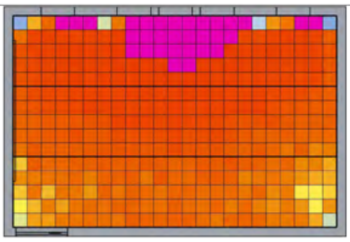
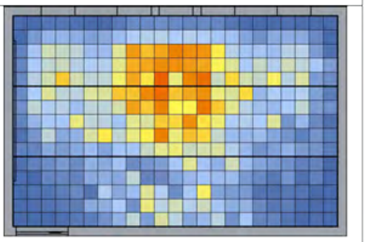
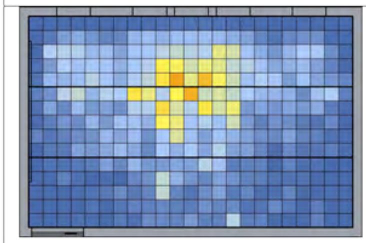
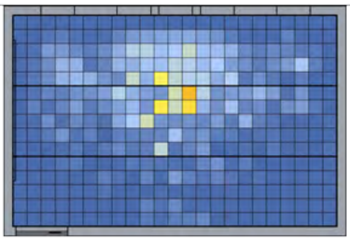
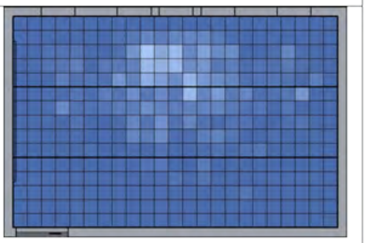
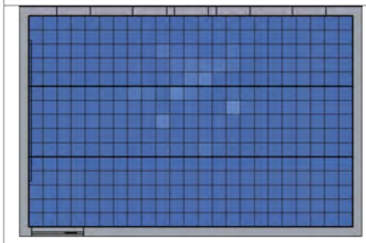
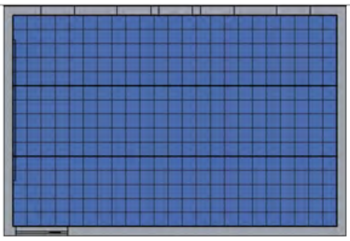
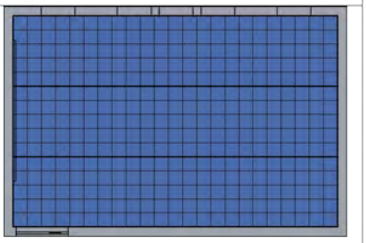
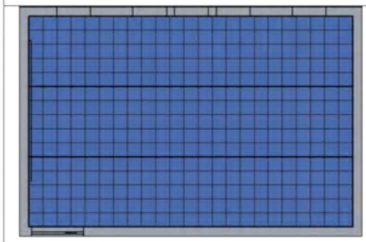
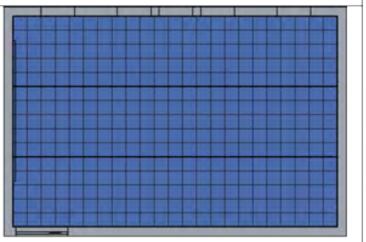
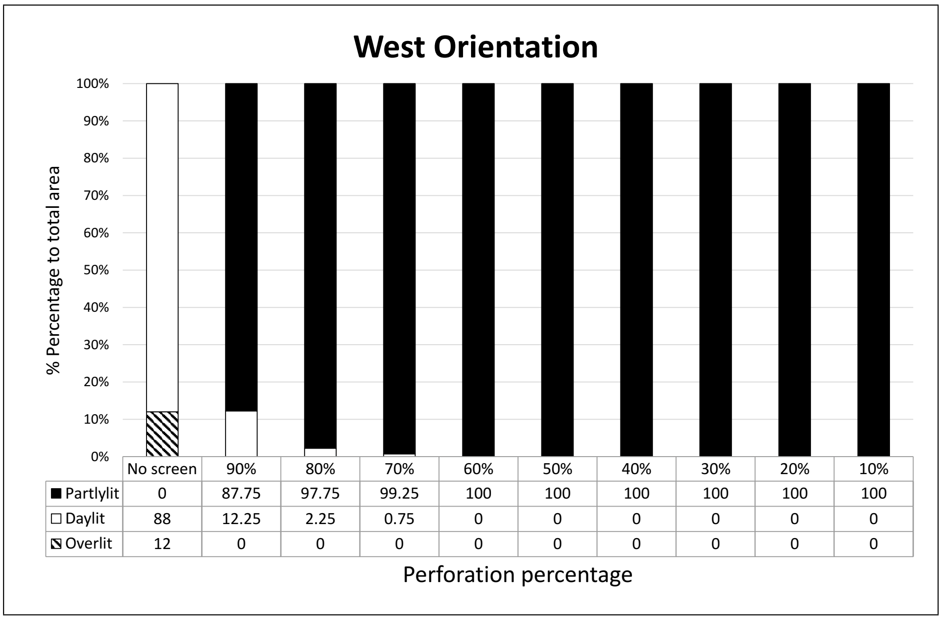
North Orientation		
Perforation percentage	No screen	90%
		
80%	70%	60%
		
50%	40%	30%
		
20%	10%	
		

Table 4.9: Distribution of DAv on the classroom plan for the west orientation with different perforation percentages (windows are located on the top side of the plan).

<table>
<tr><th colspan="3">West Orientation</th></tr>
<tr><td>Perforation percentage</td><td>No screen</td><td>90%</td></tr>
<tr><td>
</td><td></td><td></td></tr>
<tr><td>80%</td><td>70%</td><td>60%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>50%</td><td>40%</td><td>30%</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>20%</td><td>10%</td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
</table>



	No screen	90%	80%	70%	60%	50%	40%	30%	20%	10%
■ Partlylit	0	87.75	97.75	99.25	100	100	100	100	100	100
□ Daylit	88	12.25	2.25	0.75	0	0	0	0	0	0
▨ Overlit	12	0	0	0	0	0	0	0	0	0

Figure 4.5: DAv of perforation percentage cases for the west orientation.

Recommended values of the studied parameter (perforation percentage)

Based on the results, the recommended values of the parameter for perforation percentages are:

- 90% perforation percentages for the south orientation.
- 80% perforation percentages for the east orientation.
- 90% perforation percentages for the north orientation.
- 90% perforation percentages for the east orientation.

These values are used to control the parameter for perforation percentage when investigating the next parameter (depth ratio).

4.2.3 The effect of depth ratio

The objective of this experiment is to define the recommended depth ratios for perforated solar screens on windows in order to provide better interior daylighting for main orientations in the context of schools in hot arid areas, by investigating a range of variation of that parameter and comparing results with the no screen cases.

Previous studies have already investigated the effect of different values of depth ratio on perforated solar screens and its performance on energy consumption, although this was not in relation to indoor daylight levels but rather overheating and energy saving, and the context was living rooms in residential spaces (Sherif et al. 2012c). However, no previous research known to the author has investigated the effect of depth ratio on daylight performance in classrooms.

Variation of the parameter

The depth is the thickness of the screen in the y direction. The depth ratio is the ratio between the depth or the thickness of the screen to the cell module size. Figure

4.6 shows examples of three screens with different depth ratios (0.15, 0.75 & 1.2) while sharing the same cell module size (8*cm*) and the same perforation percentage (70%). Values of depth ratio are tested in a range of ten cases from 0.15 to 1.5 in 0.15 intervals.

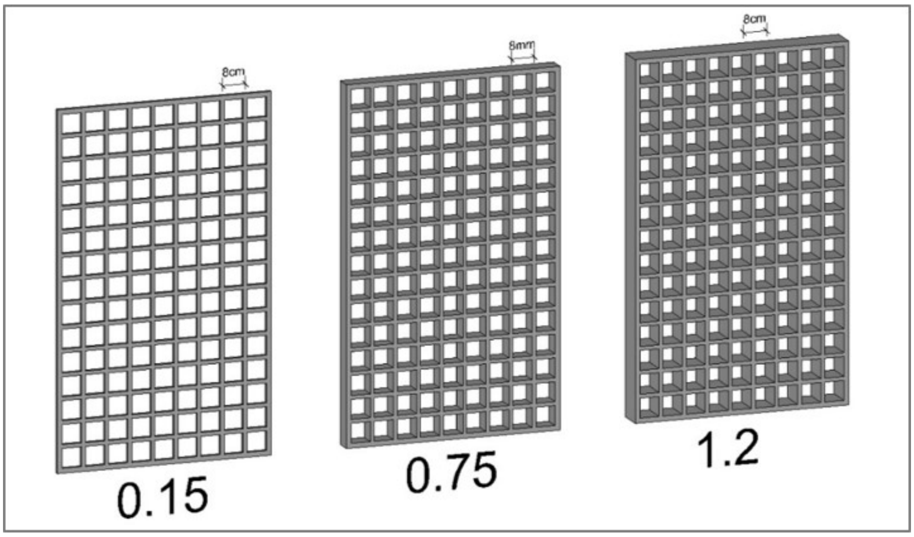


Figure 4.6: Examples of screen with depth ratios 0.15, 0.75 and 1.35.

Controlled parameters

To study the effect of depth ratio parameter on the daylight performance of perforated screens, all other parameters are controlled; Table 4.10 presents the controlled screen parameters. Similar to the previous experiment, cell module size is controlled using 6*cm* as a starting point since it has not been studied before; the 6*cm* is used as a module as it gives flexibility for further investigation of aspect ratio. The opening aspect ratio is controlled using 1:1 aspect ratio (square cells) as a starting point. Previous research of a similar nature started with square cells to control aspect ratio when testing parameters of perforated solar screens (Chi et al. 2017; Sabry et al. 2011; Sherif et al. 2012b). The values of perforation percentage are controlled using the recommended values according to the results of the previous experiment in this phase (Section 4.2.2). Table 4.10 presents values of the controlled parameters, and highlights the parameter that is controlled using a previous experiment in this research.

Table 4.10: Values of all parameters when testing the depth ratio (bold columns represent parameters values based on results of a previous experiment).

	Controlled screen parameters		
Orientation	**Perforation percentage**	Aspect ratio	Cell module size
south	**90%**	1:1	$6cm$
east	**80%**	1:1	$6cm$
north	**90%**	1:1	$6cm$
east	**90%**	1:1	$6cm$

4.2.4 Results

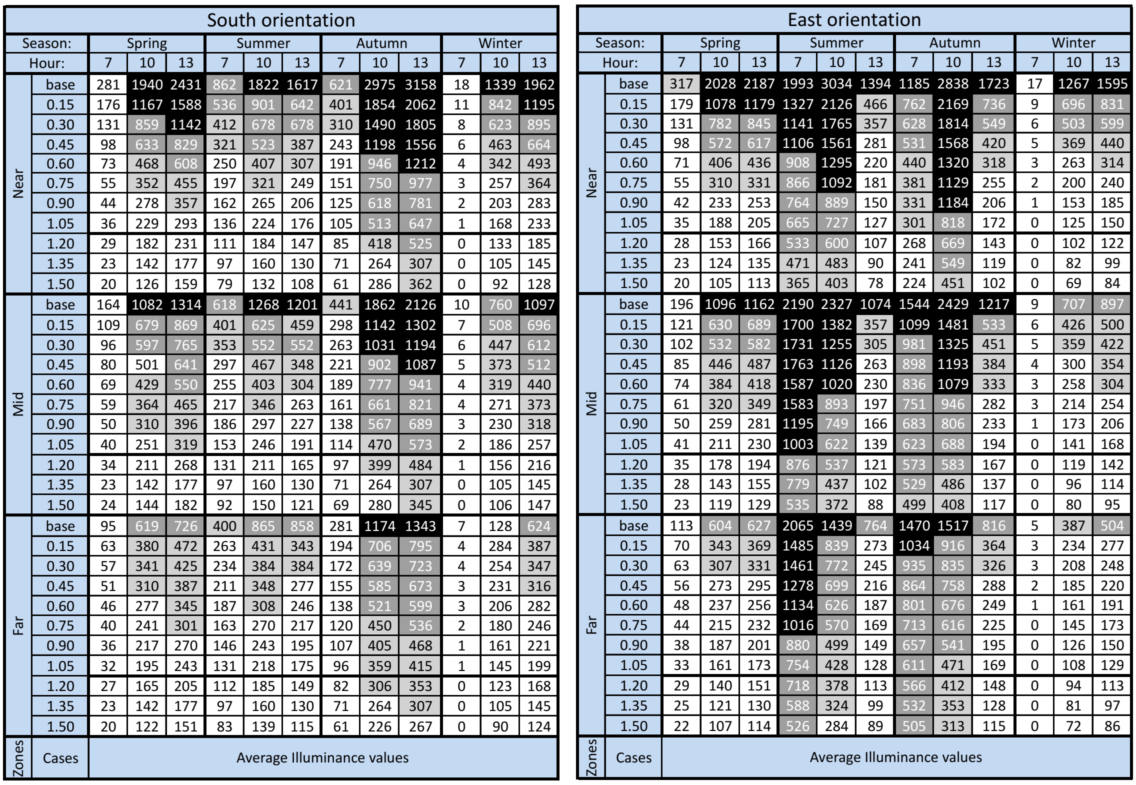
A copy of the method of representing results of daylight simulation is printed in A3 and attached in Appendix H.

The results of the two daylight metrics used: average illuminance and Daylight Availability are displayed and compared with the case for a windows with no screens attached, and results are discussed for each of the four main orientations.

Average illuminance levels

The results of simulating average illuminance levels are presented in Table 4.11. The results of this experiment show that in the south orientation, a range of depth ratios between 0.3–0.75 would provide acceptable illuminance levels between $300lx$ and $1000lx$ in most cases except in autumn and spring where higher depth ratio is needed (Table 4.11a). In the east, slightly higher range of depth ratios is needed in most cases 0.45–0.9 except in summer and spring mornings where perforated screens with a depth ratio as high as 1.5 is needed (Table 4.11b). In both north and west orientations, screens with a 0.15 depth ratio successfully achieve acceptable illuminance levels in all zones, although providing slightly high illuminance in the Near zone in spring (Tables 4.11c & 4.11d).

Table 4.11: Average illuminance (lx) for depth ratio cases in the three zones of each orientation (black cells, $\geq$ 1000lx; grey cells, between 500lx and 999lx; light grey between 300lx and 499lx).

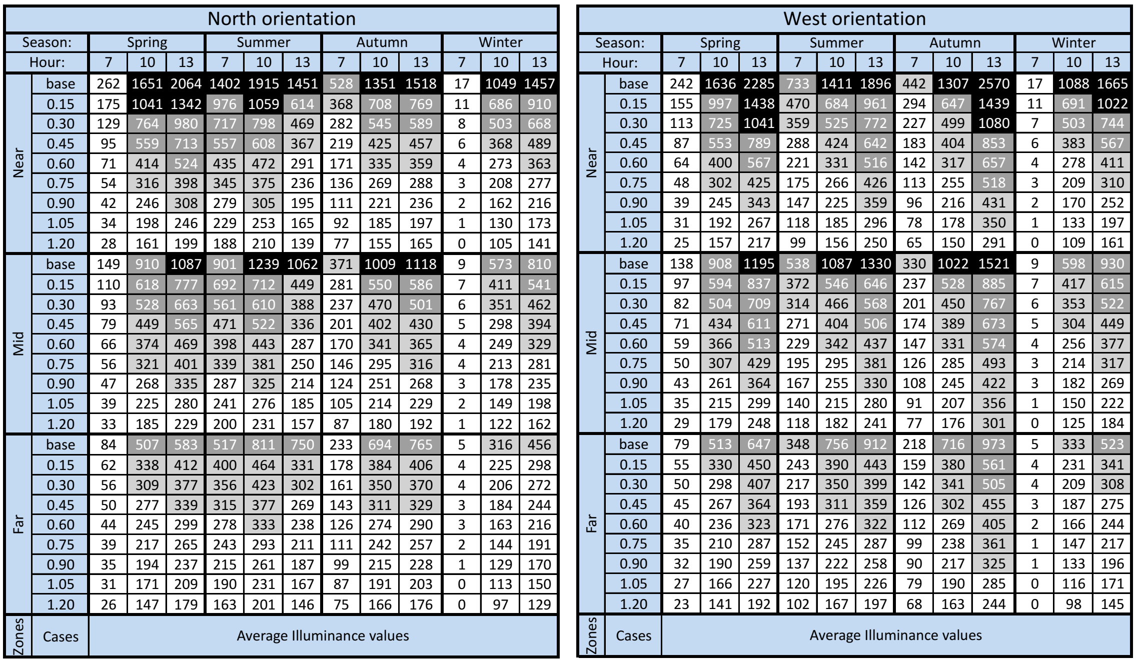


South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	0.15	176	1167	1588	536	901	642	401	1854	2062	11	842	1195
	0.30	131	859	1142	412	678	678	310	1490	1805	8	623	895
	0.45	98	633	829	321	523	387	243	1198	1556	6	463	664
	0.60	73	468	608	250	407	307	191	946	1212	4	342	493
	0.75	55	352	455	197	321	249	151	750	977	3	257	364
	0.90	44	278	357	162	265	206	125	618	781	2	203	283
	1.05	36	229	293	136	224	176	105	513	647	1	168	233
	1.20	29	182	231	111	184	147	85	418	525	0	133	185
	1.35	23	142	177	97	160	130	71	264	307	0	105	145
	1.50	20	126	159	79	132	108	61	286	362	0	92	128
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	0.15	109	679	869	401	625	459	298	1142	1302	7	508	696
	0.30	96	597	765	353	552	552	263	1031	1194	6	447	612
	0.45	80	501	641	297	467	348	221	902	1087	5	373	512
	0.60	69	429	550	255	403	304	189	777	941	4	319	440
	0.75	59	364	465	217	346	263	161	661	821	4	271	373
	0.90	50	310	396	186	297	227	138	567	689	3	230	318
	1.05	40	251	319	153	246	191	114	470	573	2	186	257
	1.20	34	211	268	131	211	165	97	399	484	1	156	216
	1.35	23	142	177	97	160	130	71	264	307	0	105	145
	1.50	24	144	182	92	150	121	69	280	345	0	106	147
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	0.15	63	380	472	263	431	343	194	706	795	4	284	387
	0.30	57	341	425	234	384	384	172	639	723	4	254	347
	0.45	51	310	387	211	348	277	155	585	673	3	231	316
	0.60	46	277	345	187	308	246	138	521	599	3	206	282
	0.75	40	241	301	163	270	217	120	450	536	2	180	246
	0.90	36	217	270	146	243	195	107	405	468	1	161	221
	1.05	32	195	243	131	218	175	96	359	415	1	145	199
	1.20	27	165	205	112	185	149	82	306	353	0	123	168
	1.35	23	142	177	97	160	130	71	264	307	0	105	145
	1.50	20	122	151	83	139	115	61	226	267	0	90	124
Zones	Cases	Average Illuminance values											

(a) South orientation.

East orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	317	2028	2187	1993	3034	1394	1185	2838	1723	17	1267	1595
	0.15	179	1078	1179	1327	2126	466	762	2169	736	9	696	831
	0.30	131	782	845	1141	1765	357	628	1814	549	6	503	599
	0.45	98	572	617	1106	1561	281	531	1568	420	5	369	440
	0.60	71	406	436	908	1295	220	440	1320	318	3	263	314
	0.75	55	310	331	866	1092	181	381	1129	255	2	200	240
	0.90	42	233	253	764	889	150	331	1184	206	1	153	185
	1.05	35	188	205	665	727	127	301	818	172	0	125	150
	1.20	28	153	166	533	600	107	268	669	143	0	102	122
	1.35	23	124	135	471	483	90	241	549	119	0	82	99
	1.50	20	105	113	365	403	78	224	451	102	0	69	84
Mid	base	196	1096	1162	2190	2327	1074	1544	2429	1217	9	707	897
	0.15	121	630	689	1700	1382	357	1099	1481	533	6	426	500
	0.30	102	532	582	1731	1255	305	981	1325	451	5	359	422
	0.45	85	446	487	1763	1126	263	898	1193	384	4	300	354
	0.60	74	384	418	1587	1020	230	836	1079	333	3	258	304
	0.75	61	320	349	1583	893	197	751	946	282	3	214	254
	0.90	50	259	281	1195	749	166	683	806	233	1	173	206
	1.05	41	211	230	1003	622	139	623	688	194	0	141	168
	1.20	35	178	194	876	537	121	573	583	167	0	119	142
	1.35	28	143	155	779	437	102	529	486	137	0	96	114
	1.50	23	119	129	535	372	88	499	408	117	0	80	95
Far	base	113	604	627	2065	1439	764	1470	1517	816	5	387	504
	0.15	70	343	369	1485	839	273	1034	916	364	3	234	277
	0.30	63	307	331	1461	772	245	935	835	326	3	208	248
	0.45	56	273	295	1278	699	216	864	758	288	2	185	220
	0.60	48	237	256	1134	626	187	801	676	249	1	161	191
	0.75	44	215	232	1016	570	169	713	616	225	0	145	173
	0.90	38	187	201	880	499	149	657	541	195	0	126	150
	1.05	33	161	173	754	428	128	611	471	169	0	108	129
	1.20	29	140	151	718	378	113	566	412	148	0	94	113
	1.35	25	121	130	588	324	99	532	353	128	0	81	97
	1.50	22	107	114	526	284	89	505	313	115	0	72	86
Zones	Cases	Average Illuminance values											

(b) East orientation.



North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	0.15	175	1041	1342	976	1059	614	368	708	769	11	686	910
	0.30	129	764	980	717	798	469	282	545	589	8	503	668
	0.45	95	559	713	557	608	367	219	425	457	6	368	489
	0.60	71	414	524	435	472	291	171	335	359	4	273	363
	0.75	54	316	398	345	375	236	136	269	288	3	208	277
	0.90	42	246	308	279	305	195	111	221	236	2	162	216
	1.05	34	198	246	229	253	165	92	185	197	1	130	173
	1.20	28	161	199	188	210	139	77	155	165	0	105	141
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	0.15	110	618	777	692	712	449	281	550	586	7	411	541
	0.30	93	528	663	561	610	388	237	470	501	6	351	462
	0.45	79	449	565	471	522	336	201	402	430	5	298	394
	0.60	66	374	469	398	443	287	170	341	365	4	249	329
	0.75	56	321	401	339	381	250	146	295	316	4	213	281
	0.90	47	268	335	287	325	214	124	251	268	3	178	235
	1.05	39	225	280	241	276	185	105	214	229	2	149	198
	1.20	33	185	229	200	231	157	87	180	192	1	122	162
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	0.15	62	338	412	400	464	331	178	384	406	4	225	298
	0.30	56	309	377	356	423	302	161	350	370	4	206	272
	0.45	50	277	339	315	377	269	143	311	329	3	184	244
	0.60	44	245	299	278	333	238	126	274	290	3	163	216
	0.75	39	217	265	243	293	211	111	242	257	2	144	191
	0.90	35	194	237	215	261	187	99	215	228	1	129	170
	1.05	31	171	209	190	231	167	87	191	203	0	113	150
	1.20	26	147	179	163	201	146	75	166	176	0	97	129
Zones	Cases	Average Illuminance values											

(c) North orientation.

West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	0.15	155	997	1438	470	684	961	294	647	1439	11	691	1022
	0.30	113	725	1041	359	525	772	227	499	1080	7	503	744
	0.45	87	553	789	288	424	642	183	404	853	6	383	567
	0.60	64	400	567	221	331	516	142	317	657	4	278	411
	0.75	48	302	425	175	266	426	113	255	518	3	209	310
	0.90	39	245	343	147	225	359	96	216	431	2	170	252
	1.05	31	192	267	118	185	296	78	178	350	1	133	197
	1.20	25	157	217	99	156	250	65	150	291	0	109	161
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	0.15	97	594	837	372	546	646	237	528	885	7	417	615
	0.30	82	504	709	314	466	568	201	450	767	6	353	522
	0.45	71	434	611	271	404	506	174	389	673	5	304	449
	0.60	59	366	513	229	342	437	147	331	574	4	256	377
	0.75	50	307	429	195	295	381	126	285	493	3	214	317
	0.90	43	261	364	167	255	330	108	245	422	3	182	269
	1.05	35	215	299	140	215	280	91	207	356	1	150	222
	1.20	29	179	248	118	182	241	77	176	301	0	125	184
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	0.15	55	330	450	243	390	443	159	380	561	4	231	341
	0.30	50	298	407	217	350	399	142	341	505	4	209	308
	0.45	45	267	364	193	311	359	126	302	455	3	187	275
	0.60	40	236	323	171	276	322	112	269	405	2	166	244
	0.75	35	210	287	152	245	287	99	238	361	1	147	217
	0.90	32	190	259	137	222	258	90	217	325	1	133	196
	1.05	27	166	227	120	195	226	79	190	285	0	116	171
	1.20	23	141	192	102	167	197	68	163	244	0	98	145
Zones	Cases	Average Illuminance values											

(d) West orientation.

The results show that using perforated screens in most cases succeeds in reducing the high illuminance values that could cause discomfort glare (above 1000lx) into an acceptable level (300–500lx) especially in south and east where the illuminance could reach as high as 3000lx in Near zones (Table 4.11). However, the required depth ratio to achieve this differ according to the orientation even for the same time of the day and season, for instance, there is a high depth ratio in summer in the morning and low depth ratio in the south. Acceptable illuminance is also achieved in Far zones in all orientations and seasons except winter.

Tables of results confirm the finding of the previous experiment, that using perforated screens has the potential to improve distribution of daylight in the space and thus achieve better uniformity. In the majority of cases, when using perforated screens the spatial distribution ratio of average illuminance levels in Mid and Near zones (using equation 4.1) increases in comparison with the same ratio of no screen cases. The only exceptions to that are six cases out of all 48 cases, three in the south, two in east and one in west orientation (Tables 4.12 & 4.13). The same ratio between Far and Near zones in most cases is also improved except in four cases, two in the south, and one each in east and west orientations. It can be noticed that in all cases on the north orientation, the spatial distribution ratio is improved with the use of perforated solar screens.

Table 4.12: Comparing spatial distribution ratio between zones with and without using perforated screens of 0.15 depth in south and east orientations (red cells represent where that the ratio without screen was higher than when using screens).

		South orientation												East orientation											
		Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	58	56	54	72	70	74	71	63	67	56	57	56	62	54	53	110	77	77	130	86	71	56	56	56
	0.15 depth	62	58	55	75	69	71	74	62	63	64	60	58	68	58	58	128	65	77	144	68	72	64	61	60
	difference	**4**	**2**	**1**	**3**	**-1**	**-3**	**3**	**-1**	**-4**	**8**	**4**	**2**	**6**	**4**	**5**	**18**	**-12**	**0**	**14**	**-17**	**2**	**8**	**5**	**4**
Far / Near x100	noscreen	34	32	30	46	47	53	45	39	43	37	10	32	36	30	29	104	47	55	124	53	47	32	31	32
	0.15 depth	36	33	30	49	48	53	48	38	39	37	34	32	78	69	68	103	52	93	205	54	87	41	71	70
	difference	**2**	**1**	**0**	**3**	**1**	**0**	**3**	**-1**	**-4**	**0**	**24**	**0**	**43**	**39**	**39**	**-1**	**5**	**38**	**81**	**1**	**39**	**9**	**40**	**39**

Table 4.13: Comparing spatial distribution ratio between zones with and without using perforated screens of 0.15 depth in north and west orientations (red cells represent where that the ratio without screen was higher than when using screens).

		West orientation												North orientation											
		Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	57	56	52	73	77	70	75	78	59	53	55	56	57	55	53	64	65	73	70	75	74	53	55	56
	0.15 depth	63	60	58	79	80	67	81	82	62	63	60	60	63	59	58	71	67	73	76	78	76	63	60	60
	difference	**6**	**4**	**6**	**6**	**3**	**-3**	**6**	**4**	**3**	**10**	**5**	**4**	**6**	**4**	**5**	**7**	**3**	**0**	**6**	**3**	**3**	**10**	**5**	**4**
Far / Near x100	noscreen	32	31	28	47	54	48	49	55	38	32	31	31	32	31	28	37	42	52	44	51	50	29	30	31
	0.15 depth	36	33	31	52	57	46	54	59	39	36	33	33	35	32	31	41	44	54	48	54	53	36	33	33
	difference	**3**	**2**	**3**	**4**	**4**	**-2**	**5**	**4**	**1**	**4**	**3**	**2**	**3**	**2**	**2**	**4**	**1**	**2**	**4**	**3**	**2**	**6**	**3**	**1**

Finally, Table 4.14 is produced to show the minimum recommended depth ratio for each case according to the analysed results when using the same controlled parameters values in the similar contexts. Architects and designers can use this table as a tool to decide the depth ratio of a perforated solar screen according to the required illuminance level and the orientation for similar contexts. The table is also useful to indicate the hours and zones that daylight illuminance is not sufficient and artificial light is needed (e.g. 7:00 in winter and spring for all zones of all orientations and 10:00 in winter in Far zone of all orientations).

Table 4.14: Minimum recommended depth ratios to achieve the target illuminance (300lx) in all studied cases and zones for specific times throughout the year. (black cells represent cases that 300lx cannot be achieved with daylight alone; lighter cells represent higher depth ratios.)

Zones:	Depth ratios												
	Season:	Spring			Summer			Autumn			Winter		
	Hour:	7	10	13	7	10	13	7	10	13	7	10	13
Near	North	■	0.75	0.90	0.75	0.90	0.45	0.15	0.60	0.60	■	0.45	0.60
	East	■	0.75	0.75	1.50	1.50	0.30	1.05	1.50	0.60	■	0.45	0.60
	South	■	0.75	0.90	0.45	0.75	0.60	0.30	1.20	1.50	■	0.60	0.75
	West	■	0.75	0.90	0.30	0.60	0.90	■	0.60	1.05	■	0.45	0.75
Mid	North	■	0.75	0.90	0.75	0.90	0.45	■	0.60	0.75	■	0.30	0.60
	East	■	0.75	0.75	1.50	1.50	0.60	1.50	1.50	0.60	■	0.30	0.60
	South	■	0.90	1.05	0.30	0.75	0.60	■	1.20	1.50	■	0.60	0.90
	West	■	0.75	0.90	0.30	0.60	0.90	■	0.60	1.20	■	0.45	0.75
Far	North	■	0.30	0.45	0.45	0.60	0.30	■	0.45	0.45	■	■	■
	East	■	0.30	0.30	1.50	1.35	■	1.50	1.50	0.30	■	■	■
	South	■	0.45	0.75	■	0.60	0.30	■	1.20	1.35	■	■	0.45
	West	■	0.15	0.60	■	0.45	0.60	■	0.45	0.90	■	■	0.30
	orientation	Minimum Depth ratios to achieve 300 lx illuminance											

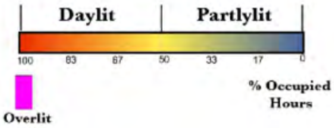
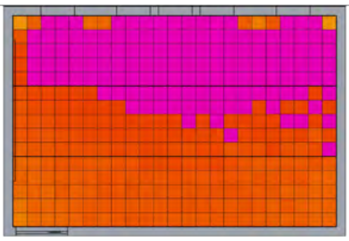
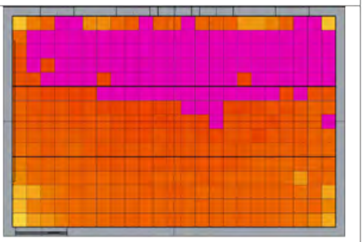
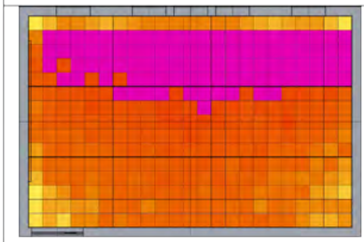
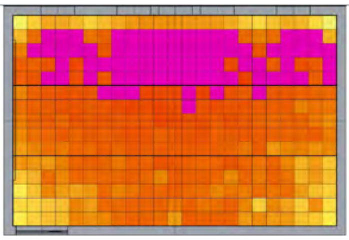
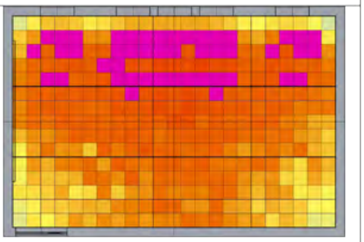
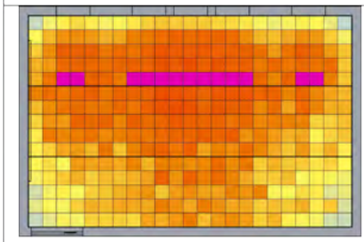
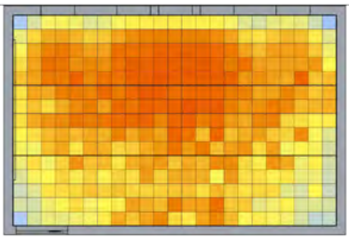
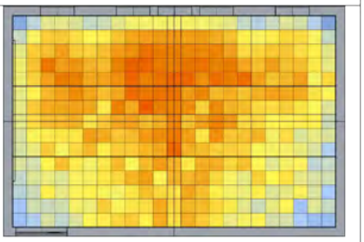
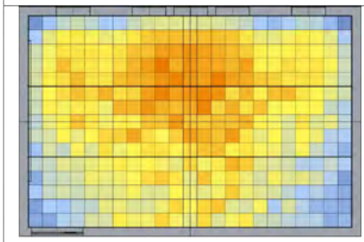
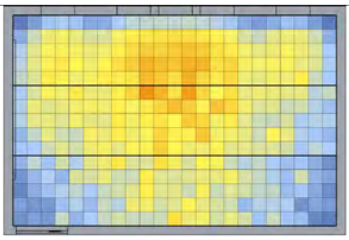
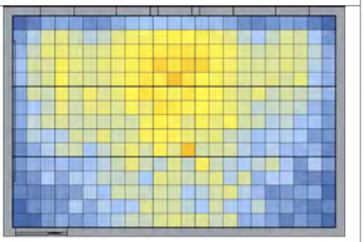
Similar to the results of the perforation percentage experiment, results show that some cases provided average illuminance of more than $2000lx$ without knowing if the area is considered as Overlit or Daylit. Therefore, the next stage of this experiment is necessary to clearly understand the situation, by using CBDM simulation and analysing data using DAv metric as one of the DDPMs.

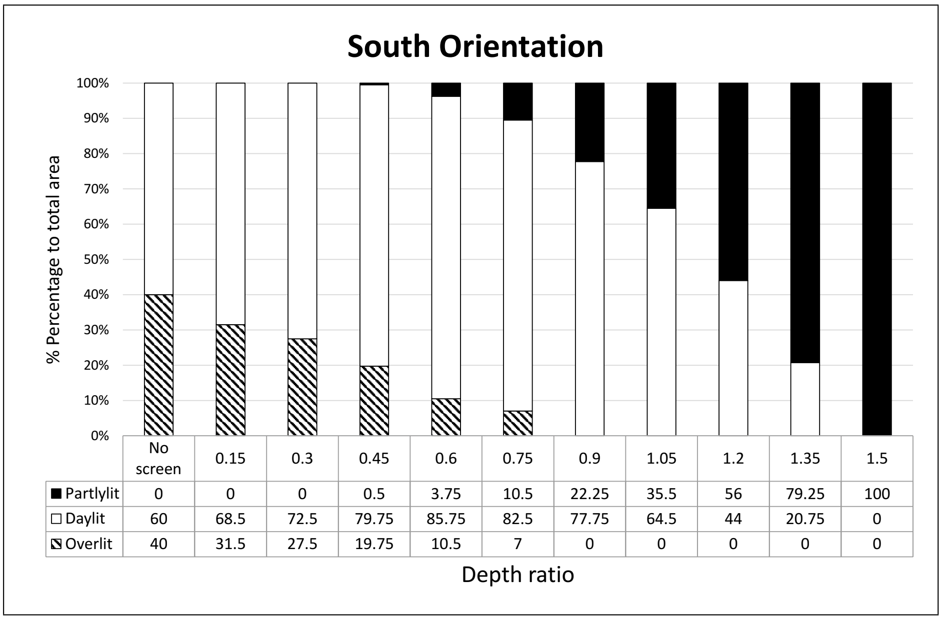
Daylight Availability

The results of light simulation of DAv in this experiment are presented in Tables 4.15, 4.16, 4.17 & 4.18 and Figures 4.7, 4.8, 4.9 & 4.10.

In the south orientation, results show that a depth ratio of 0.6 achieves more Daylit areas than other depth ratios (82.5%) although it still has some Overlit and Partlylit areas (Table 4.15 and Figure 4.7). However, according to the results, screens with a depth ratio between 0.15 and 1.05 provide a Daylit area of more than 50% of the total area of the studied space which is an acceptable result according to the used criteria. The actual choice can be made by designers considering other factors, e.g. to diminish Overlit area by using depth ratio of 0.9 or to diminish the Partlylit area by using a depth ratio of 0.45.

Table 4.15: Distribution of DAv on the classroom plan for the south orientation with different depth ratios (windows are located on the top side of the plan).

South Orientation		
Depth ratio	No screen	0.15
		
0.3	0.45	0.60
		
0.75	0.9	1.05
		
1.2	1.35	1.5
		

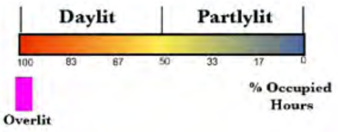
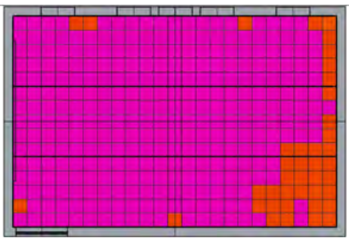
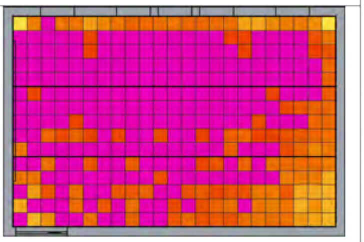
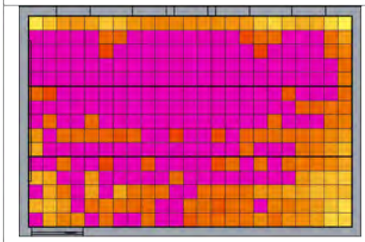
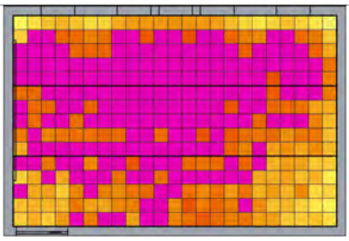
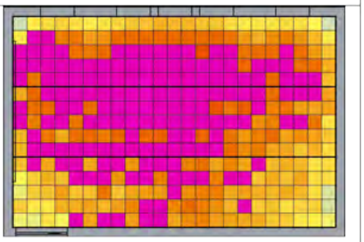
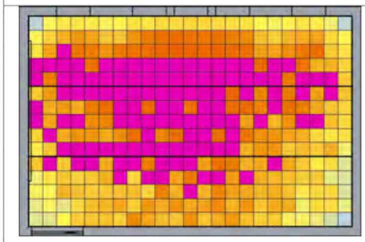
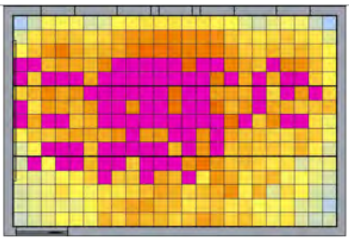
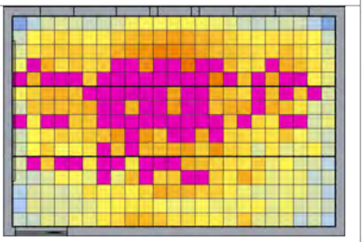
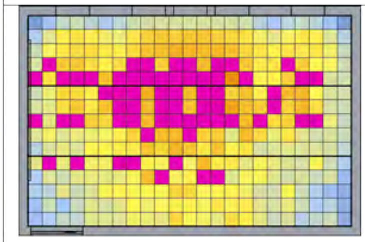
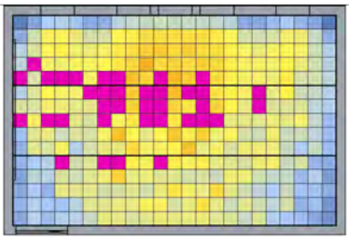
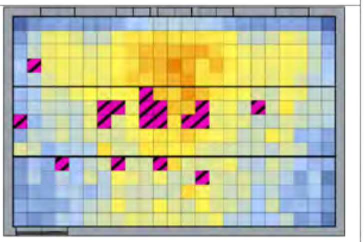


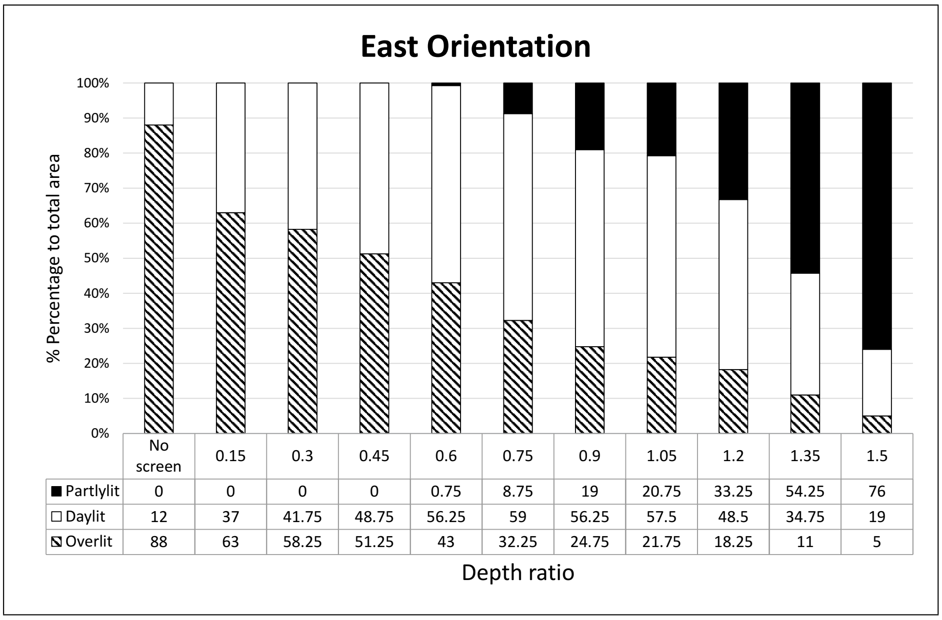
	No screen	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5
■ Partlylit	0	0	0	0.5	3.75	10.5	22.25	35.5	56	79.25	100
□ Daylit	60	68.5	72.5	79.75	85.75	82.5	77.75	64.5	44	20.75	0
▨ Overlit	40	31.5	27.5	19.75	10.5	7	0	0	0	0	0

Figure 4.7: DAv of depth ratio cases for the south orientation.

In the east orientation, it is relatively difficult to diminish Overlit area, however; cases a with depth ratio between 0.75–1.05 achieve acceptable levels of Daylit areas, and screens with a 0.75 depth ratio provide the most Daylit areas with 59% of the total area. Although this also causes Overlit areas of 32.25%, that could be acceptable considering the direct sun from the east side during school hours (Figure 4.8 and Table 4.16). Architects and designers can also use the chart to choose an appropriate depth ratio in cases where minimising the Overlit area was more significant than providing more of the Daylit area.

Table 4.16: Distribution of DAv on the classroom plan for the east orientation with different depth ratios (windows are located on the top side of the plan).

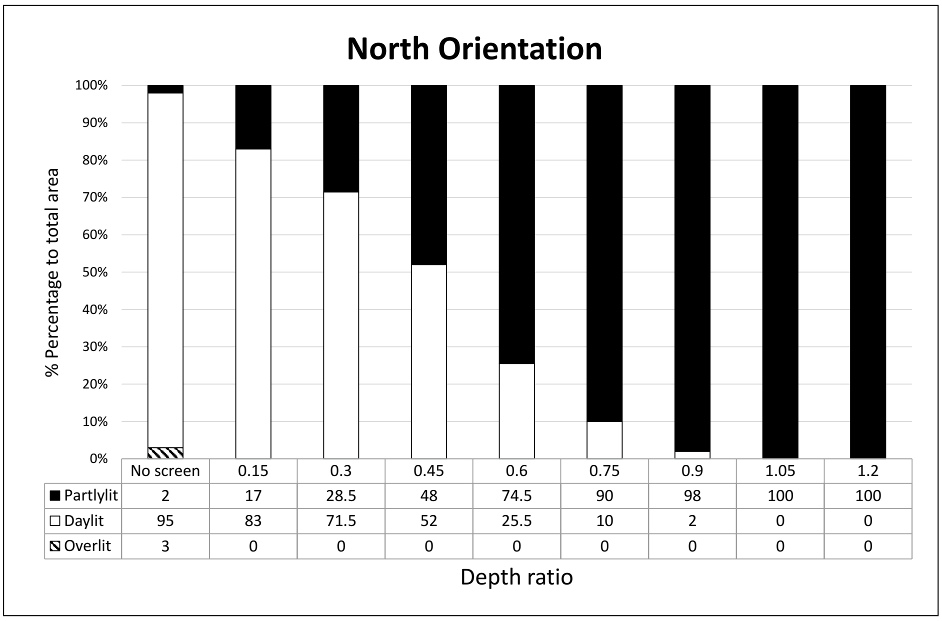
East Orientation		
Depth ratio	No screen	0.15
		
0.3	0.45	0.60
		
0.75	0.9	1.05
		
1.2	1.35	1.5
		



	No screen	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5
■ Partlylit	0	0	0	0	0.75	8.75	19	20.75	33.25	54.25	76
☐ Daylit	12	37	41.75	48.75	56.25	59	56.25	57.5	48.5	34.75	19
▨ Overlit	88	63	58.25	51.25	43	32.25	24.75	21.75	18.25	11	5

Figure 4.8: DAv of depth ratio cases for the east orientation.

In both north and west orientations, results show a near linear correlation between depth ratio and the size of Daylit area. The lower the depth ratio is, the more Daylit area it provides, and thus, depth ratio of 0.15 provides the biggest Daylit area with more than 80% of the total area. Interestingly, a thin screen with 0.15 depth ratio could still diminish the Overlit area in both orientations (Figures 4.9 & 4.10) and (Tables 4.17 & 4.18).



	No screen	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2
■ Partlylit	2	17	28.5	48	74.5	90	98	100	100
☐ Daylit	95	83	71.5	52	25.5	10	2	0	0
▨ Overlit	3	0	0	0	0	0	0	0	0

Figure 4.9: DAv of depth ratio cases for the north orientation.

Table 4.17: Distribution of DAv on the classroom plan for the north orientation with different depth ratios (windows are located on the top side of the plan).

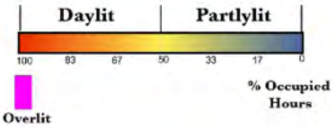
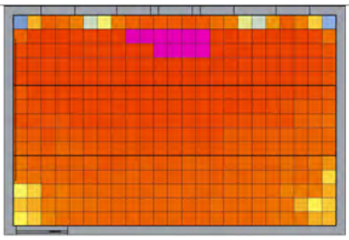
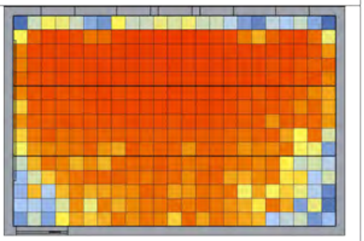
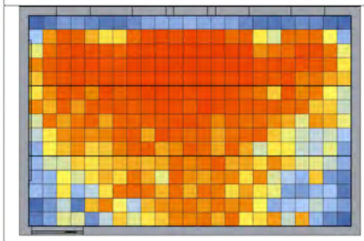
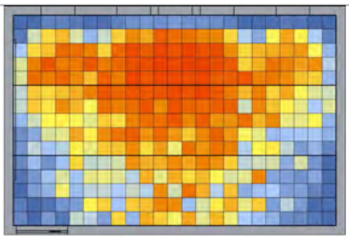
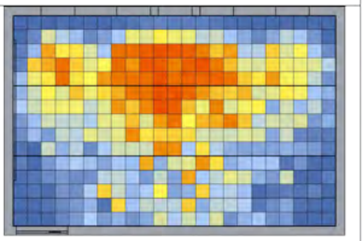
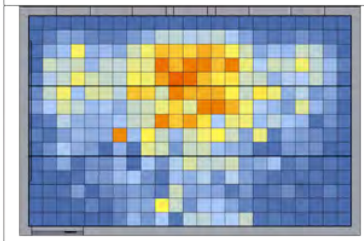
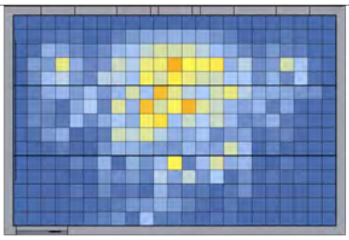
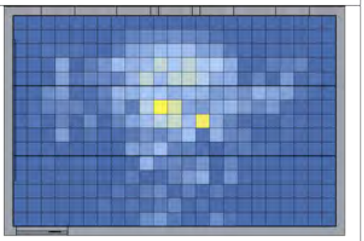
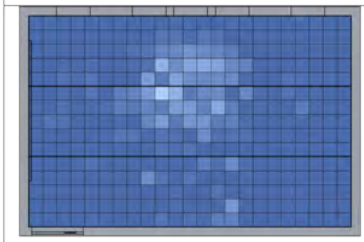
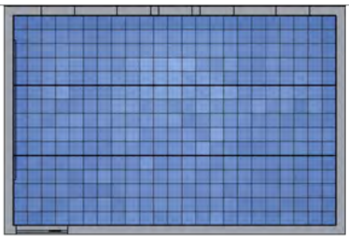
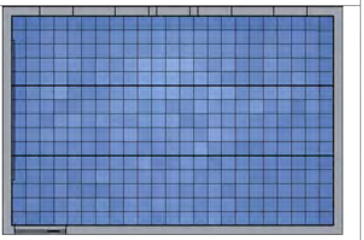
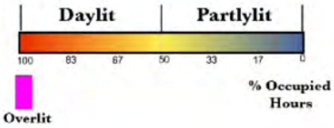
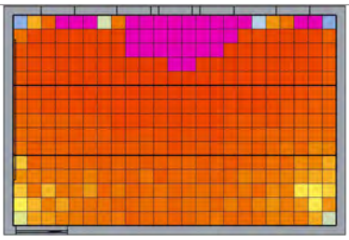
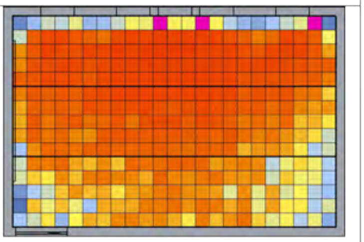
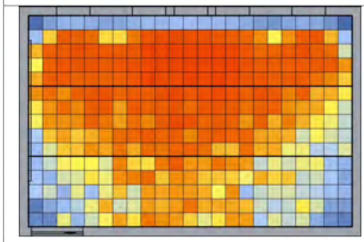
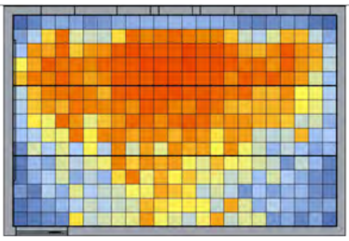
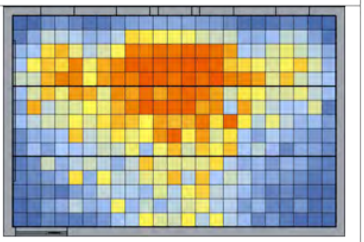
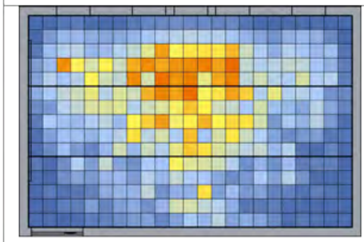
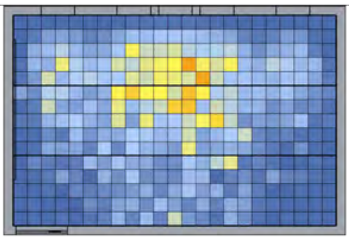
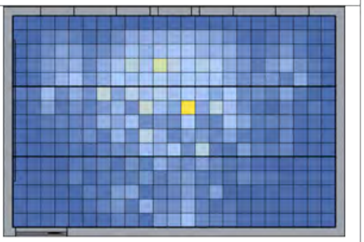
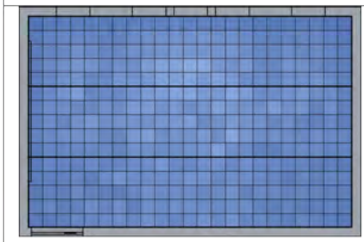
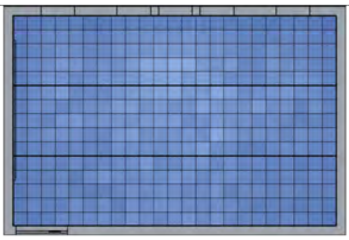
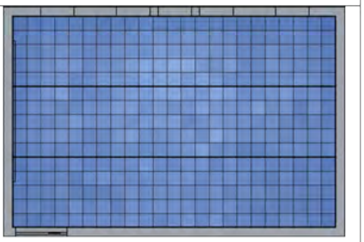
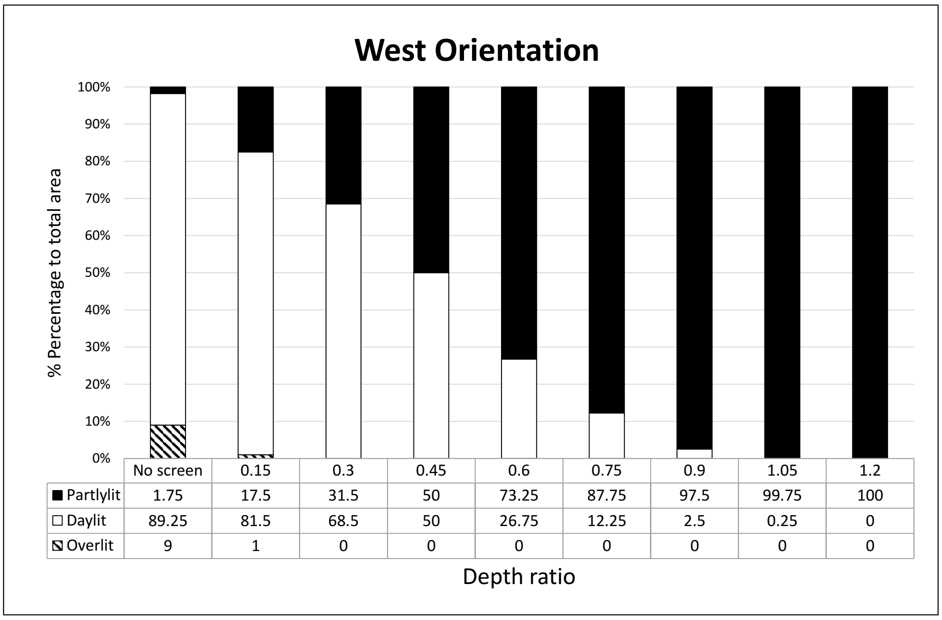
North Orientation		
Depth ratio	No screen	0.15
		
0.3	0.45	0.60
		
0.75	0.9	1.05
		
1.2	1.35	1.5
		

Table 4.18: Distribution of DAv on the classroom plan for the west orientation with different depth ratios (windows are located on the top side of the plan).

West Orientation		
Depth ratio	No screen	0.15
		
0.3	0.45	0.60
		
0.75	0.9	1.05
		
1.2	1.35	1.5
		



	No screen	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2
■ Partlylit	1.75	17.5	31.5	50	73.25	87.75	97.5	99.75	100
□ Daylit	89.25	81.5	68.5	50	26.75	12.25	2.5	0.25	0
▨ Overlit	9	1	0	0	0	0	0	0	0

Figure 4.10: DAv of depth ratio cases for the west orientation.

Results of this stage prove that using perforated solar screens on all orientations can provide more Daylit area than cases where no screens are attached to windows, except in the north orientation where Daylit area is bigger with no screen but accompanied with Overlit area (Figure 4.9). Results also show that depth ratio has a significant effect on the performance of the solar screen in providing Daylight Availability; results however, vary according to the orientation.

Recommended values of the studied parameter

Based on the results, the recommended values of the parameter of depth ratio are:

- A 0.6 depth ratio for the south orientation.
- A 0.75 depth ratios for the east orientation.
- A 0.15 depth ratio for the north orientation.
- A 0.15 depth ratio for the west orientation.

These values are used to control the parameter of depth ratio when investigating the next parameter (cell module size).

4.2.5 The effect of cell module size

The objective of this experiment is to investigate the effect of changing the cell module size on the daylight performance of perforated solar screens. The aim is to find the recommended value of cell module size to enhance interior daylighting and provide acceptable daylight levels for the main orientations in the context of schools in hot arid areas. Most previous studies have fixed cell module size to investigate other screen parameters in different studies (Sabry et al. 2011; Sherif et al. 2012a,c; Wagdy and Fathy 2015). However, no previous research known to the author has investigated the effect of different cell module size on the daylight performance of perforated solar screens. This perspective is considered to be novel, as no other research focusing on this aspect and context is known to the author.

Variation of the parameter

A range of square cell module sizes are tested in a range of cases from $1cm \times 1cm$ to $12cm \times 12cm$. Figure 4.11 shows examples of different cases of cell module sizes ($3cm \times 3cm$, $6cm \times 6cm$, $12cm \times 12cm$). The cases of cell module sizes are selected according to the dimensions of the studied windows ($120cm \times 72cm$), because the cell module size should be a number that could be multiplied to give an exact number of the window dimension. Therefore, cell module sizes of $2cm \times 2cm$ $3cm \times 3cm$, $4cm \times 4cm$, $6cm \times 6cm$, $8cm \times 8cm$ and $12cm \times 12cm$ are investigated in this experiment.

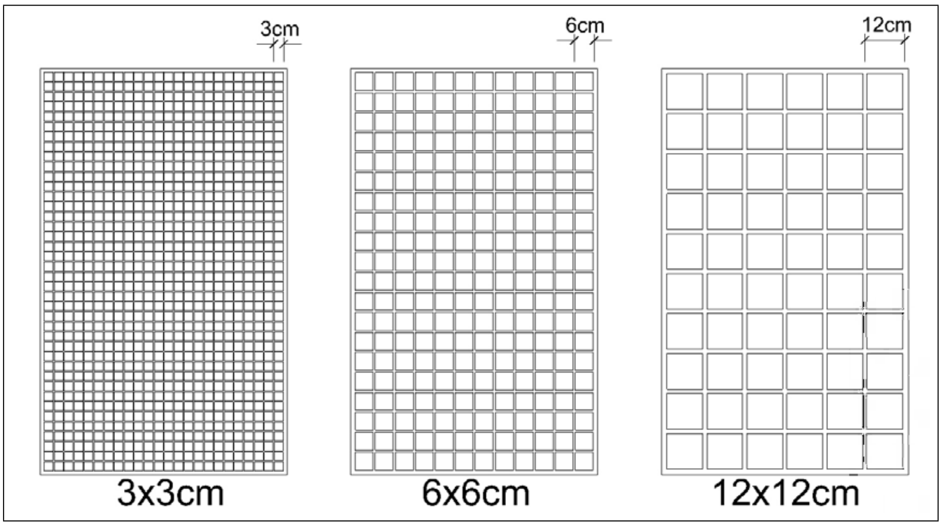


Figure 4.11: Examples of screens with different cell module size sharing the same perforation percentage, depth ratio and aspect ratio.

Controlled parameters

To study the effect of cell module size, it is isolated by controlling other parameters; Table 4.19 presents the controlled screen parameters. Values of controlled parameters are selected according to results of the previous experiments in this research (perforation percentage and depth ratio), whereas, the parameter of aspect ratio is set to 1:1 in all orientations as it has not been studied yet in this research.

Table 4.19: Values of all parameters when testing cell module size (bold columns represent parameters values based on results of previous experiments).

	Controlled screen parameters		
Orientation	**Perforation percentage**	**Depth ratio**	Aspect ratio
south	**90%**	**0.6**	1:1
east	**80%**	**0.75**	1:1
north	**90%**	**0.15**	1:1
east	**90%**	**0.15**	1:1

4.2.6 Results

A copy of the method of representing results of daylight simulation is attached in Appendix H.

The results of the two daylight metrics used in the experiments: average illuminance and Daylight Availability are displayed and compared with the case with no screens attached to the windows, and results are discussed for each of the four main orientations.

Average illuminance levels

The results of simulating average illuminance levels are presented in Table 4.20. Results show that changing cell module size does not have a notable effect on the average illuminance. The average illuminance levels have only slight differences between each case (less than 5% difference); this slight variation is most likely caused by the accuracy of the computer simulation that has a range of ±3% . This finding can be seen in all orientations (Table 4.20).

Contrary to the previous experiments, results can not be used to produce a table as a tool to recommend values of this parameter since similar light performance is achieved using values of all cases.

Table 4.20: Average illuminance (lx) for cell module size cases in the three zones of each orientation (black cells, $\geq 1000lx$; grey cells, between $500lx$ and $999lx$; light grey between $300lx$ and $499lx$).

South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	2x2	61	388	505	209	340	262	160	786	1044	3	284	402
	3x3	74	476	620	253	411	312	193	944	1249	4	349	511
	4x4	72	463	601	248	404	307	189	926	1218	4	338	480
	6x6	76	489	636	258	420	317	196	954	1261	4	358	510
	8x8	73	469	611	250	406	310	190	935	1235	4	343	495
	12x12	73	466	605	249	405	308	190	938	1237	4	341	479
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	2x2	58	363	464	216	342	259	161	656	814	4	270	371
	3x3	70	435	556	258	407	307	191	780	962	4	324	445
	4x4	69	431	552	255	404	305	189	770	958	4	321	442
	6x6	70	435	557	257	407	306	191	777	965	4	324	446
	8x8	69	428	548	255	403	303	189	772	955	4	319	438
	12x12	69	425	544	252	400	302	188	774	960	4	316	435
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	2x2	39	232	289	158	261	210	116	437	516	1	172	236
	3x3	45	273	341	185	306	245	136	512	605	3	203	278
	4x4	46	277	345	188	310	248	138	516	609	3	206	281
	6x6	45	273	341	185	306	245	136	511	606	2	203	278
	8x8	46	275	343	187	308	246	137	515	608	3	205	280
	12x12	45	272	340	184	305	244	136	515	610	3	202	277
Zones	Cases	Average Illuminance values											

(a) South orientation.

East orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	317	2028	2187	1993	3034	1394	1185	2838	1723	17	1267	1595
	2x2	37	203	221	765	758	126	274	808	176	1	134	161
	3x3	55	314	337	720	1109	183	387	1158	259	2	204	244
	4x4	55	312	336	891	1108	182	385	1149	258	2	203	243
	6x6	55	318	335	1129	1093	183	387	1141	258	2	202	242
	8x8	53	305	325	862	1085	180	375	1124	253	2	197	236
	12x12	54	303	327	1128	1096	180	380	1134	253	2	198	237
Mid	base	196	1096	1162	2190	2327	1074	1544	2429	1217	9	707	897
	2x2	41	216	236	900	623	135	459	662	191	1	145	172
	3x3	63	326	355	1661	905	200	705	955	287	3	218	258
	4x4	61	321	349	1265	895	197	682	947	282	3	215	254
	6x6	62	323	351	1263	897	198	691	958	283	3	216	256
	8x8	61	319	348	1583	895	195	750	952	279	2	214	253
	12x12	61	318	346	1850	897	195	652	939	279	3	213	252
Far	base	113	604	627	2065	1439	764	1470	1517	816	5	387	504
	2x2	31	152	164	692	404	118	627	440	157	0	103	122
	3x3	45	219	236	1049	575	171	830	623	228	0	148	176
	4x4	44	218	235	1178	574	172	812	621	228	0	148	176
	6x6	44	216	232	1261	569	170	803	621	225	0	146	174
	8x8	44	218	234	930	575	171	717	626	227	0	147	175
	12x12	42	209	225	964	565	165	763	608	219	0	142	169
Zones	Cases	Average Illuminance values											

(b) East orientation.

North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	2x2	173	1038	1338	980	1050	614	365	705	767	11	683	907
	3x3	173	1037	1336	975	1053	613	365	704	766	11	682	906
	4x4	174	1039	1340	970	1051	616	364	704	768	11	684	908
	6x6	171	1023	1317	966	1045	604	364	699	758	11	673	906
	8x8	171	1023	1317	966	1045	604	364	699	758	11	673	893
	12x12	172	1029	1327	960	1044	609	362	697	760	11	678	900
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	2x2	107	605	760	680	701	442	276	541	576	7	402	530
	3x3	108	609	766	668	701	444	277	543	579	7	405	534
	4x4	107	604	757	667	696	440	275	538	573	7	401	528
	6x6	107	606	761	678	699	441	276	540	575	7	403	537
	8x8	107	606	761	678	699	441	276	540	575	7	403	531
	12x12	109	618	776	679	711	448	280	549	585	7	411	541
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	2x2	62	343	419	404	471	337	181	392	414	4	228	303
	3x3	61	336	410	398	461	330	178	383	404	4	223	296
	4x4	63	347	423	406	473	338	182	394	416	4	231	306
	6x6	61	336	410	397	461	330	177	383	404	4	224	298
	8x8	61	336	410	397	461	330	177	383	404	4	224	296
	12x12	62	341	417	400	467	333	179	387	409	4	227	301
Zones	Cases	Average Illuminance values											

(c) North orientation.

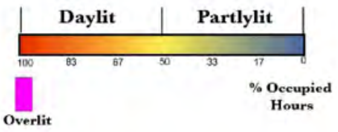
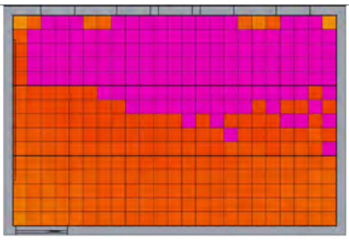
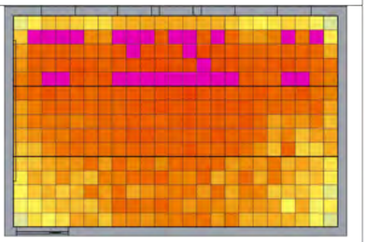
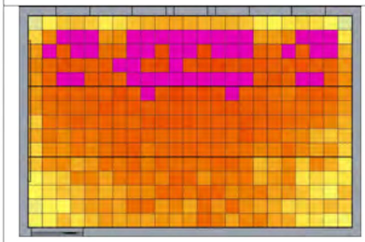
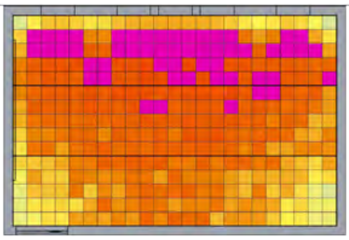
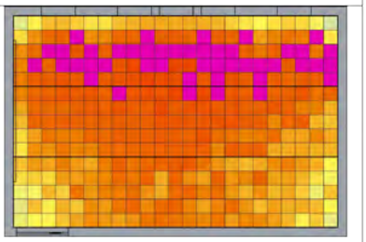
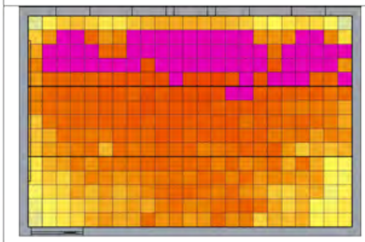
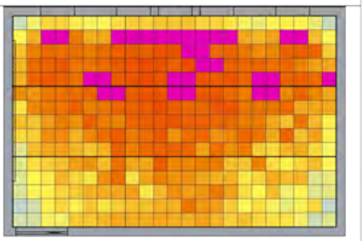
West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	2x2	155	1002	1450	472	687	960	295	650	1451	11	694	1028
	3x3	157	1010	1473	476	690	966	297	654	1501	11	700	1037
	4x4	155	1000	1442	471	685	960	295	648	1434	11	693	1025
	6x6	155	997	1460	470	684	989	294	648	1486	10	691	1024
	8x8	155	1000	1442	471	685	959	295	648	1436	11	693	1025
	12x12	152	977	1409	462	672	953	289	636	1409	10	677	1001
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	2x2	95	583	822	364	537	637	233	519	873	7	410	604
	3x3	96	591	833	368	542	642	236	524	878	7	415	612
	4x4	97	595	838	371	546	645	237	527	881	7	418	616
	6x6	97	592	833	370	544	642	237	527	881	7	415	612
	8x8	95	584	823	365	537	636	233	520	872	6	410	605
	12x12	97	594	837	371	547	648	237	529	888	7	417	615
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	2x2	55	331	451	244	394	445	160	384	562	4	232	343
	3x3	55	329	448	242	389	441	158	379	556	4	231	340
	4x4	55	330	451	243	391	444	159	381	559	4	232	342
	6x6	55	330	449	243	393	443	159	383	560	4	231	341
	8x8	55	326	443	240	386	439	157	377	555	4	228	336
	12x12	55	331	451	244	392	446	159	382	564	4	232	342
Zones	Cases	Average Illuminance values											

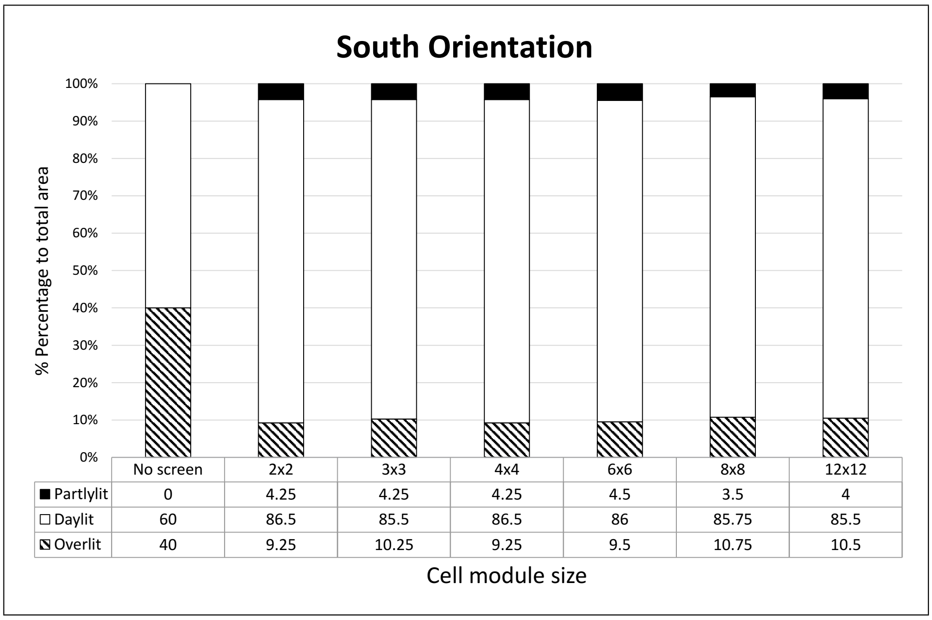
(d) West orientation.

Daylight Availability

The results of light simulation of DAv in this experiment are presented in Tables 4.21, 4.22, 4.23 & 4.24 and Figures 4.12, 4.13, 4.14 & 4.15.

Table 4.21: Distribution of DAv on the classroom plan for the south orientation with different cell module sizes (windows are located on the top side of the plan).

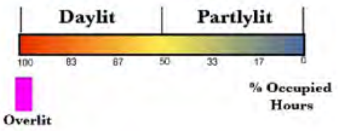
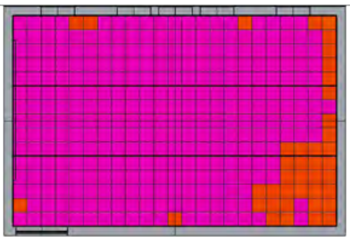
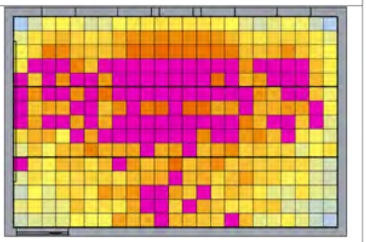
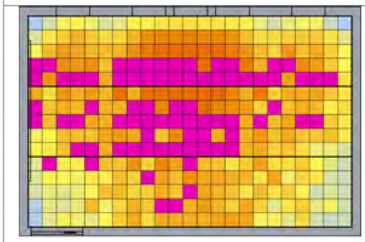
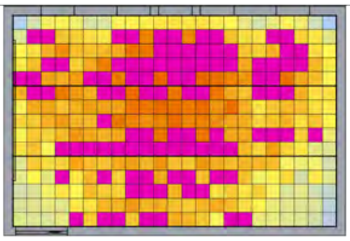
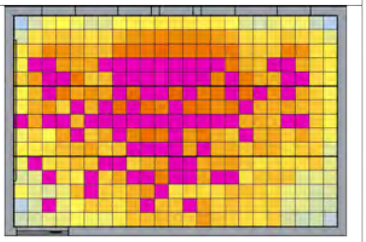
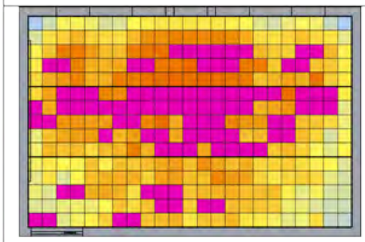
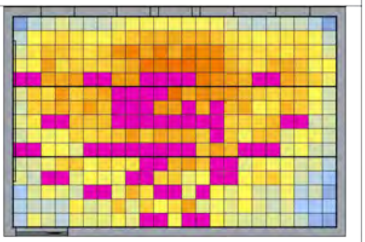
South Orientation		
Module cell size	No screen	12×12
		
8×8	6×6	4×4
		
3×3	2×2	
		

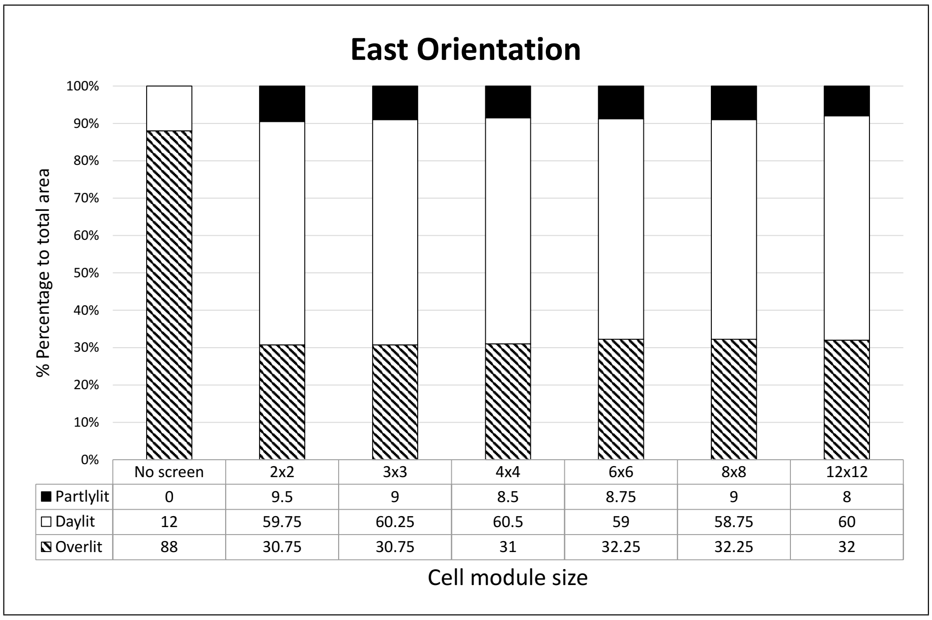


	No screen	2x2	3x3	4x4	6x6	8x8	12x12
■ Partlylit	0	4.25	4.25	4.25	4.5	3.5	4
☐ Daylit	60	86.5	85.5	86.5	86	85.75	85.5
▨ Overlit	40	9.25	10.25	9.25	9.5	10.75	10.5

Figure 4.12: DAv of cell module size cases for the south orientation.

Table 4.22: Distribution of DAv on the classroom plan for the east orientation with different cell module sizes (windows are located on the top side of the plan).

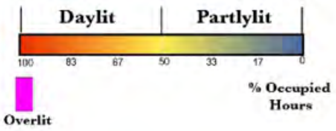
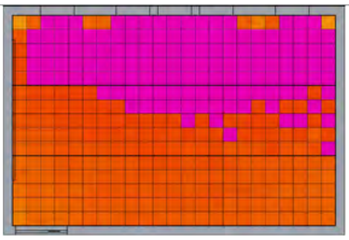
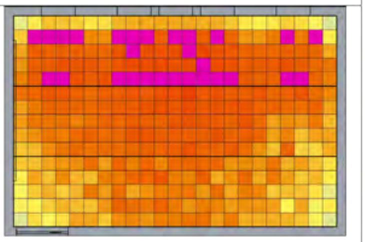
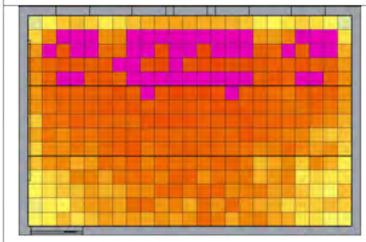
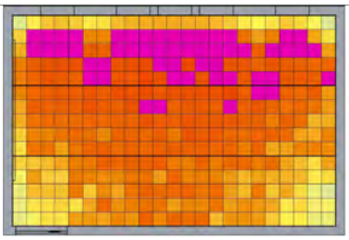
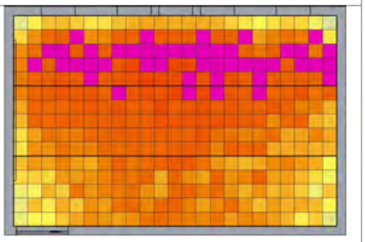
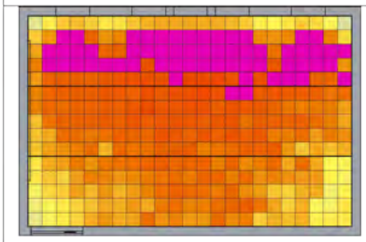
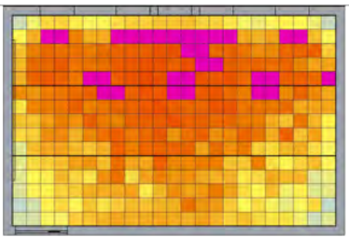
East Orientation		
Module cell size	No screen	12×12
		
8×8	6×6	4×4
		
3×3	2×2	
		

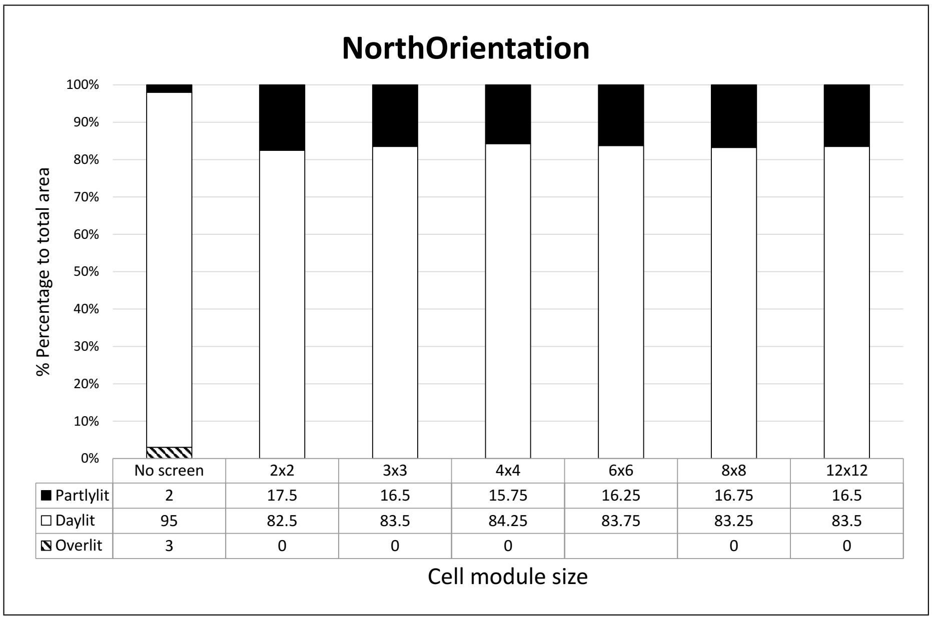


	No screen	2x2	3x3	4x4	6x6	8x8	12x12
■ Partlylit	0	9.5	9	8.5	8.75	9	8
☐ Daylit	12	59.75	60.25	60.5	59	58.75	60
▨ Overlit	88	30.75	30.75	31	32.25	32.25	32

Figure 4.13: DAv of cell module size cases for the east orientation.

Table 4.23: Distribution of DAv on the classroom plan for the north orientation with different cell module sizes (windows are located on the top side of the plan).

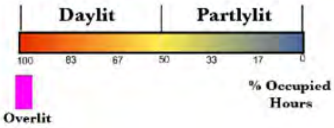
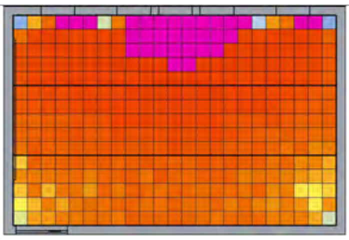
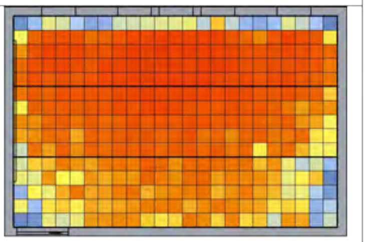
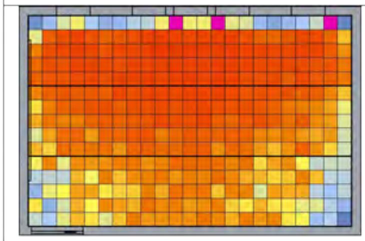
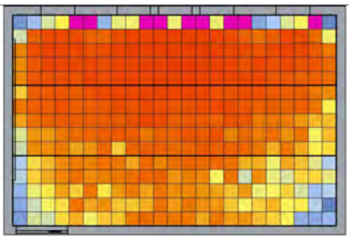
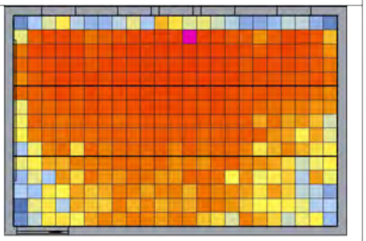
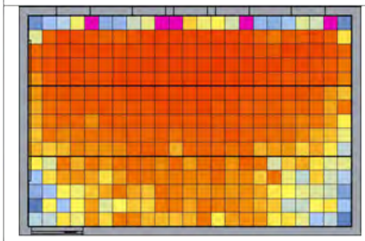
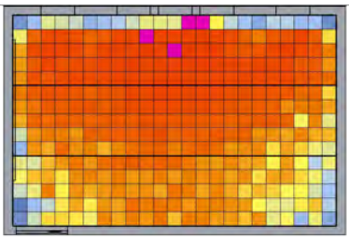
North Orientation		
Module cell size	No screen	12×12
		
8×8	6×6	4×4
		
3×3	2×2	
		

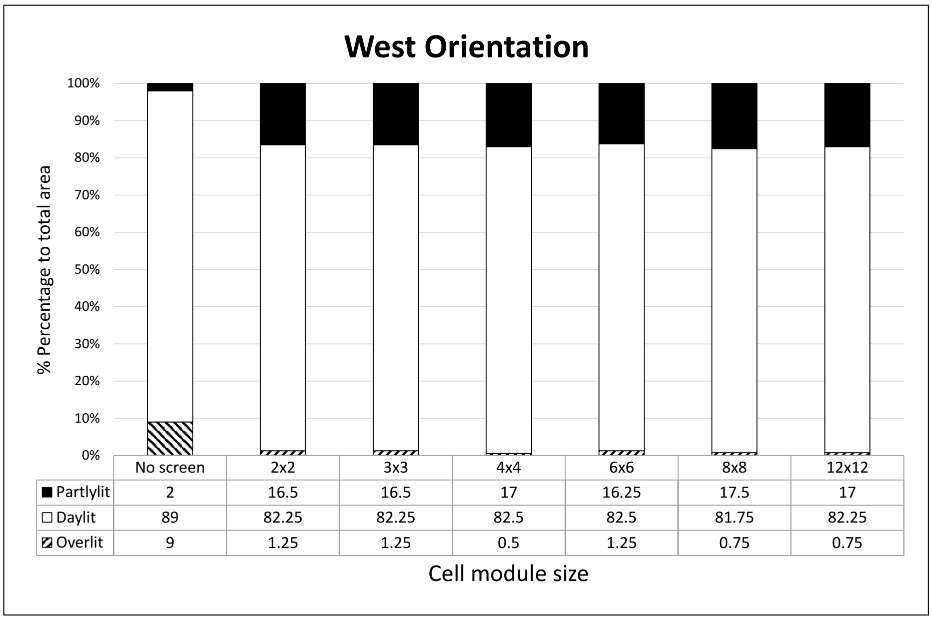


	No screen	2x2	3x3	4x4	6x6	8x8	12x12
■ Partlylit	2	17.5	16.5	15.75	16.25	16.75	16.5
☐ Daylit	95	82.5	83.5	84.25	83.75	83.25	83.5
▨ Overlit	3	0	0	0		0	0

Figure 4.14: DAv of cell module size cases for the north orientation.

Table 4.24: Distribution of DAv on the classroom plan for the west orientation with different cell module sizes (windows are located on the top side of the plan).

West Orientation		
Module cell size	No screen	12×12
		
8×8	6×6	4×4
		
3×3	2×2	
		



	No screen	2x2	3x3	4x4	6x6	8x8	12x12
■ Partlylit	2	16.5	16.5	17	16.25	17.5	17
☐ Daylit	89	82.25	82.25	82.5	82.5	81.75	82.25
▨ Overlit	9	1.25	1.25	0.5	1.25	0.75	0.75

Figure 4.15: DAv of cell module size cases for the west orientation.

The results of this stage of this experiment agreed with the result of the first stage (average illuminance). Simulating DAv proves that changing the cell module size has a minimal effect on the performance of a perforated solar screen in all orientations. It is noticeable as well that all results are laying on an acceptable level of DAv, which is providing a Daylit area of more than 50% of the total space area. This confirms the recommended values of the previous two experiments and that the recommended values of perforation percentage and depth ratio are able to provide better lighting performance of screens.

Recommended values of the studied parameter

It appears that the parameter of the cell module size has a limited effect on the daylight performance of perforated screens. Designers could use the required cell module size according to other preferences regarding other functions of perforated solar screens. For example, bigger cell module sizes can be used when it is preferable to see the outside view, and smaller cell module sizes could be used when maintaining privacy is preferable. These design decisions would not affect the light performance of screens as long as the other parameters are maintained at the recommended values.

4.2.7 The effect of opening aspect ratio

The objective of this experiment is to examine a range of aspect ratios of perforated screens, to find the values providing acceptable interior daylighting in classrooms in hot arid areas for the four main orientations (north, south, east and west). Sherif et al. (2013) have investigated the effect of opening aspect ratios on daylighting and on energy consumption for residential living rooms. Sabry et al. (2012) have previously investigated the effect of aspect ratios on daylight performance in living rooms in residential spaces. However, no previous research known to the author has investigated the effect of aspect ratio on daylight performance in classrooms.

Variation of the parameter

The opening aspect ratio is defined as the ratio between the horizontal width (H) and vertical length (V) of the cell H:V. In order to create as many aspect ratio cases as possible according to the window dimensions ($72cm \times 120cm$), a $6cm \times 6cm$ cell module size was selected. This allows screens to have a total of nine different aspect ratios, four ratios with horizontal direction (2:1, 4:1, 6:1, 12:1) and four with vertical direction (1:2, 1:4, 1:10, 1:20) and one square cell with a 1:1 ratio. Table 4.25 displays the variations of $6cm$ module to create the variations of studied aspect ratios. Using this module size allowed screens with all aspect ratios to cover the window size exactly; this would provide more accurate results than allowing screen boundaries to pass the window size. Figure 4.16 shows examples of some of the aspect ratio variations used in this experiment; it also shows the difference between Vertical direction cells and Horizontal direction cells. All of these cases are examined and compared in this experiment to find the values for the aspect ratio that achieves acceptable interior daylight for each façade orientation.

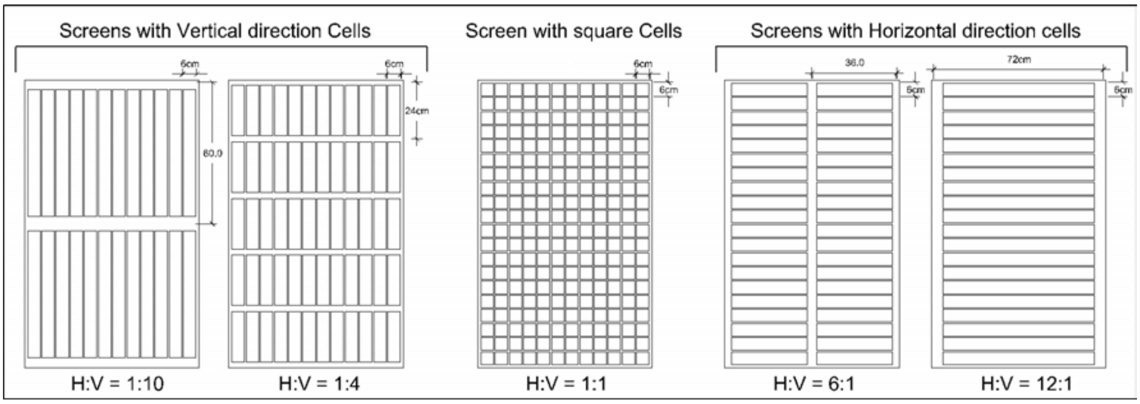


Figure 4.16: Examples of screens with different aspect ratios.

Table 4.25: Actual sizes of each perforation of the variations of opening aspect ratios tested in this experiment.

V direction		**H direction**	
Aspect ratio	**Actual size**	**Aspect ratio**	**Actual size**
1:2	$6cm \times 12cm$	2:1	$12cm \times 6cm$
1:4	$6cm \times 24cm$	4:1	$24cm \times 6cm$
1:10	$6cm \times 60cm$	6:1	$36cm \times 6cm$
1:20	$6cm \times 120cm$	12:1	$72cm \times 6cm$

Controlled parameters

To study the effect of the opening aspect ratio, it is isolated by controlling other parameters. Table 4.26 presents the controlled screen parameters. Values of controlled parameters are selected according to the results of the previous experiments in this research (perforation percentage and depth ratio), and since previous results indicate that there is minimal effect of different cell module size, this parameter is selected to be $6cm$ for the reason discussed above.

Table 4.26: Values of all parameters when testing opening aspect ratio (bold columns represent parameters values based on the results of previous experiments).

	Controlled screen parameters		
Orientation	**Perforation percentage**	**Depth ratio**	**Cell module size**
south	**90%**	**0.6**	**6**cm
east	**80%**	**0.75**	**6**cm
north	**90%**	**0.15**	**6**cm
east	**90%**	**0.15**	**6**cm

4.2.8 Results

A copy of the method of representing the results of daylight simulation is attached in Appendix H.

The results of the two daylight metrics used in the research: average illuminance and Daylight Availability are displayed and compared with the case of windows with no screens attached, and results are discussed for each of the four main orientations.

Average illuminance levels

The results of simulating average illuminance levels are presented in Table 4.27. In the south orientation, results show that using any other aspect ratio than 1:1 (square cells) could provide higher illuminance levels in all zones than screens with vertical or horizontal cells (Table 4.27a). That does not mean however, that better lighting conditions are provided since higher illuminance could result in heat and discomfort glare.

In the east orientation, screens with square cells have also provided less illuminance values than other cases. The cases of Vertical cells provided slightly higher illuminance levels than cases with Horizontal cells (Table 4.27b).

In the north orientation, there is a slight difference showing that in general, screens with horizontal direction provide higher illuminance (Table 4.27c).

In the west orientation, it is very difficult to notice any difference between the results of average illuminances (Table 4.27d).

Results show that usually cases differ from one direction to another (cases with higher V and cases with higher H); the difference however was minimal and most results were acceptable according to the set criteria. Therefore, the next stage (using DAv) would give more detailed information to allow comparison of the cases since it considers conditions with an oversupply of interior daylight.

Table 4.27: Average illuminance (lx) for opening aspect ratio cases in the three zones of each orientation (black cells, $\geq 1000lx$; grey cells, between $500lx$ and $999lx$; light grey between $300lx$ and $499lx$).

South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	12:1	100	638	827	344	554	413	269	1323	1594	6	467	670
	6:1	101	649	842	346	559	414	269	1320	1596	6	475	661
	4:1	95	608	788	327	528	393	255	1255	1523	6	444	639
	2:1	87	555	720	297	483	362	229	1144	1418	5	406	574
	1:1	71	455	591	245	399	304	187	928	1219	4	333	468
	1:2	107	700	969	337	556	414	252	1227	1552	6	509	728
	1:4	133	874	1209	400	671	499	296	1481	1761	8	636	919
	1:10	98	642	890	296	495	380	216	1049	1475	6	468	694
	1:20	107	708	982	321	537	411	233	1143	1574	7	516	763
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	12:1	92	572	729	349	549	411	264	1019	1175	6	427	583
	6:1	90	558	712	339	532	399	255	987	1154	6	416	570
	4:1	88	548	699	329	518	388	247	965	1133	6	408	559
	2:1	80	498	638	299	471	355	223	894	1074	5	371	510
	1:1	70	436	559	257	406	306	190	782	975	4	325	448
	1:2	83	519	668	303	473	353	223	898	1119	5	388	534
	1:4	87	546	702	317	495	367	233	948	1154	5	408	562
	1:10	67	420	542	239	376	282	174	729	1005	4	313	434
	1:20	69	434	561	248	389	293	181	758	1033	4	324	449
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	12:1	58	348	431	243	402	324	181	644	724	4	259	353
	6:1	57	343	426	238	393	316	177	633	714	4	256	348
	4:1	55	329	409	228	376	303	169	609	692	4	245	334
	2:1	52	313	390	216	356	286	160	586	671	3	234	318
	1:1	45	274	342	186	307	246	137	518	612	3	204	279
	1:2	49	300	374	202	333	265	149	564	679	3	223	305
	1:4	52	313	391	211	347	276	155	593	714	3	233	319
	1:10	40	245	309	162	265	212	117	468	626	2	183	251
	1:20	42	257	324	170	278	221	123	486	651	2	192	263
Zones	Cases	Average Illuminance values											

(a) South orientation.

East orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	317	2028	2187	1993	3034	1394	1185	2838	1723	17	1267	1595
	12:1	68	375	413	834	1311	237	441	1475	332	3	251	301
	6:1	64	361	389	1023	1264	224	422	1408	313	3	236	284
	4:1	62	346	380	779	1229	218	419	1382	306	3	231	277
	2:1	55	311	334	1212	1112	193	386	1216	268	2	202	243
	1:1	42	229	250	995	884	149	331	961	205	1	152	183
	1:2	75	429	464	1286	1337	220	454	1348	322	3	277	331
	1:4	104	623	663	1522	1581	283	540	1577	426	5	392	469
	1:10	117	707	761	1463	1635	315	578	1717	476	6	447	535
	1:20	126	746	820	1773	1758	333	605	1837	508	6	481	576
Mid	base	196	1096	1162	2190	2327	1074	1544	2429	1217	9	707	897
	12:1	77	402	439	1862	1030	262	781	1144	370	4	272	322
	6:1	77	399	435	1716	1024	258	796	1125	366	4	269	319
	4:1	71	368	402	2177	973	240	763	1071	338	3	248	295
	2:1	64	333	363	1711	904	213	726	991	302	3	224	265
	1:1	52	267	290	1504	761	170	634	823	239	1	179	212
	1:2	67	351	383	2372	978	208	732	1021	301	3	235	278
	1:4	80	419	456	2197	1086	236	784	1146	347	4	280	330
	1:10	83	435	474	2235	1127	241	845	1189	357	4	291	342
	1:20	85	441	481	1835	1133	243	880	1199	361	4	295	347
Far	base	113	604	627	2065	1439	764	1470	1517	816	5	387	504
	12:1	56	277	298	1683	669	232	855	735	303	2	188	225
	6:1	55	270	291	1409	655	226	906	724	294	2	184	219
	4:1	53	261	281	1410	639	217	892	701	284	2	177	211
	2:1	48	237	255	1591	598	194	805	655	254	1	161	192
	1:1	39	191	206	819	507	152	770	551	201	0	129	154
	1:2	45	222	239	1176	617	171	827	655	229	0	150	178
	1:4	50	245	264	1285	680	185	890	715	250	1	166	196
	1:10	52	255	275	1335	712	191	872	747	259	1	173	204
	1:20	52	253	273	1671	713	189	880	745	257	1	171	203
Zones	Cases	Average Illuminance values											

(b) East orientation.

North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	12:1	191	1140	1469	1085	1165	670	406	776	841	12	751	996
	6:1	187	1114	1436	1067	1141	654	398	760	823	12	734	974
	4:1	186	1112	1433	1072	1130	655	395	755	820	12	732	971
	2:1	183	1096	1413	1035	1114	645	386	743	808	12	721	958
	1:1	174	1037	1336	971	1056	614	366	705	767	11	683	906
	1:2	192	1150	1485	1036	1151	672	395	764	835	12	757	1004
	1:4	172	1035	1336	877	1040	610	353	689	755	11	681	904
	1:10	180	1082	1398	909	1083	637	367	717	787	11	712	945
	1:20	190	1148	1484	952	1144	671	385	752	828	12	755	1002
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	12:1	119	669	839	770	775	489	309	602	639	7	445	586
	6:1	116	657	825	747	759	478	301	587	625	7	437	575
	4:1	114	645	810	737	745	471	296	577	614	7	429	566
	2:1	112	635	797	714	735	463	291	568	604	7	422	556
	1:1	108	613	770	679	708	447	280	548	583	7	408	537
	1:2	112	633	796	690	724	457	286	561	598	7	421	554
	1:4	104	590	742	617	672	426	263	520	556	7	392	517
	1:10	106	598	753	627	679	429	267	525	561	7	398	524
	1:20	109	616	775	646	702	441	276	543	579	7	410	540
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	12:1	67	366	446	440	506	363	195	422	445	4	244	322
	6:1	65	354	431	422	489	351	188	407	430	4	236	312
	4:1	65	358	436	426	490	351	189	408	431	4	238	315
	2:1	64	350	427	416	482	344	185	400	423	4	233	308
	1:1	61	338	413	397	464	331	178	385	407	4	225	298
	1:2	62	342	418	399	467	334	179	388	411	4	228	302
	1:4	59	325	397	371	442	314	169	366	387	4	216	286
	1:10	60	331	404	379	450	320	172	373	394	4	220	291
	1:20	61	334	409	379	454	324	173	377	399	4	223	295
Zones	Cases	Average Illuminance values											

(c) North orientation.

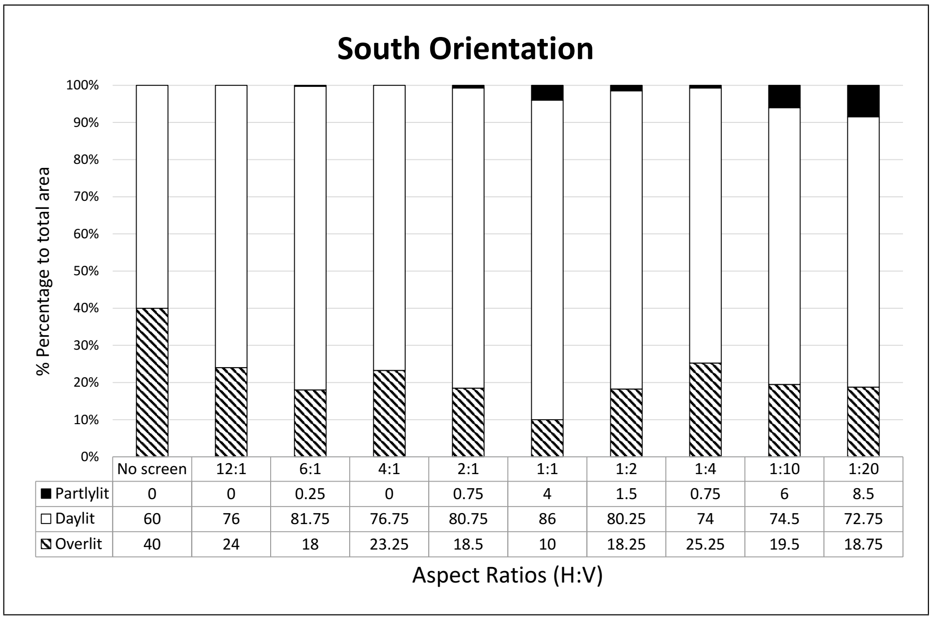
West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	12:1	170	1096	1600	515	748	1055	322	708	1608	12	759	1124
	6:1	170	1096	1600	515	748	1055	322	708	1608	12	759	1124
	4:1	168	1086	1587	511	740	1018	319	702	1610	12	752	1114
	2:1	162	1042	1523	492	713	1019	308	676	1546	11	722	1070
	1:1	152	979	1412	462	672	953	289	636	1416	10	678	1002
	1:2	169	1091	1597	505	735	1036	315	694	1607	12	756	1118
	1:4	180	1167	1703	531	774	1081	331	730	1698	13	808	1195
	1:10	184	1193	1743	540	787	1098	336	742	1735	13	826	1222
	1:20	187	1211	1753	548	799	1107	341	752	1724	13	838	1239
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	12:1	102	627	883	393	579	672	252	561	930	7	441	649
	6:1	102	627	883	393	579	672	252	561	930	7	441	649
	4:1	102	623	878	391	575	667	249	556	924	7	438	645
	2:1	100	615	867	384	564	658	245	546	911	7	432	637
	1:1	95	581	818	365	537	639	233	519	868	7	408	601
	1:2	100	612	863	382	562	663	244	543	908	7	430	634
	1:4	102	624	881	389	570	674	248	551	925	7	439	647
	1:10	101	621	876	385	565	673	246	546	918	7	436	643
	1:20	101	622	877	387	568	671	247	549	920	7	437	644
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	12:1	58	343	467	254	411	458	166	400	583	4	240	354
	6:1	58	343	467	254	411	458	166	400	583	4	240	354
	4:1	57	342	466	253	408	457	166	397	580	4	240	354
	2:1	57	339	462	250	403	453	163	393	574	4	238	351
	1:1	55	330	450	243	391	446	158	381	562	4	232	341
	1:2	55	331	451	244	393	453	159	383	564	4	232	342
	1:4	56	337	459	248	401	462	162	390	575	4	237	348
	1:10	56	337	460	248	397	462	162	388	575	4	237	349
	1:20	57	339	463	250	403	464	164	392	580	4	238	351
Zones	Cases	Average Illuminance values											

(d) West orientation.

Daylight Availability

The results of light simulation of DAv in this experiment are presented in Tables 4.28, 4.29, 4.30 & 4.31) and Figures 4.17, 4.18, 4.19 & 4.20. Results show that according to the orientation, using different openings with a different aspect ratio than 1:1 could slightly improve the daylight performance of screens and provide acceptable interior daylight levels in all cases except in the south orientation where the square opening performs better.

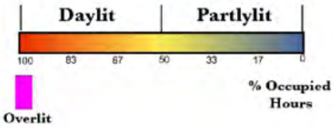
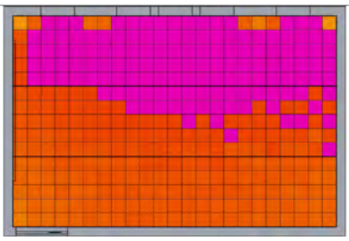
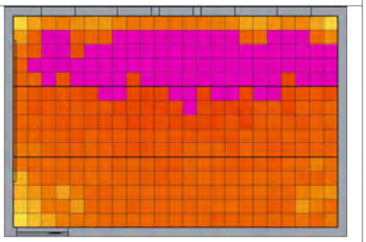
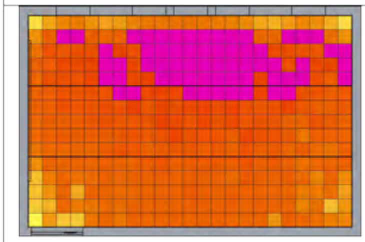
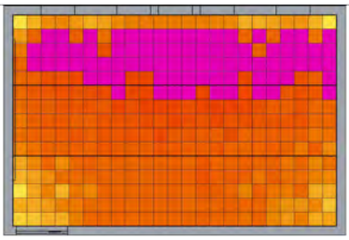
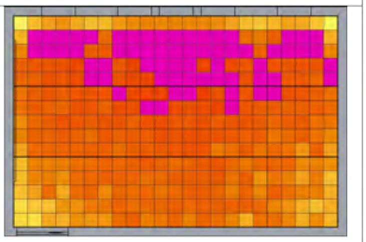
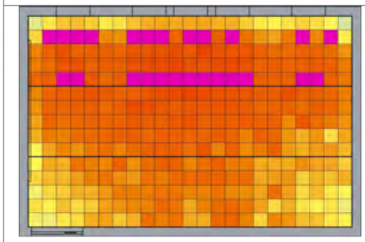
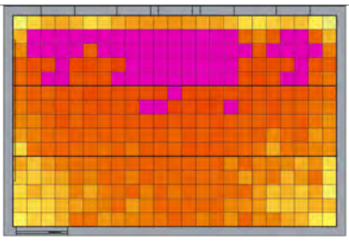
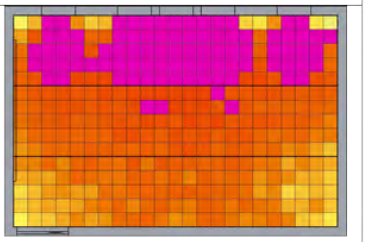
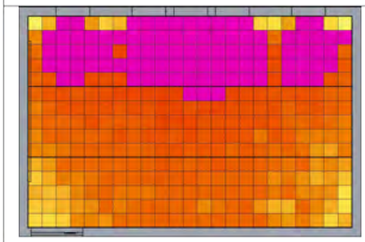
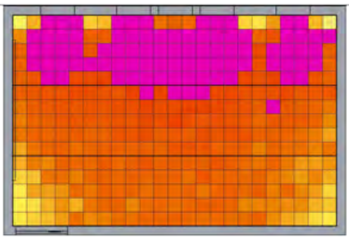
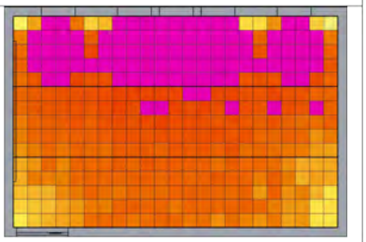
In the south orientation, the best aspect ratio to provide higher Daylit area is 1:1 with square cells; using other aspect ratios for southern orientation could reduce the daylight performance of the perforated solar screen as it reduced the Daylit area when testing the DAv metric in Figure 4.17 and Table 4.28.



	No screen	12:1	6:1	4:1	2:1	1:1	1:2	1:4	1:10	1:20
■ Partlylit	0	0	0.25	0	0.75	4	1.5	0.75	6	8.5
☐ Daylit	60	76	81.75	76.75	80.75	86	80.25	74	74.5	72.75
▧ Overlit	40	24	18	23.25	18.5	10	18.25	25.25	19.5	18.75

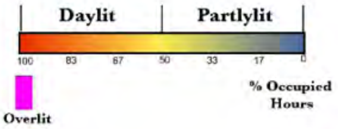
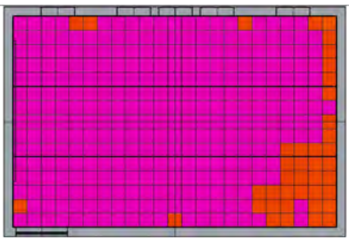
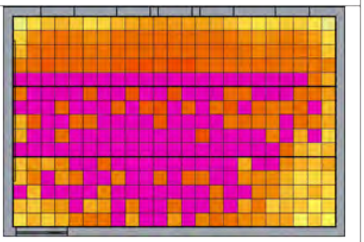
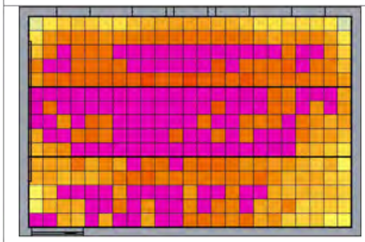
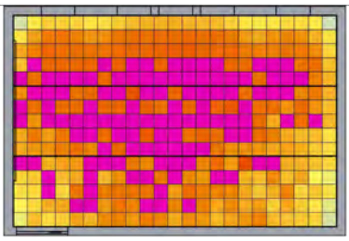
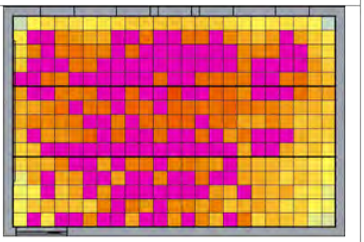
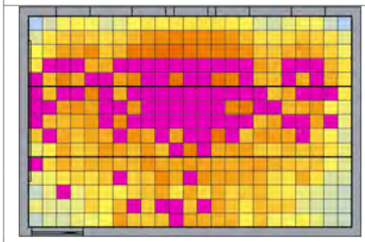
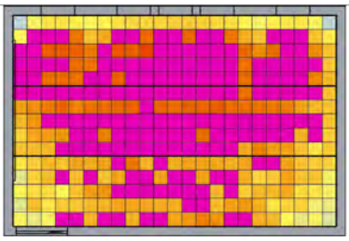
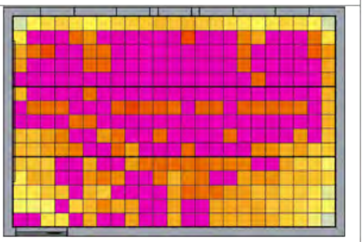
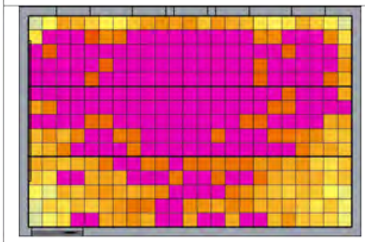
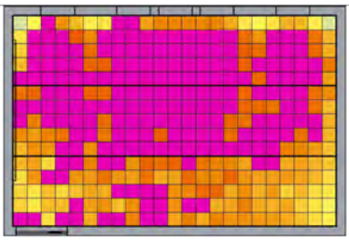
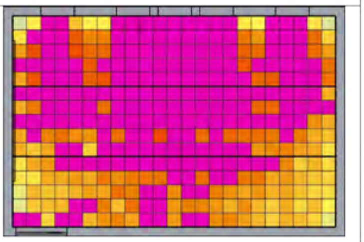
Figure 4.17: DAv of aspect ratio cases for the south orientation.

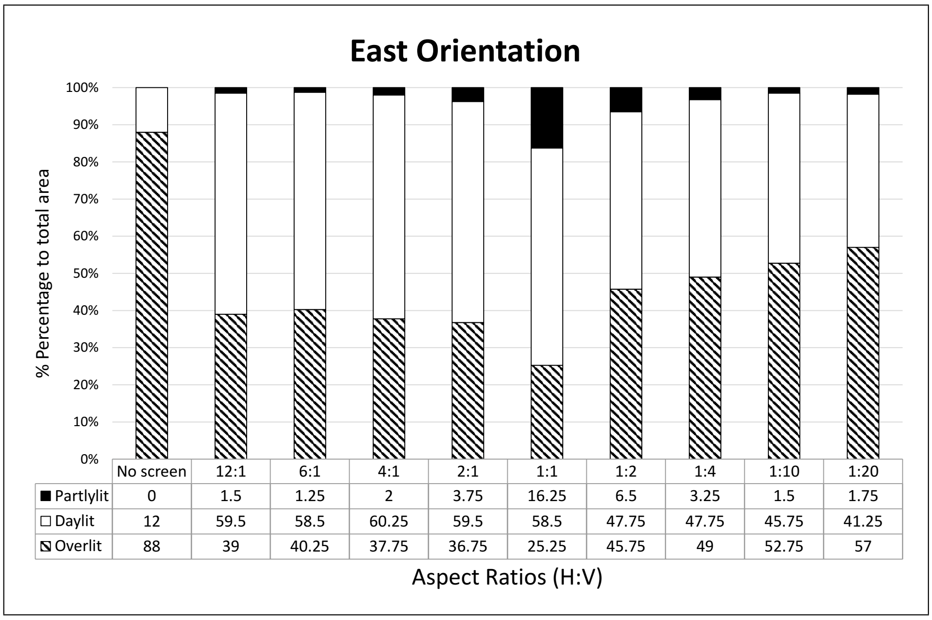
Table 4.28: Distribution of DAv on the classroom plan for the south orientation with different aspect ratios (windows are located on the top side of the plan).

South Orientation		
Aspect ratio	No screen	12:1
		
6:1	4:1	2:1
		
1:1	1:2	1:4
		
1:6	1:10	1:20
		

The results of the east orientation are displayed in Table 4.29 and show that using cells with a horizontal direction is likely to provide slightly more Daylit area and reduce Partlylit area. Although screens with vertical direction cells result in higher illuminance values in the first stage, they increased the Overlit area dramatically and thus reduced the Daylit area in Figure 4.18.

Table 4.29: Distribution of DAv on the classroom plan for the east orientation with different aspect ratios (windows are located on the top side of the plan).

East Orientation		
Aspect ratio	No screen	12:1
		
6:1	4:1	2:1
		
1:1	1:2	1:4
		
1:6	1:10	1:20
		

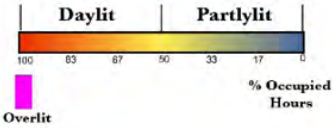
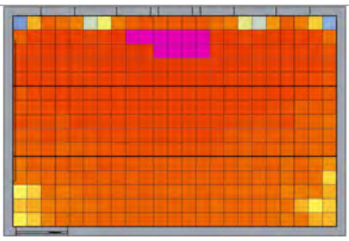
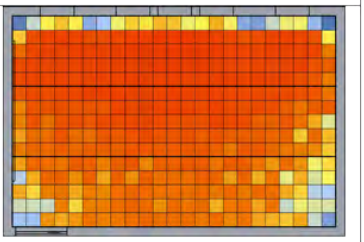
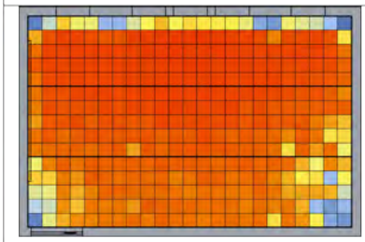
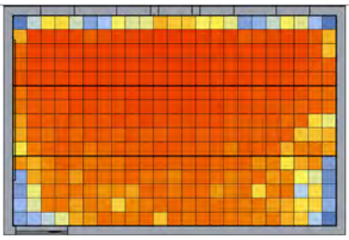
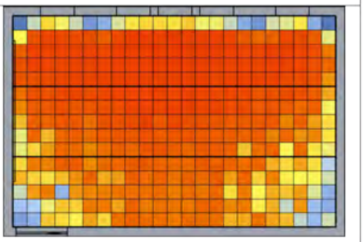
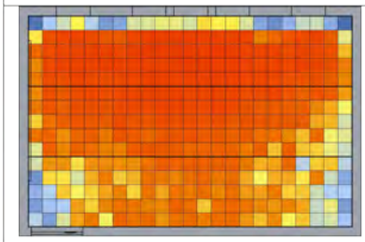
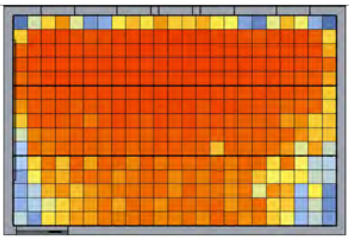
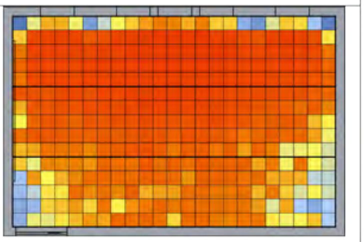
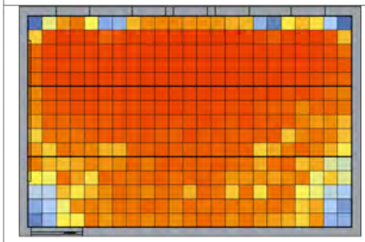
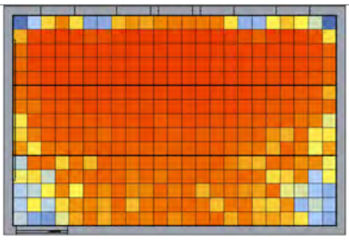
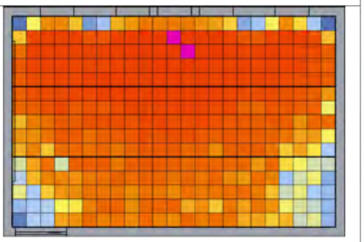


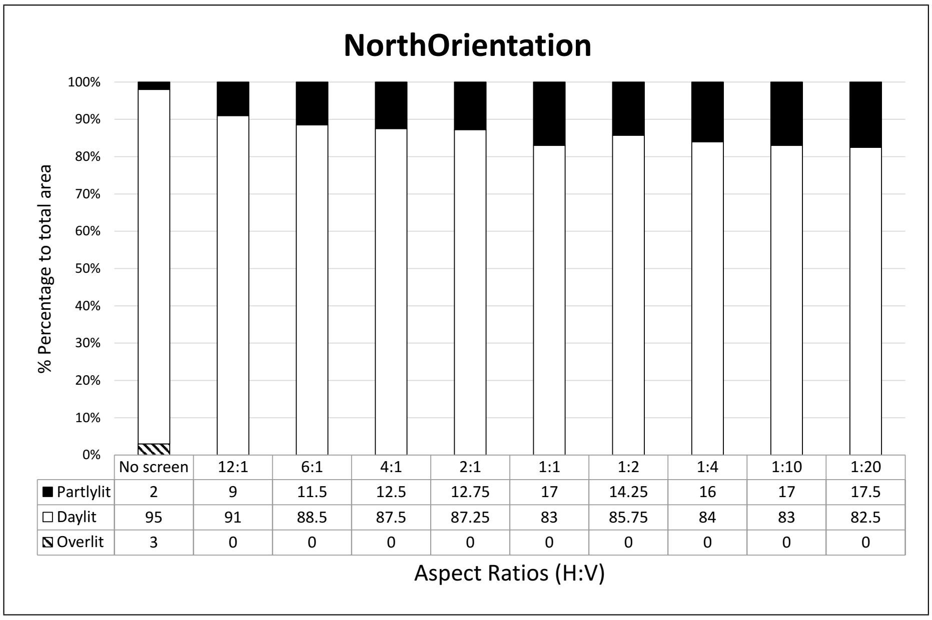
	No screen	12:1	6:1	4:1	2:1	1:1	1:2	1:4	1:10	1:20
■ Partlylit	0	1.5	1.25	2	3.75	16.25	6.5	3.25	1.5	1.75
□ Daylit	12	59.5	58.5	60.25	59.5	58.5	47.75	47.75	45.75	41.25
▧ Overlit	88	39	40.25	37.75	36.75	25.25	45.75	49	52.75	57

Figure 4.18: DAv of aspect ratio cases for the east orientation.

In the west and north orientations, results show that using screens with either horizontal or vertical direction cells provides more Daylit area than square cells, with a slightly more Daylit area for screens with horizontal cells in Figures 4.19 & 4.20 and Tables 4.30 & 4.31.

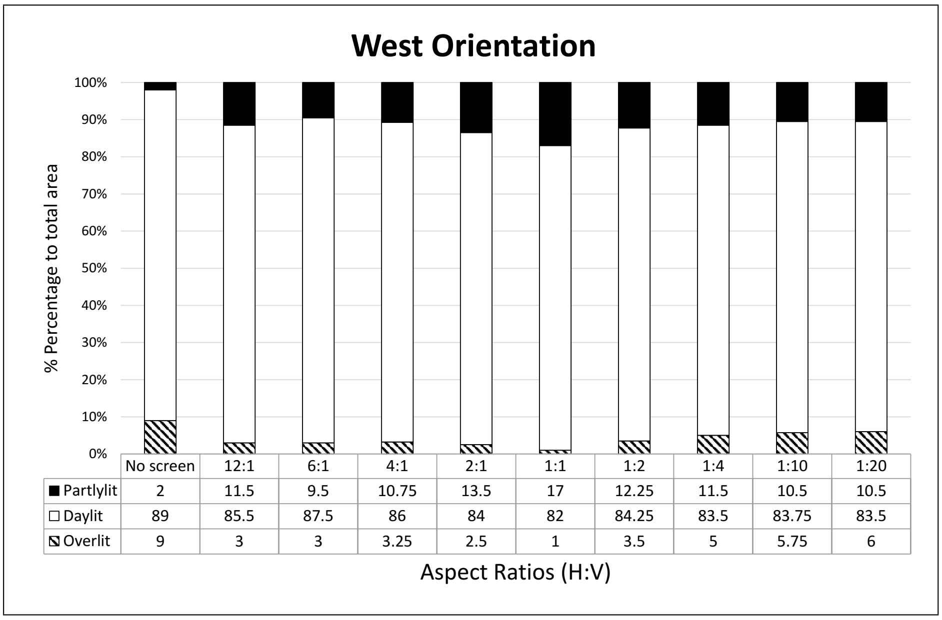
Table 4.30: Distribution of DAv on the classroom plan for the north orientation with different aspect ratios (windows are located on the top side of the plan).

North Orientation		
Aspect ratio	No screen	12:1
		
6:1	4:1	2:1
		
1:1	1:2	1:4
		
1:6	1:10	1:20
		



	No screen	12:1	6:1	4:1	2:1	1:1	1:2	1:4	1:10	1:20
■ Partlylit	2	9	11.5	12.5	12.75	17	14.25	16	17	17.5
☐ Daylit	95	91	88.5	87.5	87.25	83	85.75	84	83	82.5
▨ Overlit	3	0	0	0	0	0	0	0	0	0

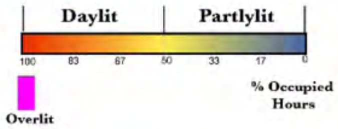
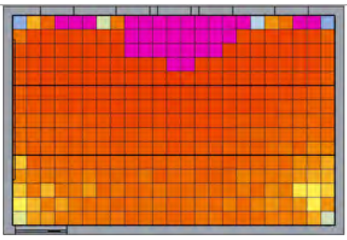
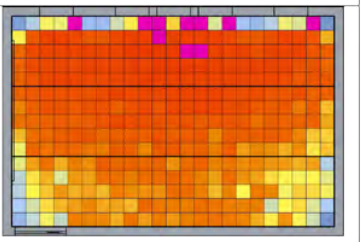
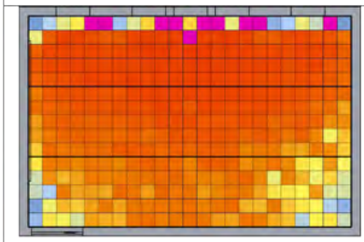
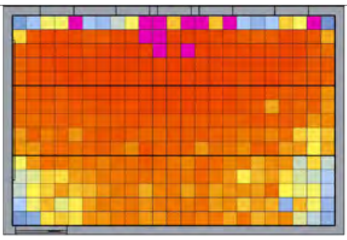
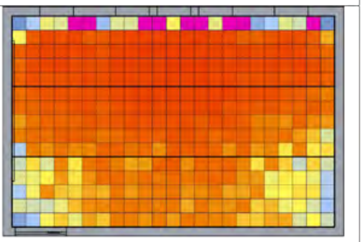
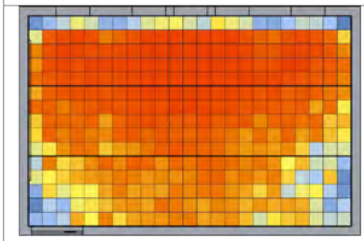
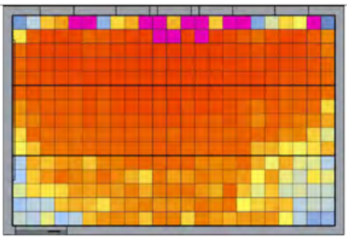
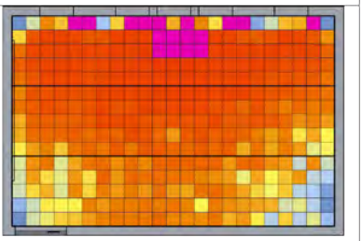
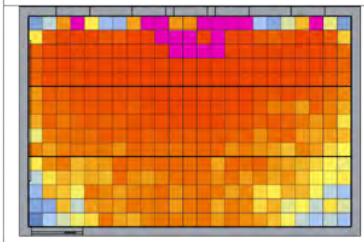
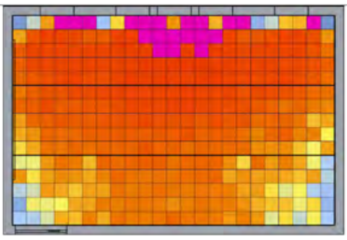
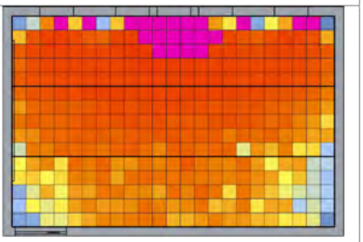
Figure 4.19: DAv of aspect ratio cases for the north orientation.



	No screen	12:1	6:1	4:1	2:1	1:1	1:2	1:4	1:10	1:20
■ Partlylit	2	11.5	9.5	10.75	13.5	17	12.25	11.5	10.5	10.5
☐ Daylit	89	85.5	87.5	86	84	82	84.25	83.5	83.75	83.5
▨ Overlit	9	3	3	3.25	2.5	1	3.5	5	5.75	6

Figure 4.20: DAv of aspect ratio cases for the west orientation.

Table 4.31: Distribution of DAv on the classroom plan for the west orientation with different aspect ratios (windows are located on the top side of the plan).

West Orientation		
Aspect ratio	No screen	12:1
		
6:1	4:1	2:1
		
1:1	1:2	1:4
		
1:6	1:10	1:20
		

Recommended values of the studied parameter

Based on the results of this experiment, the recommended values of the parameter of thr opening aspect ratio are:

- Square cells with a 1:1 aspect ratio for the south orientation.
- Cells with a horizontal direction, especially with a 4:1 aspect ratios for the east orientation.
- Cells with a horizontal direction, especially with a 12:1 aspect ratio for the north orientation.
- Cells with a horizontal direction, especially with a 6:1 aspect ratio for the east orientation.

However, the difference is barely notable and most cases have successfully achieved Daylit areas of more than 50% of the total area, except cells with a vertical direction cells on the east facing façade.

4.2.9 Discussion of phase one

The results of all experiments of phase one are summarised in Table 4.32. This table displays the recommended value for each parameter for each of the main orientations that helped to achieve an acceptable level of indoor daylight in the studied classroom by providing a Daylit area of more than 50% of the total space area.

Table 4.32: Summary of recommended values of the studied parameters on main orientations based on the results of phase one.

	south	**east**	**north**	**east**
Perforation %	90%	80%	90%	90%
Depth Ratio	0.6	0.75	0.15	0.15
Cell module size	No effect	No effect	No effect	No effect
Aspect Ratio	1:1	4:1	12:1	6:1

The simulation of a range of perforation percentages for a solar screen demonstrates that the effect of perforation percentage on indoor daylight is related to the orientation of the window and the time of the day. In the east and south orientations, there is a linear reduction of Overlit area with the use of solar screens with lower perforation percentage. In the west orientations however, there are minimal Overlit areas as would be expected considering the fact that school days in this context finish at 13:30 before the direct sun can hit the eastern façade. Similarly, minimal Overlit areas are also noticed in the north orientation because of the location of Riyadh, 24.7° north of the tropic of Cancer. Results indicate that 70%, 80% and 90% perforation percentages would provide acceptable Daylit area in the east orientation (≥50% of the total area) and 90% & 70% perforation percentages in the south orientations. In the west and north orientations, there is a dramatic reduction of Daylit areas between the 'no screen' case and the 90% perforation percentage screen when the depth ratio is controlled to 0.75 in the first experiment. Other parameters could be the reason for that leap, for example, using a lower depth ratio could provide more indoor daylight with a screen having the same perforation percentage.

The results of analysing the effect of perforation percentage can be tested against the results of similar work of Sherif et al. (2012b) which would provide confidence in the results. Table 4.33 displays a comparison between the results of testing the perforation percentage in this research and in the aforementioned paper; it compares the perforation percentages that achieved the highest Daylit area and also the achieved Daylit area between this research and the work by Sherif et al. (ibid.).

Table 4.33: Results comparison with a previous study by Sherif et. al (2012b).

	south	**east**	**north**	**east**
the results of Sherif et. al	90%	90%	NA	90%
Achieved Daylit by Sherif et. al	46%	23%	NA	23%
the results of this research	90%	80%	90%	90%
Achieved Daylit in this research	82.5%	58.5%	8.5%	12.25%

The table shows similarity between the results of both studies. They both recommend 90% perforation percentage for the south and the west orientations, a slight difference can be found on the east orientation. This research recommends an 80% perforation percentage and the previous study by Sherif et. al (2012b) recommends a 90%; however, a 90% perforation percentage also provides acceptable Daylit areas in this research with more than 50% of the total area. The north orientation was not studied by Sherif et al. (2012b) and therefore, no results were available for comparison in the table. It can be noticed that the achieved daylit area is higher in this research in the south orientation than the achieved daylight by Sherif et al. with 82.5% compared to 46%. The achieved daylit area was also higher in this research in the east orientation with 58.5% compared to 23%. This can be explained by the difference in the studied context. The virtual classroom in this study has five windows, whereas, the virtual living room in the compared experiment has one window. Conversely, this research achieved lower Daylit area in the west. The reason for that is the difference in the occupancy schedule; indoor daylight in this research is tested only for school hours which finishes at 13:00, which means less daylight during afternoon hours at the west orientation.

The results of simulated screens using a range of different values of depth ratio in the second experiment prove that using perforated solar screens could enhance Daylight Availability and increase Daylit area effectively; in some cases the percentage of Daylit area multiplied from 12% with no screen to about 60% in the east orientation. It is also proven that lower depth ratios than 0.75 could emit more daylight through solar screens especially on north and west orientations, despite that Sherif et al. (2012c) and Sherif et al. (2011) recommended the use of 0.75 depth ratio to save energy. In this research, the provision of indoor daylight for school pupils for health and productivity concerns is of greater significance than saving energy. As mentioned in Chapter 2, to the author's knowledge, previous research has not tested the effect of depth ratio on indoor daylight alone by isolating other parameters. Instead, Sherif et al. (2012c) have tested the effect of depth ratio on energy consumption and Wagdy and Fathy (2015, 2016) have tested some cases with a combination of different values of different parameters at the same time. Therefore, a comparison cannot be made between the results of recommended depth ratios in this research and any previous study.

This phase also indicates that cell module size has minimal effect on the daylight performance of perforated screens as long as depth ratio and perforation percentage are maintained, meaning that the cell module size can be selected according to the preferences of the designer and the required function of the screen. For example, if the designer preferred not to obstruct the view to the outside in a similar context, a bigger cell module size can be used without affecting the daylight performance of the screen as long the recommended depth ratio and perforation percentages were used according to the orientation. Conversely, if the privacy was the priority function, cell module size can be set as small as possible which could provide privacy without affecting the daylight performance. Similar to the depth ratio results, a comparison cannot be made between the results of the recommended cell module size in this research and any previous study.

When testing the effect of opening aspect ratios, the selected range of variations is selected intentionally to allow the dimension of screens to be exactly as the dimension of the window ($0.72m \times 1.2m$). The author is questioning the accuracy of previous research that used screens bigger than windows when testing the effect of aspect ratios. For example, Sabry et al. (2014) used a cell module size of $14cm$ and an opening aspect ratio of 12:1. That would make the dimension of each perforation $172cm \times 14cm$, and the screen dimension $3.44m \times 1.54m$ on a window size $2m \times 1.4m$.

The results of testing variations of opening aspect ratios recommend using a different aspect ratio than 1:1 for the north and west façades, and using a 1:1 aspect ratio in the south. For the east orientation, results also recommend using only screens with cells of horizontal direction. However, the Daylit area is increased only slightly and most cases of aspect ratios in all main orientations achieved adequate levels of daylighting performance providing a Daylit area of more than 50% of the total space. Only the screens with cells in a vertical direction in the east orientation failed to achieve acceptable Daylit areas; in these cases, Overlit areas occupied about half of the total area of the classroom. Therefore, even if the aspect ratio is kept at 1:1 in all orientations, screens would still provide acceptable interior daylight levels, and when using horizontal direction screens the Daylit area is increased only less than 5%.

The results of analysing the effect of the opening aspect ratio can be tested against the results of similar work by Sherif et al. (2012a) which would provide confidence in the results. Table 4.34 displays a comparison between the results of testing the opening aspect ratio in this research and in the aforementioned paper; it compares the opening aspect ratio that achieved the highest Daylit area and also the achieved Daylit area in this research and the work of Sherif et al. (ibid.).

Table 4.34: Results comparison with a previous study by Sherif et. al (2012a).

	south	**east**	**north**	**east**
The results of Sherif et. al	18:1	18:1	12:1	18:1
Achieved Daylit by Sherif et. al	73%	53%	91%	87.5%
The results of author	1:1	4:1	12:1	6:1
Achieved Daylit in this research	82.5%	58.5%	8.5%	12.25%

The table shows similarity between the results of both studies; they both recommend using screens with cells in a horizontal direction cells in the east, north and west orientations. Although the values were different, the recommended ratios by the previous study have also provided acceptable indoor daylight in the experiment of this research by achieving 50% or more Daylit area. The achieved Daylit area in the two experiments on the east orientation are very close, whereas, in the west orientation the achieved area in this research is much less due to the different occupancy time as the school day finishes at 13:00 and afternoon daylight after school hours is not considered. The results for the south orientation show some differences between this research and the study by Sherif et al. (ibid.). The aspect ratio that achieved the highest Daylit area is the square cell with a 1:1 aspect ratio, whereas it was the cell with an 18:1 aspect ratio which is a cell of a horizontal direction in the previous study by . However, all screens with horizontal direction cells achieve acceptable Daylit levels of more than 50% Daylit area. It can be also seen in the table that the achieved Daylit area in this research is much lower than the one in the previous study by Sherif et. al (2012a). The reason for that is the difference in the occupancy schedule, as indoor daylight in this research is tested only for school hours which finish at 13:00 meaning that there is less daylight during afternoon hours at the west orientation.

4.3 Phase two: Testing if selected order of experiments produced bias

The results of the previous phase (phase one) recommend values of four parameters for perforated screens to improve indoor daylighting in classrooms. The recommended values of each parameter are presented in Table 4.32. These recommended values of each previously studied parameter are used to control all parameters except the one that is being studied in that experiment. Therefore, the four experiments depend on each other and one can challenge that the selected sequence of the four experiments might have an effect on the results and using a different sequence might have resulted in different outcomes. For example, the depth ratio is controlled to 0.75 when testing the perforation percentage, then the results of that experiment recommended using a 90% perforation in the north orientation. Then the results of testing the effect of depth ratio recommended using a 0.15 depth ratio in the north orientation. One might argue that if the depth ratio was tested first then the 0.15 depth ratio might increase the Overlit area when testing the perforation percentage, and 90% might provide a higher Overlit area and thus a lower Daylit area.

Therefore, this phase aims to verify that the selected order of the experiments in phase one had no effect on the final result by repeating the first experiment conducted in phase one (the effect of perforation percentage) using the final recommended values for each orientation in Table 4.32 to control other parameters, for instance a depth ratio of 0.15 in the north.

4.3.1 The effect of perforation percentage

The objective of this experiment is to make sure that the random sequence of the experiments has no effect on the final results of phase one. The same range of cases of different perforation percentages used in phase one are tested again using parameters value of the results of all the experiments in phase one. The results of this phase are compared with the results of the first phase, where the perforation percentage is tested using assumed values to control the other parameters.

The studied cases

The first experiment studying the effect of perforation percentages on the performance of perforated screens is repeated here for west, north and south facing façades using the results of phase one to control other parameters (Depth ratio, aspect ratio), cell module size is ignored since it was found from the results of phase one that it does not affect the daylight performance of screens. Table 4.35b represents values of controlled parameters used to repeat the perforation percentage study in this phase. However, the test for the east-facing façade is not repeated in this phase since the result of the depth ratio experiment in phase one recommends using 0.75 for the east orientation and this value is exactly what is used in the first experiment and thus, would result in similar results. Although the opening aspect ratio experiment recommends using 4:1 in the east orientation, the difference is insignificant (less than 1%) and it would not have a strong effect on the result. The same lighting simulation methods explained and used in phase one are used here in this phase.

Table 4.35: Comparing values of controlled parameters when testing perforation percentages in phase one and in phase two (the east orientation is bold to show that it is the same and does not need to be repeated).

(a) Phase one.

	Controlled parameters		
Orientation	Depth ratio	Aspect ratio	Cell module size
south	0.75	1:1	6cm
east	**0.75**	**1:1**	**6**cm
north	0.75	1:1	6cm
west	0.75	1:1	6cm

(b) Phase two.

	Controlled parameters		
Orientation	Depth ratio	Aspect ratio	Cell module size
south	0.6	6:1	6cm
east	**0.75**	**4:1**	**6**cm
north	0.15	12:1	6cm
west	0.15	1:1	6cm

Controlled parameters

The only difference between this study and the previous one in phase one, is the values used to control the other parameters. Table 4.35 compares the values of controlled parameters between phase one (Table 4.35a) and phase two (Table 4.35b). The table also highlights the parameter values of the east-facing façade to show the similarity between them and to justify that it is unnecessary to repeat the test for the east-facing Façade.

4.3.2 Results

A copy of the method of representing the results of daylight simulation is attached in Appendix H.

The results of the two used daylight metrics: average illuminance and Daylight Availability are displayed and compared with the case for windows with no screens attached, and results are discussed for each of the four main orientations.

Average illuminance levels

The results of simulating average illuminance levels are presented in Table 4.36. The results show that using perforated screens is able to reduce the high illuminance values in comparison to to the case for windows with no screens into acceptable levels (300–500lx), especially in Mid and Near zones. The only times that using perforated screens is not recommended are in early mornings of Winter and Spring where even without screens the illuminance is less than 300lx in Table 4.36. When compared with the results of studying perforation percentages in phase one (when using a depth ratio of 0.75), it can be noticed that illuminance levels at Far zones are improved dramatically, especially in the north and west (when using a depth ratio of 0.15).

The results in table 4.36 also confirms the finding of the same experiment in phase one, that is to say that using perforated screens is able to improve the interior daylight distribution and uniformity by increasing illuminance levels in Far and Mid zones comparing with Near zones. When comparing the ratio between Mid and Near zones for the case of 90% perforation and the case with no screen, it can be noticed that this spatial ratio when using screens is higher in all cases except the afternoon in summer and autumn only in the west orientation. Exactly similar for the Far zones, the spatial ratio is also higher when using screens except in afternoon in summer and winter in the west orientation.

Table 4.36: Average illuminance (lx) for perforation percentage cases in the three zones of each orientation (black cells, $\geq 1000lx$; grey cells, between $500lx$ and $999lx$; light grey, between $300lx$ and $499lx$).

South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	90%	75	478	620	256	416	317	194	922	1211	4	350	492
	80%	59	378	490	205	334	253	157	780	994	3	277	389
	70%	47	296	383	164	267	203	126	628	797	3	217	305
	60%	34	219	282	123	202	155	95	480	606	1	160	226
	50%	25	156	201	90	147	115	70	346	438	0	114	162
	40%	17	105	134	61	101	78	47	236	294	0	76	110
	30%	9	60	76	35	59	46	28	136	169	0	43	60
	20%	3	22	28	14	22	18	10	50	62	0	16	22
	10%	0	6	7	3	6	5	2	12	15	0	4	6
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	90%	74	460	588	273	430	323	201	773	957	4	342	471
	80%	57	357	456	213	338	255	158	650	787	4	265	366
	70%	46	289	370	172	273	206	127	528	639	3	215	296
	60%	37	233	297	139	221	167	103	422	509	1	173	238
	50%	26	160	204	96	154	117	72	297	358	0	119	163
	40%	17	109	138	66	105	80	49	204	243	0	80	111
	30%	10	64	82	40	64	49	29	120	144	0	47	66
	20%	3	20	25	13	20	16	9	38	46	0	15	20
	10%	0	6	7	4	6	5	2	11	13	0	4	6
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	90%	49	296	369	201	330	263	147	522	614	3	220	301
	80%	37	227	283	153	254	203	113	432	496	1	169	230
	70%	32	192	240	129	213	169	95	360	416	0	143	195
	60%	25	151	189	101	167	134	74	282	327	0	112	154
	50%	18	108	134	72	120	96	53	202	234	0	80	110
	40%	13	77	96	51	85	68	38	144	165	0	57	78
	30%	8	45	56	30	51	41	23	85	98	0	34	46
	20%	2	15	18	10	16	13	7	27	32	0	11	15
	10%	0	5	6	4	6	5	2	9	11	0	4	5
Zones	Cases	Average Illuminance values											

(a) South orientation.

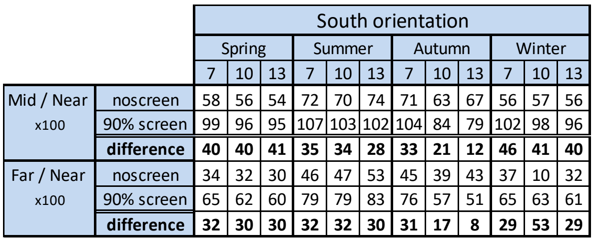
North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	90%	191	1141	1470	1085	1166	671	404	775	840	12	751	997
	80%	171	1018	1310	991	1047	596	365	695	750	11	670	888
	70%	147	881	1135	845	900	518	312	599	649	9	580	769
	60%	122	728	938	712	746	428	260	497	538	7	479	636
	50%	99	592	763	575	604	347	210	403	437	6	390	517
	40%	73	435	559	440	450	257	158	300	324	4	286	380
	30%	48	284	365	289	295	169	104	198	214	3	187	248
	20%	26	153	195	164	164	94	58	110	118	0	100	133
	10%	9	53	68	60	58	33	20	39	42	0	35	46
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	90%	118	665	835	765	769	485	306	596	633	7	442	582
	80%	105	589	739	687	683	429	272	528	561	7	392	515
	70%	91	514	645	599	597	376	237	462	491	6	342	451
	60%	78	439	552	505	505	318	200	390	416	5	292	385
	50%	60	340	427	389	396	248	156	305	323	4	226	298
	40%	46	257	323	296	299	188	118	230	244	2	171	225
	30%	31	174	219	201	203	127	80	155	165	1	116	153
	20%	17	96	120	114	114	71	44	86	91	0	64	84
	10%	7	37	47	44	44	28	17	34	35	0	25	32
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	90%	66	362	441	438	500	358	193	416	439	4	241	319
	80%	59	323	393	394	446	319	173	371	391	4	215	284
	70%	50	277	337	339	384	275	148	319	336	3	184	244
	60%	42	233	284	286	322	230	124	267	282	2	155	205
	50%	33	184	225	227	254	181	97	210	222	0	123	162
	40%	25	137	167	171	189	134	73	156	165	0	91	121
	30%	16	91	111	113	126	89	48	104	109	0	60	80
	20%	10	54	66	68	75	53	29	61	65	0	36	48
	10%	3	19	23	24	26	18	10	21	23	0	12	17
Zones	Cases	Average Illuminance values											

(b) North orientation.

West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	90%	170	1091	1588	514	745	1053	321	706	1591	12	756	1118
	80%	146	941	1356	446	648	920	279	614	1348	10	652	964
	70%	123	793	1141	376	546	783	235	517	1135	8	549	811
	60%	102	655	943	313	455	646	196	432	950	7	454	672
	50%	85	549	791	262	379	518	164	359	780	6	381	563
	40%	85	384	553	185	268	369	116	254	549	4	266	394
	30%	38	244	351	119	174	246	75	166	367	2	169	251
	20%	15	95	134	51	76	114	32	72	72	0	66	97
	10%	7	43	62	22	33	49	14	32	68	0	30	45
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	90%	103	629	885	394	579	673	251	560	929	7	441	650
	80%	91	558	785	349	513	596	223	497	827	6	392	577
	70%	78	476	670	299	440	513	191	425	710	5	334	492
	60%	64	393	553	245	361	424	156	349	588	4	276	407
	50%	54	331	467	205	300	334	131	290	482	4	232	342
	40%	54	235	332	145	213	237	93	206	343	2	165	243
	30%	24	146	205	91	135	162	58	130	225	0	102	151
	20%	13	78	109	49	72	89	31	70	70	0	54	80
	10%	5	30	42	18	28	34	12	27	47	0	21	31
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	90%	58	348	473	257	416	466	168	406	588	4	244	359
	80%	51	306	417	227	367	410	149	358	521	4	215	317
	70%	43	256	349	189	305	344	123	298	438	3	180	265
	60%	36	213	290	157	253	285	102	247	364	1	149	220
	50%	30	177	243	130	207	222	84	202	294	0	125	183
	40%	30	123	168	89	143	153	58	139	204	0	86	127
	30%	13	82	112	60	96	109	39	93	141	0	58	85
	20%	7	41	56	30	49	58	20	48	48	0	29	43
	10%	2	16	22	12	20	23	8	19	29	0	11	17
Zones	Cases	Average Illuminance values											

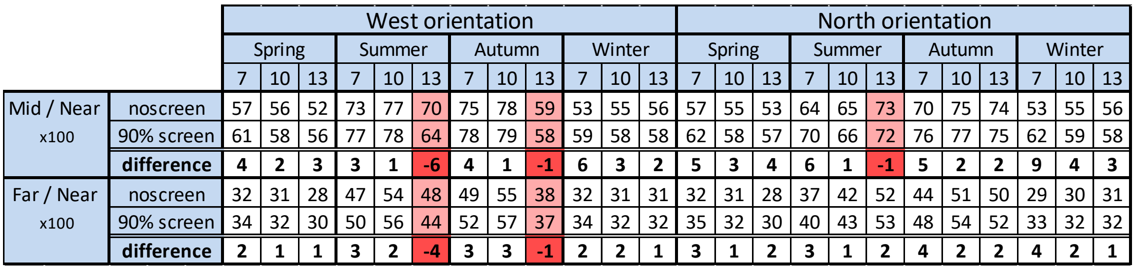
(c) West orientation.

Table 4.37: Comparing spatial distribution ratio between zones with and without using perforated screens of 90% perforation percentage in the south and east orientations.



		South orientation											
		Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	58	56	54	72	70	74	71	63	67	56	57	56
	90% screen	99	96	95	107	103	102	104	84	79	102	98	96
	difference	**40**	**40**	**41**	**35**	**34**	**28**	**33**	**21**	**12**	**46**	**41**	**40**
Far / Near x100	noscreen	34	32	30	46	47	53	45	39	43	37	10	32
	90% screen	65	62	60	79	79	83	76	57	51	65	63	61
	difference	**32**	**30**	**30**	**32**	**32**	**30**	**31**	**17**	**8**	**29**	**53**	**29**

Table 4.38: Comparing spatial distribution ratio between zones with and without using perforated screens of 90% perforation percentage in the north and west orientations, (red cells represent where that the ratio without screen was higher than when using screens).

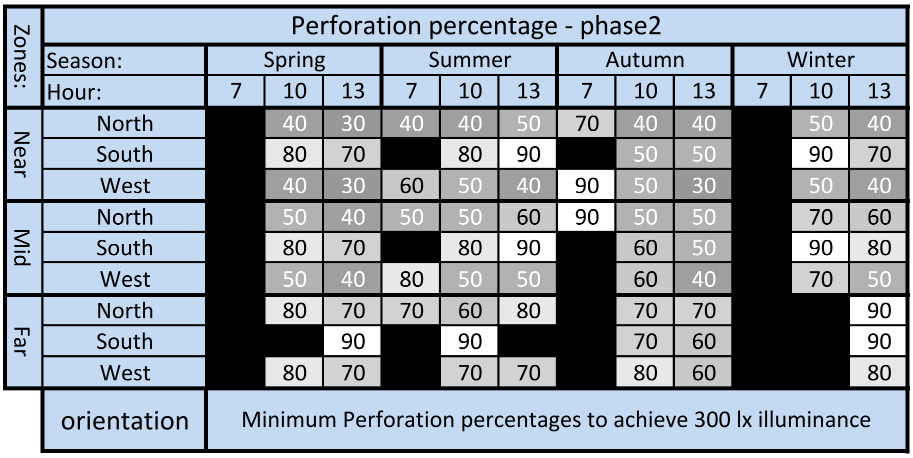


		West orientation												North orientation											
		Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
		7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13	7	10	13
Mid / Near x100	noscreen	57	56	52	73	77	70	75	78	59	53	55	56	57	55	53	64	65	73	70	75	74	53	55	56
	90% screen	61	58	56	77	78	64	78	79	58	59	58	58	62	58	57	70	66	72	76	77	75	62	59	58
	difference	**4**	**2**	**3**	**3**	**1**	**-6**	**4**	**1**	**-1**	**6**	**3**	**2**	**5**	**3**	**4**	**6**	**1**	**-1**	**5**	**2**	**2**	**9**	**4**	**3**
Far / Near x100	noscreen	32	31	28	47	54	48	49	55	38	32	31	31	32	31	28	37	42	52	44	51	50	29	30	31
	90% screen	34	32	30	50	56	44	52	57	37	34	32	32	35	32	30	40	43	53	48	54	52	33	32	32
	difference	**2**	**1**	**1**	**3**	**2**	**-4**	**3**	**3**	**-1**	**2**	**2**	**1**	**3**	**1**	**2**	**3**	**1**	**2**	**4**	**2**	**2**	**4**	**2**	**1**

Comparing results with the same experiment in phase one, it can be indicated that using the recommended configuration (depth ratio of 0.15 and horizontal direction cells) is able to improve the performance of perforated solar screens in the west and north significantly in all zones as shown in Tables 4.36b & 4.36c.

Illuminance values helps also to produce Table 4.39, which indicates the minimum recommended perforation percentages to be used as a tool to help architects to decide the perforation percentage required according to the orientation and times of occupancy for school classrooms in spaces with similar areas and dimensions in similar contexts. However, this table can only be used when other parameters are controlled by using the same values used in this experiment (e.g. a depth ratio of 0.15 in the north and west, 0.6 in south).

Table 4.39: Minimum recommended perforation percentage to achieve target illuminance in all studied cases and zones for specific times throughout the year (lighter cells represent higher perforation percentages).



Zones:	Perforation percentage - phase2												
	Season:	Spring			Summer			Autumn			Winter		
	Hour:	7	10	13	7	10	13	7	10	13	7	10	13
Near	North	■	40	30	40	40	50	70	40	40	■	50	40
	South	■	80	70	■	80	90	■	50	50	■	90	70
	West	■	40	30	60	50	40	90	50	30	■	50	40
Mid	North	■	50	40	50	50	60	90	50	50	■	70	60
	South	■	80	70	■	80	90	■	60	50	■	90	80
	West	■	50	40	80	50	50	■	60	40	■	70	50
Far	North	■	80	70	70	60	80	■	70	70	■	■	90
	South	■	■	90	■	90	■	■	70	60	■	■	90
	West	■	80	70	■	70	70	■	80	60	■	■	80
	orientation	Minimum Perforation percentages to achieve 300 lx illuminance											

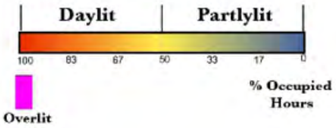
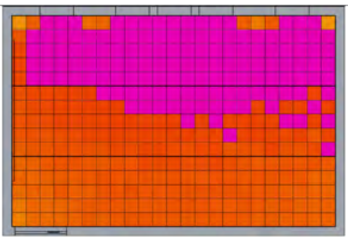
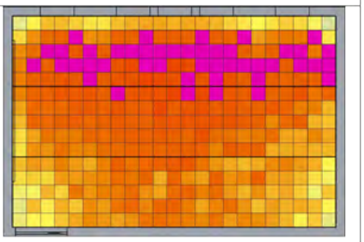
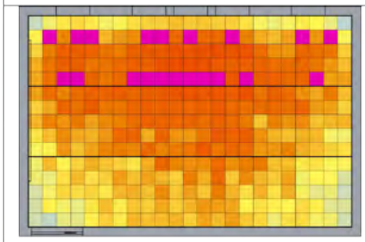
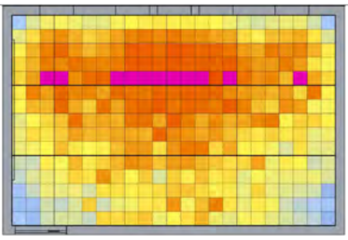
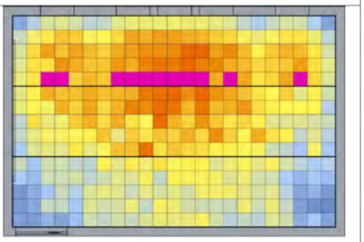
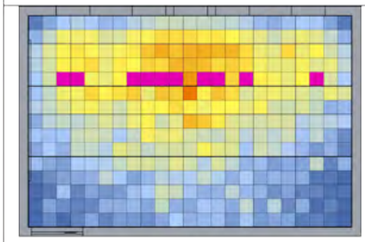
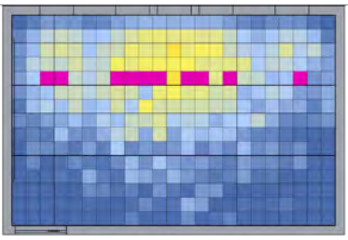
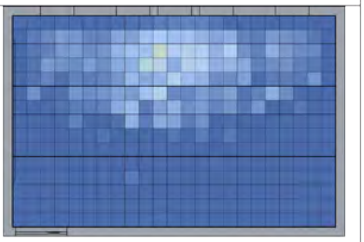
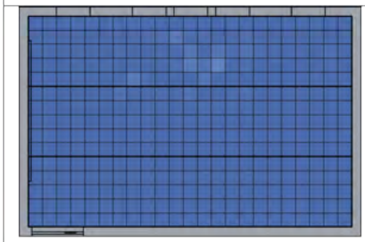
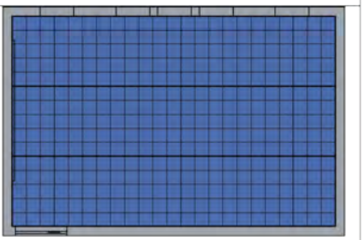
The table is also useful to indicate the hours and zones in which daylight illuminance is not sufficient when using perforated screens with associated parameter values, thus, artificial light is needed (e.g. 7:00 in winter and spring for all orientations; 7:00 in south in all seasons; 10:00 in the winter in Far zones). Artificial lighting fixtures are also needed at 7:00 in most orientations for the whole year.

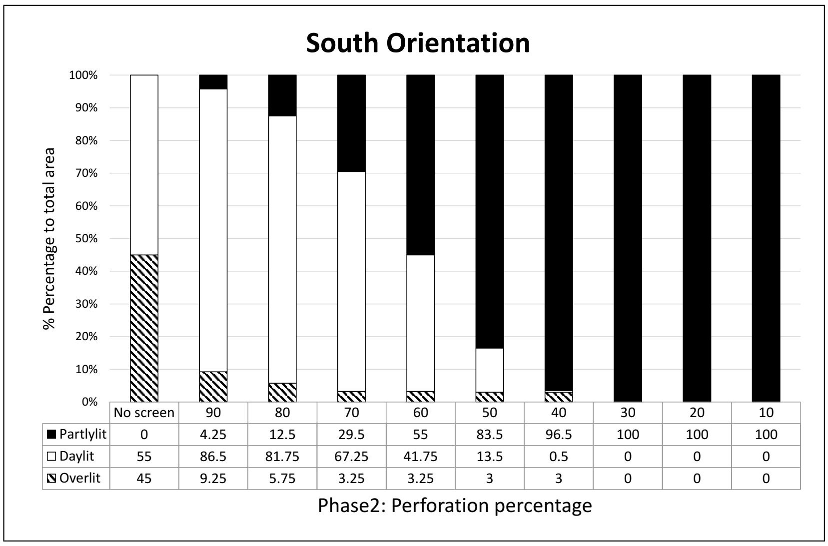
Daylight Availability

The results of simulation DAv in this experiment are presented in Tables 4.40, 4.41 & 4.42 and Figures 4.21, 4.22 & 4.23.

In the south Orientation, a 90% perforation percentage achieves more indoor daylight than other perforation percentages, 70% and 80% perforation percentages also achieve acceptable results of more than 50% 'Daylit' area of the total area in Figure 4.21 and Table 4.40.

Table 4.40: Distribution of DAv on the classroom plan for the south orientation with different perforation percentages in phase two (windows are located on the top side of the plan).

South Orientation		
Perforation percentage	No screen	90%
		
80%	70%	60%
		
50%	40%	30%
		
20%	10%	
		

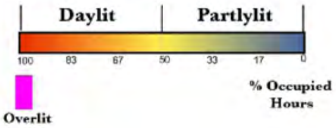
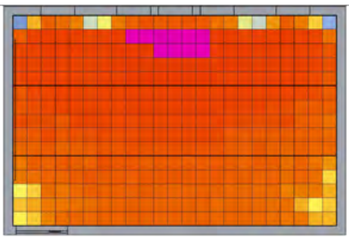
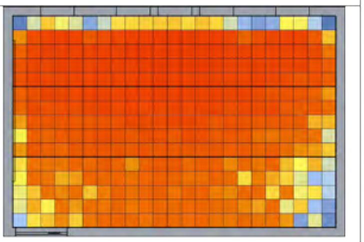
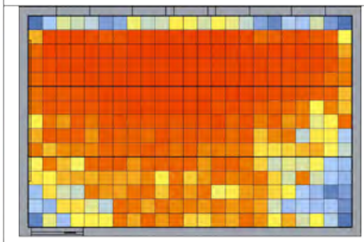
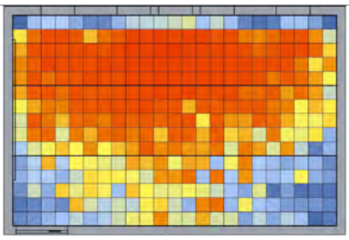
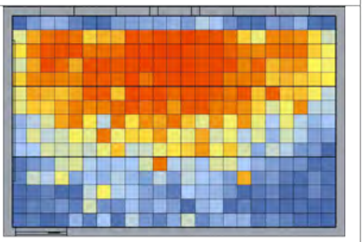
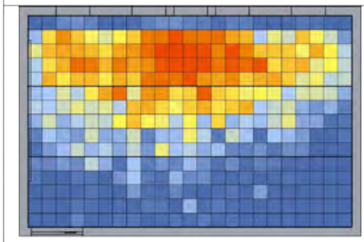
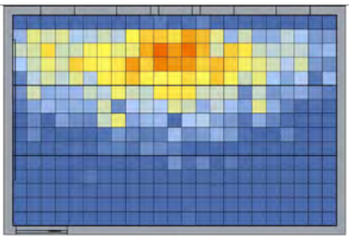
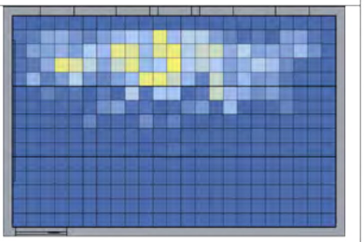
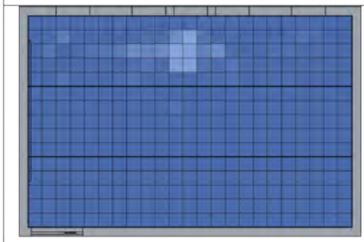
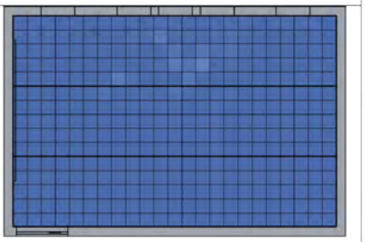


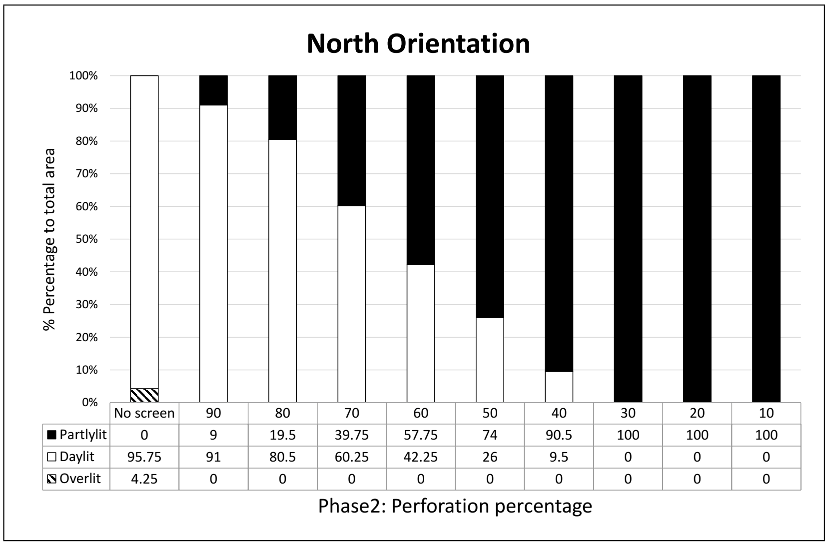
	No screen	90	80	70	60	50	40	30	20	10
■ Partlylit	0	4.25	12.5	29.5	55	83.5	96.5	100	100	100
□ Daylit	55	86.5	81.75	67.25	41.75	13.5	0.5	0	0	0
▧ Overlit	45	9.25	5.75	3.25	3.25	3	3	0	0	0

Figure 4.21: DAv of perforation percentage cases for the south orientation in phase two.

In the north orientation, screens with a 90% perforation percentage achieve a remarkable 91% Daylit area with no Overlit area at all. Screens with 70% and 80% perforation percentages also provide acceptable levels of Daylit area of 60% and 80% of the total area shown in Figure 4.22 and Table 4.41.

Table 4.41: Distribution of DAv on the classroom plan for the north orientation with different perforation percentages in phase two (windows are located on the top side of the plan).

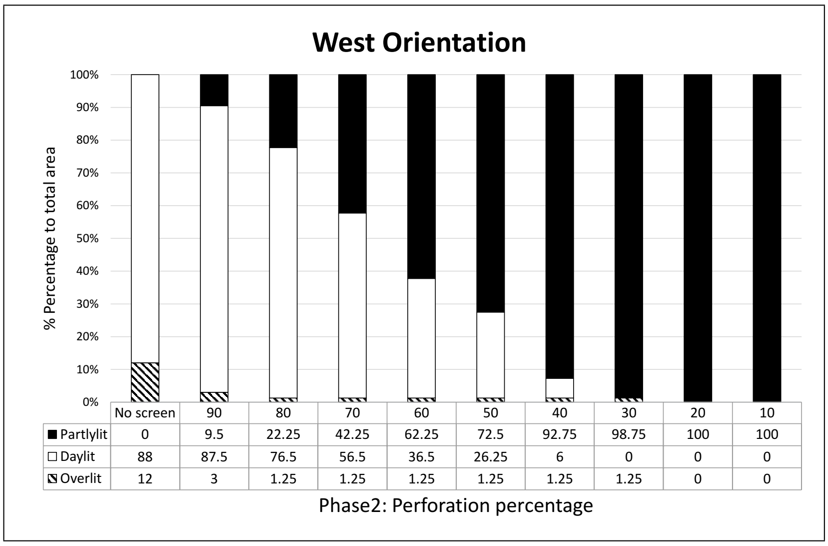
North Orientation		
Perforation percentage	No screen	90%
		
80%	70%	60%
		
50%	40%	30%
		
20%	10%	
		



	No screen	90	80	70	60	50	40	30	20	10
■ Partlylit	0	9	19.5	39.75	57.75	74	90.5	100	100	100
□ Daylit	95.75	91	80.5	60.25	42.25	26	9.5	0	0	0
▨ Overlit	4.25	0	0	0	0	0	0	0	0	0

Figure 4.22: DAv of perforation percentage cases for the north orientation in phase two.

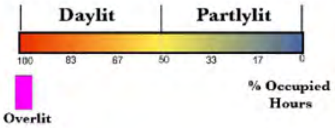
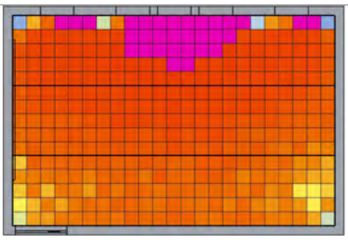
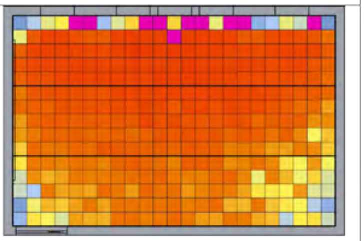
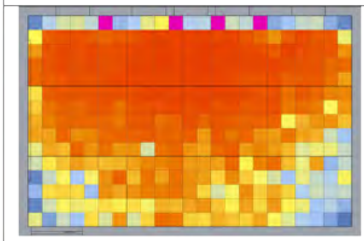
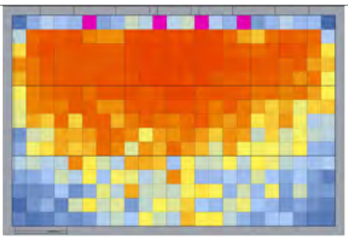
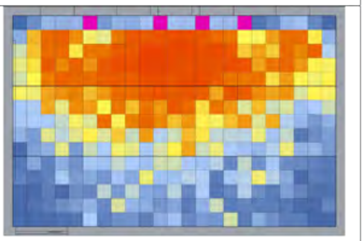
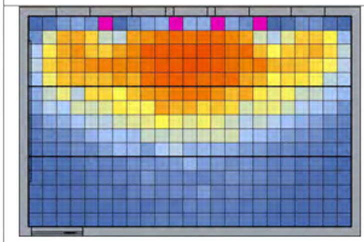
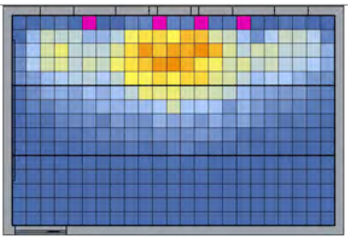
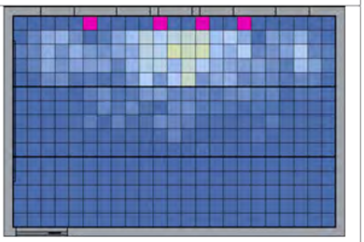
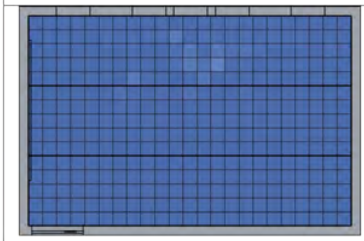
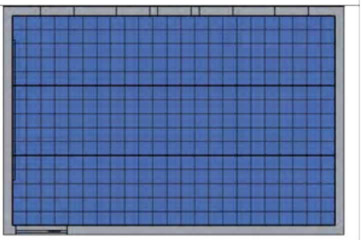
In the west orientation, quite similar to the result of the north orientation, screens with 90% perforation percentage achieve a Daylit area as high as 87.5% with only 3% Overlit area. Screens with 70% and 80% perforation percentages also provide acceptable levels of Daylit area of 56.5% and 76.5% respectively as shown in Figure 4.23 and Table 4.42.



	No screen	90	80	70	60	50	40	30	20	10
■ Partlylit	0	9.5	22.25	42.25	62.25	72.5	92.75	98.75	100	100
□ Daylit	88	87.5	76.5	56.5	36.5	26.25	6	0	0	0
▨ Overlit	12	3	1.25	1.25	1.25	1.25	1.25	1.25	0	0

Figure 4.23: DAv of perforation percentage cases for the west orientation in phase two.

Table 4.42: Distribution of DAv on the classroom plan for the west orientation with different perforation percentages in phase two (windows are located on the top side of the plan).

West Orientation		
Perforation percentage	No screen	90%
		
80%	70%	60%
		
50%	40%	30%
		
20%	10%	
		

The results show a linear increase of the Daylit area and decrease of the Partlylit area in all orientations when increasing the perforation percentage starting from 30% perforation. The results of this experiment prove that even when using screens with depth ratio as low as 0.15, screens would still be able to minimise the Overlit area and provide acceptable levels of Daylit area.

4.3.3 Discussion of phase two

Based on the results, the recommended values of the parameter of perforation percentages to provide the highest Daylit area based in simulating DAv were:

- A 90% perforation percentages for the south orientation.
- A 90% perforation percentages for the north orientation.
- A 90% perforation percentages for the west orientation.

These recommended values of the parameter of perforation percentage are identical to the recommended values when testing the perforation percentage in phase one. This agreement of the recommended values has proven that the selected random sequence of the four experiments in phase one has not affected the final results of phase one. Therefore, the recommended values of studied parameters in phase one are used in the next phase (phase three) to study the effect of perforated solar screens on maintaining privacy.

At the end of these two phases, the first part of the research hypothesis has been confirmed as it is proven that using perforated solar screens is able to enhance indoor daylighting in classrooms for all of the main orientations by applying the proper values of each parameter of perforated solar screens.

4.4 Phase three: The effect of screen parameters on privacy level

This phase is the only phase that is looking at the privacy aspect of perforated solar screens.

The objective of this phase is to investigate screen parameters by studying their effect on maintaining visual privacy for occupants of a building.The research will identify the angle of screen axial tilting to provide privacy for occupants by blocking viewing from outside observers of occupants inside buildings. In this phase, results and recommended values for studied parameters in previous phases are used to produce three full-scale models of perforated solar screens. The results from the experiment in this phase will provide recommendations for the axial tilting of solar screens to provide privacy behind perforated solar screens. Data for the experiment are collected by interviewing 28 subjects using a questionnaire completed by the examiner after recording responses of subjects. The method and questionnaire are discussed in Chapter 2, and a copy of the questionnaire is attached in Appendix E.

Results of evaluating the effect of depth ratio on the indoor lighting in previous phases show that increasing the depth ratio would reduce the indoor lighting significantly, especially in the west and north orientations, into less than the acceptable level. Therefore, in order to achieve the research objectives of providing acceptable levels of daylight and simultaneously maintain privacy,a depth ratio of 0.15 is the only tested value of the range of depth ratios since it is the only ratio that could achieve acceptable daylight in all orientations. Testing privacy in this research is based on using worst-case scenarios and therefore, if a perforated screen with depth ratio of 0.15 was able to maintain privacy then it is more likely to succeed with higher ratios that are recommended in east and south orientations.

Results of evaluating the perforation percentage on the indoor lighting in previous phases show that perforation percentages of 70%, 80% and 90% have achieved acceptable levels in all studied orientations. Decreasing the perforation percentage lower than 70% will not achieve this and thus fail to achieve research objectives. Therefore, these three values of perforation percentage are tested to find the recommended configuration to maintain privacy.

As mentioned in the results discussion of the previous phases, the cell module size and the opening aspect ratios show minimal effect on indoor lighting, and therefore, these two parameters are not tested in phase three and are controlled to one value to reduce experiment time that might cause fatigue to participants and might affect the result.

Since the effect of screen axial tilting has not been tested yet in this research, a range from 0° to 90° is tested to find out the recommended angle that succeeds in blocking the view between an observer outside and an object behind the screen.

4.4.1 The effect of screen's axial tilting on privacy

The parameter of axial tilting of perforated solar screens is investigated on the way it affects the visibility through perforated screens when viewing from outside buildings. Axial tilting is one of the parameters of perforated solar screens. Different types of the axial tilting of perforated solar screens are discussed in Chapter 2; these types are: vertical axis tilting; horizontal upper axis tilting and horizontal lower axis tilting. In this research the author decided to test only the horizontal upper axis as theoretically it has the most potential to block view from outside to inside for higher floors similar to the studied context explained in this research. Tilted screens using the upper horizontal axis also have the potential to allow more daylight to admit inside buildings as it maximises the sky views and minimises the influence of obstructions around the building. Figure 4.24 displays an example of perforated screens tilted using the upper horizontal axis. The effect of axial tilting on daylight performance of perforated screens is studied in the next phase (phase four), whereas this phase looks at the privacy aspect of the axial tilting of solar screens.

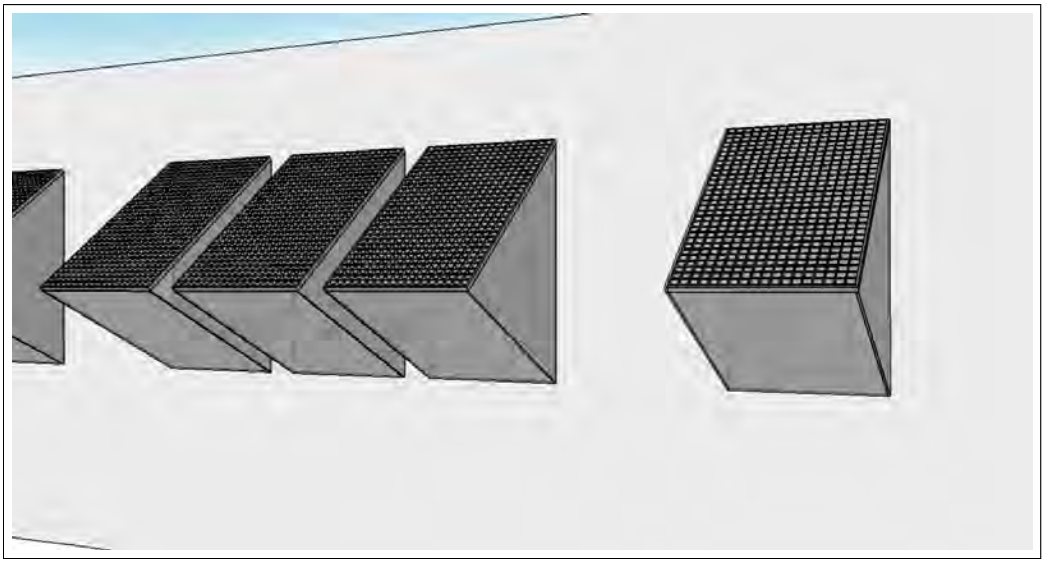


Figure 4.24: Example of perforated screens tilted on the upper horizontal axis.

4.4.2 The selected screens

Three different perforated screens are selected for this experiment based on results of previous phases. The three screens are tested with each subject, and the parameter values of the three modelled screens are selected as following:

1. Perforation percentages:

   The results of phase one and phase two show that perforation percentages above 70% are able to provide an acceptable level of DAv which was previously set to equate to achieving 50% or more daylit area out of the classroom area. Therefore three perforation percentages are used to create three perforated screens to be tested with subjects in this phase: 90%; 70% and 50%. A 50% perforation percentage is used to confirm the effect of perforation percentage on privacy and in case the higher perforation percentages failed to maintain privacy behind solar screens.

2. Depth ratio:

   Since the aim is to test the worst-case scenarios in this phase, the depth ratio applied was the lowest (0.15). Although higher values are recommended in some orientations (0.6 in south, 0.75 in east), only the 0.15 depth ratio is tested in the privacy study, because if a screen with a 0.15 depth ratio succeeded in maintaining privacy, then any screen with a higher depth ratio would satisfy the visual privacy requirements. Hence, the research is testing the worst-case scenario.

3. Cell size:

   Since this parameter has no effect on the daylight performance of perforated screens, the cell size is chosen as the minimum cell size that the laser cutter is able to cut without burning the screens, which is $1mm$ according to the setting used on the machine. Since the depth ratio used is 0.15 and the highest perforation is 90%, the author decided to use $3mm$ thick plywood sheets to cut the screens, and therefore using a cell size of $2cm$ would allow the minimum cut to be not less than 1mm.

4. Aspect ratio:

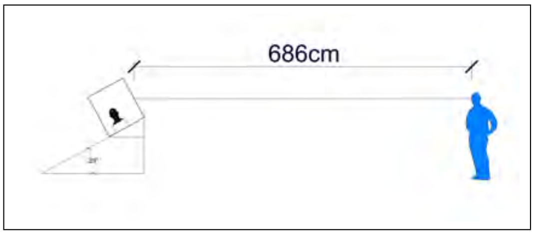
   In order to avoid tiring the subjects with possible adverse impacts on their concentration during the test, only one value of aspect ratio is used. Screens with square cells only (1:1 aspect ratio) are used which provided the highest DAv in the south orientation. Although previous phases in this research recommended using 4:1 in the east, 6:1 in the west and 12:1 in the north, the difference between DAv provided by using these aspect ratios and using 1:1 is minimal, between 2%–8%. Using four different aspect ratios would result in testing 63 cases instead of nine, which would multiply the test time more than four times for every subject considering the transition time between cases. An aspect ratio of 1:1 is chosen for all constructed screens as it is the optimal aspect ratio for the south orientation and is also successful in providing acceptable level of DAv in all other orientations (Daylit area of $\geq$50% of total area).

   The parameter values used to construct the three solar screens are summarised in Table 4.43.

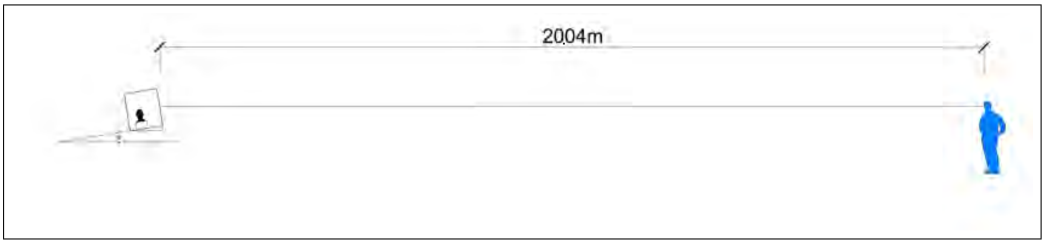
Table 4.43: parameter values of constructed perforated solar screens.

	Screen-1	**Screen-2**	**Screen-3**
Perforation percentage	50%	70%	90%
Depth ratio	0.15	0.15	0.15
Aspect ratio	1:1	1:1	1:1

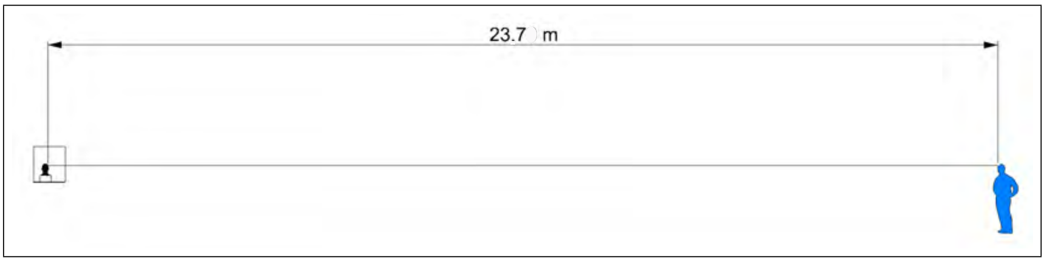
The three screens are tested with the three cases of breaching privacy that are studied in Chapter 3. Copies of these three cases are brought here in Figure 4.25 to relate results to the cases.



(a) A copy of case-1.



(b) A copy of case-2.



(c) A copy of case-3.

Figure 4.25: Copies of the experimental cases to test the privacy aspect.

Controlling the environment

This experiment took place under the sky dome facility in Cardiff University as explained before. The light output of the sky dome was set to achieve 5400lx on the working plane where the box is placed. To control the effect of illuminance contrast between outdoor and indoor illuminance as one of the ten factors to be controlled explained in Section 3.4.4, DF is used to control this factor according to the worst-case scenario which is the lowest ratio between indoor and outdoor illuminances. Using the same screens that are studied in this privacy experiment, the 3D model was used to simulate DF behind each screen. The DF ratios are displayed in Table 4.44.

Table 4.44: DF values used to control the illuminance contrast between outside and inside.

Screen	**DF**
Perforation 50%	1.5%
Perforation 70%	2.1%
Perforation 90%	4%

These values are used to make sure that the DF and thus the illuminance contrast during the experiment is controlled similar to the result of the simulated DF using the 3D virtual model.

4.4.3 Results

Collected data in this phase are presented in tables; Table 4.45 presents the personal and background data of subjects, then three tables, one for each case, presents the response of each subject for each screen. The results of testing the three solar screens with 28 subjects in three cases of privacy breach are demonstrated in three tables (Tables 4.46, 4.47 & 4.48). The highest rotation angle is recorded to be used in the next phase to test how well this angle would provide daylight into the studied classroom.

Personal and background data are collected from subjects to check if there is any effect on the their judgement and presented in Table 4.45. The collected data also includes the background of each subject, and they are classified as having a conservative background if they are of Middle Eastern or Muslim origin.

Table 4.45: Personal and background data of participating subjects.

Subject no.:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Age group:	25-29	35-39	35-39	30-34	30-34	35-39	30-34	35-39	30-34	25-29	30-34	30-34	25-29	25-29	25-29	35-39	25-29	30-34	35-39	18-25	35-39	18-25	30-34	18-25	18-25	30-34	30-34	35-39
Conservative Background:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Gender:	F	F	M	F	M	F	F	M	F	F	M	F	F	F	M	F	F	M	M	M	M	M	F	M	F	M	M	M
childern:	0	2	3	3	3	3	2	1	1	1	1	0	0	2	0	2	0	2	2	0	3	0	0	0	0	0	3	3
school age ch.:	0	2	2	2	1	2	1	1	1	1	1	0	0	1	0	2	0	1	2	0	2	0	0	0	0	0	2	3
Girls:	0	0	1	1	3	2	2	1	1	1	1	0	0	1	0	2	0	2	1	0	2	0	0	0	0	0	0	1
Girls in school:	0	0	1	1	1	2	1	1	1	1	1	0	0	0	0	2	0	1	1	0	2	0	0	0	0	0	0	1

Case-1

Case-1 is when the box including the screen and the image behind it are inclined 29° (Figure 4.25a) and subjects are placed 6*m* away from the screen as explained in Chapter 3. Each case is tested with all subjects using screens with three different perforation percentages starting from the 50% screen and ending with the 90% screen.

Table 4.46: Results of case-1: Highest recorded angles that maintain privacy for each subject viewing a random Kay picture. (-) = all angles; black cells = highest angle for each case.

			Case-1																											
subject number:			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Perforation Percentage	50%	Angle	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		image no.	1	4	6	4	5	3	5	2	5	3	1	5	3	1	3	5	1	6	6	2	6	2	1	6	2	1	1	6
	70%	Angle	5	10	6	5	6	5	12	7	11	6	5	10	-	8	4	12	9	5	5	-	10	-	-	10	10	-	8	11
		image no.	2	4	6	4	5	3	5	2	5	3	1	5	3	1	3	5	1	6	6	2	6	2	1	6	3	3	1	5
	90%	Angle	9	12	17	11	13	13	14	11	13	10	10	13	10	12	11	10	12	12	10	9	12	10	10	12	12	12	11	17
		image no.	3	5	5	3	6	4	6	1	6	4	2	6	3	6	2	1	2	3	3	2	3	2	1	3	2	3	3	6

Results show that a 50% perforation percentage is successful in providing privacy to the interior of the building in case-1 by preventing subjects from seeing the image behind the perforated screen (Table 4.46). When using a 70% perforation percentage, results show that the maximum angle able to prevent subjects from seeing the image is 12° measured from the vertical as explained in Figure 3.3.2. The same angle (highlighted in the table) is recorded as the responses of two subjects (Subjects no.: 7 & 16). When using a 90% perforation percentage, the maximum angle to maintain privacy is 17° (highlighted in the table) and is recorded as the response of two subjects (subjects no.: 3 & 28). In order to understand how would the tilting angle translated into perforated screens to cover windows in actual classrooms, Figure 4.26 gives a section of a classroom as an example of using the 12° as a tilting angle for perforated solar screens.

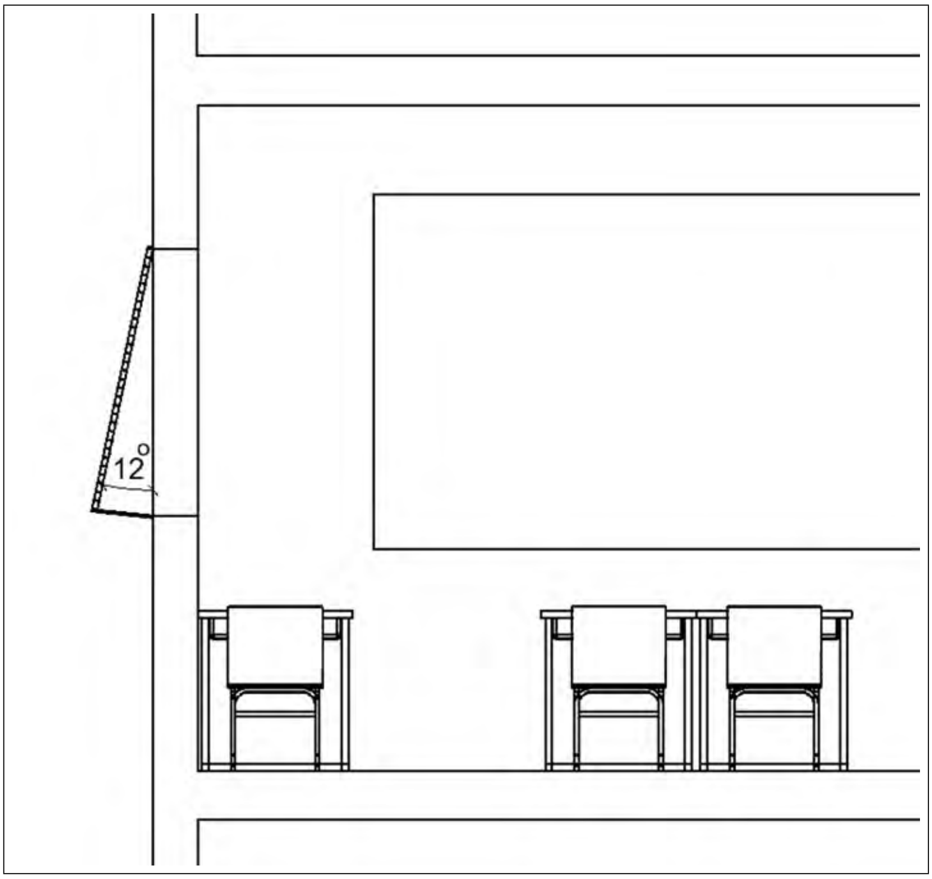


Figure 4.26: Section of a classroom showing a perforated solar screen tilted 12°.

Case-2

Case-2 is when the box including the screen and the image behind it are inclined 9° (Figure 4.25b) and subjects are placed 20m away from the screen.

Similar to case-1, results of case-2 show that a 50% perforation percentage is successful in providing privacy to the interior of the building in case-2 by preventing subjects from seeing the image behind the perforated screen (Table 4.47). When using a 70% perforation percentage, results show that the maximum angle able to

Table 4.47: Results of Case-2: highest recorded angles that maintain privacy for each subject viewing a random Kay picture. (-) = all angles; black cells = highest angle for each case.

			Case-2																											
subject number:			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Perforation Percentage	50%	Angle	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		image no.	6	1	3	1	4	1	2	5	3	1	6	3	5	5	5	4	6	2	1	1	1	1	6	2	1	1	2	2
	70%	Angle	25	14	24	11	27	24	15	23	24	25	27	23	25	30	20	30	29	28	22	15	25	22	20	19	26	30	22	29
		image no.	6	1	3	1	4	1	2	5	3	1	6	3	5	5	5	4	6	2	1	1	1	1	6	2	4	5	2	3
	90%	Angle	35	35	37	37	32	35	32	37	40	29	35	38	36	35	31	38	37	42	37	33	38	38	30	36	35	34	37	31
		image no.	4	3	4	6	1	6	1	4	4	2	5	1	2	3	1	2	4	4	4	5	4	4	4	5	1	1	4	2

prevent subjects from seeing the image is 30° (highlighted in the table); the same angle is recorded as the responses of three subjects (Subjects no.: 14, 16 & 26). When using a 90% perforation percentage, the maximum angle to maintain privacy is 42° (highlighted in the table) and it is recorded as the response of only one subject (Subject no.: 18).

Case-3

Case-3 is when the screen and the image behind it are straight without any inclinations (Figure 4.25c) and subjects are placed $20m$ away from the screen.

Table 4.48: Results of Case-3: highest recorded angles that maintain privacy for each subject viewing a random Kay picture. (-) = all angles; black cells = highest angle for each case.

			Case-3																											
subject number:			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Perforation Percentage	50%	Angle	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		image no.	5	2	1	5	5	5	4	6	2	5	4	2	6	2	6	6	5	1	2	6	2	6	2	1	6	2	6	1
	70%	Angle	33	17	32	38	26	39	27	33	26	36	36	31	22	34	26	37	38	36	24	37	22	32	21	35	39	30	31	39
		image no.	5	2	1	5	2	5	4	6	2	5	4	2	6	2	6	6	5	1	2	6	2	3	2	1	5	4	6	4
	90%	Angle	43	42	48	45	45	45	50	47	47	45	46	52	46	48	45	45	51	49	50	41	52	47	43	50	50	40	50	44
		image no.	2	5	2	2	3	2	3	3	1	6	3	4	2	4	4	3	3	5	5	3	5	5	5	4	6	2	5	1

Similar to case-1 and case-2, results of case-3 show that a 50% perforation percentage is successful in providing privacy to the occupants of the building in case-3 by preventing subjects from recognising the image behind the perforated screen (Table 4.48). When using a 70% perforation percentage, results show that the maximum angle able to prevent subjects from seeing the image is 39° (highlighted in the table) the same angle is recorded as the responses of three subjects (Subjects no.: 6, 25 & 28). When using 90% perforation percentages, the maximum angle to maintain privacy is 52° (highlighted in the table) and is recorded as the response of two subjects (subjects no.: 12 & 21).

4.4.4 Discussion of phase three

To summarise experiments in phase three, results are demonstrated in Table 4.49 which presents the maximum rotation angle that prevents subjects from seeing the image behind perforated screens.

Table 4.49: Maximum rotation angles to maintain privacy in phase three; the biggest recorded angle of all cases of all screens is highlighted in a square.

	Case-1	**Case-2**	**Case-3**
Perforation 50%	all angles	all angles	all angles
Perforation 70%	$\geq 12°$	$\geq 30°$	$\geq 39°$
Perforation 90%	$\geq 17°$	$\geq 42°$	$\boxed{\geq 52°}$

Since the objective of this experiment is to find the configuration that maintains privacy and prevents visibility for all possible scenarios, then according to the result of phase four, the designer has three choices to achieve this: using a perforated screen with a 50% perforation percentage without tilting; using perforated screen with a 70% perforation percentage tilted 39° ; using perforated screen with 90% perforation percentage tilted 52°. This could work with any depth ratio since the the lowest ratio is used in this phase (depth ratio of 0.15). However, increasing the depth ratio would reduce Daylit area in north orientation as concluded in previous phases of this research. The following section examines whether the personal characteristics and background of the interviewees affects the results.

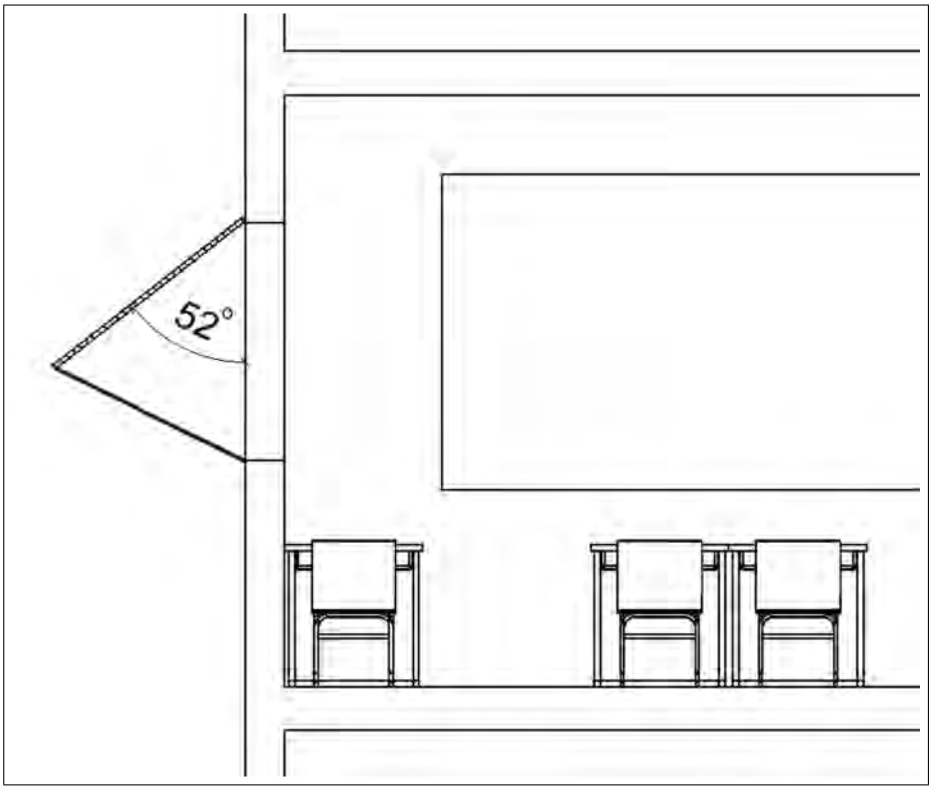


Figure 4.27: Section of a classroom showing a perforated screen tilted 52°.

Effect of personal characteristics of subjects

For further investigation, the author looks at whether the personal attributes and background of subjects had any effect on the results.

It appears that there is no significant difference between results of male and female subjects. The average angle recorded for males and females show similarity in Table 4.50. The recorded maximum tilt angles to prevent visibility through perforated screens are also spread almost equally between male and female subjects, seven females and six males.

Table 4.50: Comparing the average maximum angle to prevent visibility through perforated screens between male and female subjects with the highest recorded angle.

		Case-1		Case-2		Case-3	
	Screen:	70%	90%	70%	90%	70%	90%
Gender	Male	8.5	12	23	35	31	47
	Female	7	12	24	36	31	47
	Highest recorded	12	17	30	42	39	52

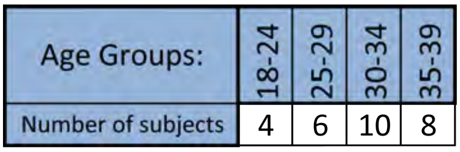
When testing case-1 with a 70% perforation screen, the highest recorded angle of 12° is reported by two female subjects with children, while with a 90% perforation screen, the highest recorded angle of 17° is reported by two male subjects with children.When testing case-2 with 70%, the highest recorded angle 30° is reported by two female subjects with children, and one male without children. While with a 90% perforation, the highest recorded angle of 42° is reported by one male subject with children. When testing case-3 with 70% the highest recorded angle of 39° is reported by one male with children and two female subjects, only one of whom has children. While with a 90% screen, the highest recorded angle of 52° is reported by one male subject with children and one female with no children. It also appears that there is no effect on the results whether subjects have children or not.

It can also be noticed that two subjects report the highest angles for two different cases: subject no. 16 reports the highest angle in case-1 and case-2 using the 70% screen; subject no. 28 reports the highest angle in case-1 using a 90% screen and in case-3 using a 70% screen. This simply means that these two subjects might have visual acuity higher than normal; their visual acuity Snellen fraction could be 6/4.8 whereas the visual acuity of a normal human eye is 6/6. Including subjects with higher visual acuity is beneficial to the experiment as it is based on worst-case scenarios, and some individuals in the real world might have higher visual acuity than normal.

Regarding the conservative background of the test subjects, three of the total 28 subjects do not have any conservative background (from a Middle East origin or a Muslim country), and the author includes them to check whether their results would be different from subjects with a conservative background. Their results do not show any difference than the average results. However, neither one of the highest recorded angles is a response of a subject with no conservative background; that can be explained by the low number of interviewees, as they are three out of 28 subjects which gives a lower chance.

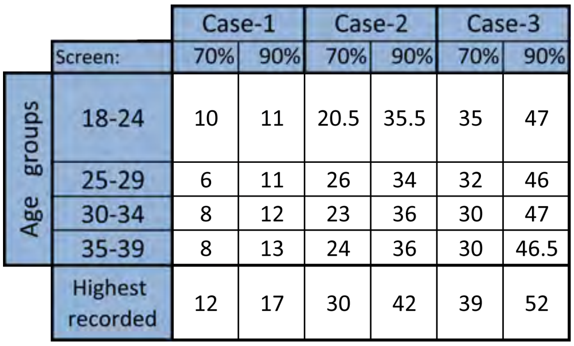
The author also looks at the effect of the age of subjects on the results. Table 4.51a displays the age groups of subjects and the number of subjects in each group. Subjects are spread in four groups: 18-24 years; 25-29 years; 30-34 years; and 35-39 years. Table 4.51b displays the average recorded angles to prevent visibility through perforated screens for each group compared to the maximum recorded angles by subjects. It appears from the tables that the age of subjects has not affected the results; in some cases the average angle is higher in the youngest group (screen 70% in case-1 and case-3) and sometimes the average angle recorded by the oldest group is higher (screen 90% in case-1 and case-2). The average angle recorded by the group of 25-29 years is also sometimes the highest (screen 70% in case-2). The reason for that might be that all subjects have normal vision and similar visual acuity as all subjects had a visual acuity test prior to participating in the experiment and results of subjects with less than normal visual acuity are excluded from the results as explained in the methodology in Chapter 3.

Table 4.51: The effect of age of subjects on results.



Age Groups:	18-24	25-29	30-34	35-39
Number of subjects	4	6	10	8

(a) Age groups and the number of subjects in each group.



		Case-1		Case-2		Case-3	
	Screen:	70%	90%	70%	90%	70%	90%
Age groups	18-24	10	11	20.5	35.5	35	47
	25-29	6	11	26	34	32	46
	30-34	8	12	23	36	30	47
	35-39	8	13	24	36	30	46.5
	Highest recorded	12	17	30	42	39	52

(b) Comparing the average maximum angle between each group and the highest recorded angle.

Effect of image selection

Kay pictures are used as the hidden images behind perforated screens. The order of viewing the Kay pictures is set randomly; the image number is recorded with the results of each subject of each case to show the effect of image choice. It appears that image number five is the easiest image to be detected and identified. Image number five is the Kay picture representing a star (Table 3.14). The star is detected five times when the highest angles are reported. This can be explained by the fact that the star is the only symmetrical image out of all Kay pictures, meaning that the star can be recognised if only half of it is detected, whereas the whole image of the other pictures need to be recognised.

Results also show that image number two (the vehicle) is detected three times each when reporting the highest angle, and images number one and six, the boot and the duck respectively, are detected two times each when the highest angles are reported. Results indicate that the pictures of the house and the apple are the hardest to be detected by subjects. These information could be useful for further investigation regarding development of Kay pictures in the optometry field.

4.5 Phase four: The effect of axial tilting on indoor daylight

This phase has one experiment that aims to study the effect of upper horizontal axial tilting on the daylight performance of perforated solar screens. The same method of daylight simulation in phase one and two is used here, although, in this experiment no range of variations of are tested. Instead, only the tilt angle that is successful in providing privacy for occupants in phase three is tested, which is the angle that allows perforated solar screens to block view in the research context. Although six tilted angles are recommended by results of the privacy study in phase three, according to the tested scenario and the perforation percentage of the tested screen, only the highest recorded angle from vertical is used in phase four to make sure that this angle can be used in different cases and different orientations.

4.5.1 Values of of axial tilting

After obtaining results from phase three, the maximum tilt angle providing privacy is used to build tilted screens. Tilting screens using only the maximum angles indicated in phase three are tested in this phase using daylight simulation methods similar to those conducted in phase one and phase two. The same criteria are also used to adjudicate how well the final screens are able to provide interior daylight while maintaining visual privacy.

Since the issue of privacy is the key in this research and providing privacy is vital in the context, there is no range of cases of tilt angles. Only the highest tilt angle that maintained privacy in phase three is used in this phase. When studying the provision of privacy in phase three, worst-case scenarios are used to make sure that privacy would not be breached, and this is also undertaken in this phase and therefore, only 52° is used, even though lower angles are successful in some scenarios (Table 4.49). Tilting screens 52° from horizontal would provide privacy in all studied scenarios. Figure 4.27 displays a section of the classroom showing how a perforated solar screens would look when tilted 52° from the upper horizontal axis. It is expected that tilting screens in such a way would allow more daylight to penetrate through perforated screens since the view to the sky is maximised and the obstruction from surrounding buildings is minimised. However, this would oversupply indoor daylight and could result in higher Overlit area and lower Daylit area. Therefore, this experiment is still vital as it would give a better understanding of the Daylit area in the space and whether or not it is still acceptable according to the criteria used.

Studied cases

Similar to phase one and phase two, daylight simulation is performed for average illuminance values in specific times and for the DAv metric using CBDM modelling, and results are presented in tables and charts. The selected best cases of each orientation are presented in Table 4.52. Since it is proven that cell size has no effect on daylighting performance of screens in phase one (Section 4.2.5), it is set to $6cm$ for all orientations.

Table 4.52: Screen configurations that achieved best results in each orientation.

	Perforation Percentage	**Depth Ratio**	**Cell Size**	**Aspect Ratio**	**Daylit Area**
South	90%	0.6	$6cm$	1:1	86.5%
East	80%	0.75	$6cm$	4:1	60.25%
North	90%	0.15	$6cm$	12:1	91%
West	90%	0.15	$6cm$	6:1	87.5%

To study the effect of tilt angle these three cases are compared for each orientation:

- The base case of a window with no screen.
- The case that achieved the highest value of Daylit area (Table 4.52).
- The case when tilting the same screen 52° .

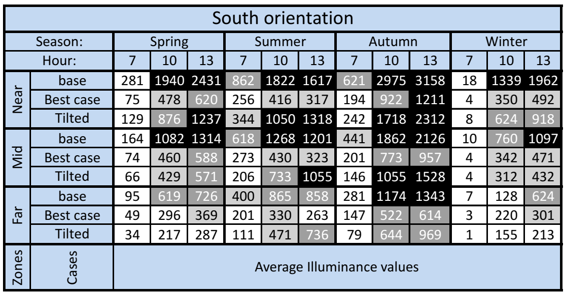
4.5.2 Results

Average illuminance levels

Results of simulating average illuminance levels are presented in Table 4.53.

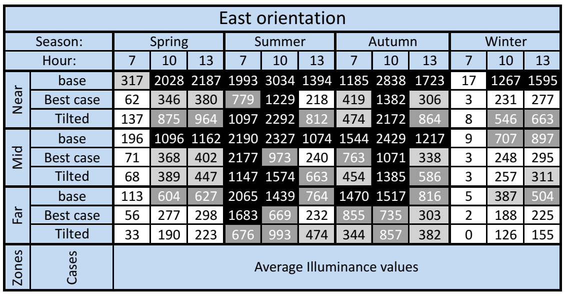
In the south orientation in Table 4.53a, it can be noticed that tilted screens are successful in increasing average illuminance at 7:00 in Summer into an acceptable level ($> 300lx$); however all other illuminance levels are still low ($< 300lx$) at 7:00

Table 4.53: The effect of axial tilting on screens on the average illuminance values (lx) in all orientations (black cells, $\geq 1000lx$; grey cells, between $500lx$ and $999lx$; light grey, between $300lx$ and $499lx$).



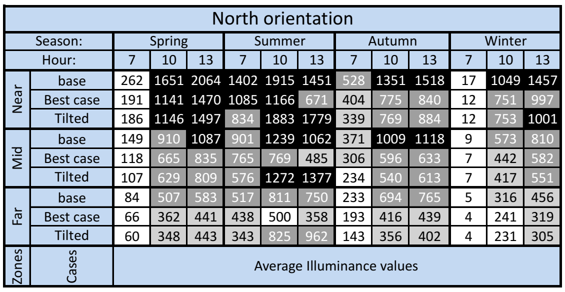
South orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	281	1940	2431	862	1822	1617	621	2975	3158	18	1339	1962
	Best case	75	478	620	256	416	317	194	922	1211	4	350	492
	Tilted	129	876	1237	344	1050	1318	242	1718	2312	8	624	918
Mid	base	164	1082	1314	618	1268	1201	441	1862	2126	10	760	1097
	Best case	74	460	588	273	430	323	201	773	957	4	342	471
	Tilted	66	429	571	206	733	1055	146	1055	1528	4	312	432
Far	base	95	619	726	400	865	858	281	1174	1343	7	128	624
	Best case	49	296	369	201	330	263	147	522	614	3	220	301
	Tilted	34	217	287	111	471	736	79	644	969	1	155	213
Zones	Cases	Average Illuminance values											

(a) South orientation.



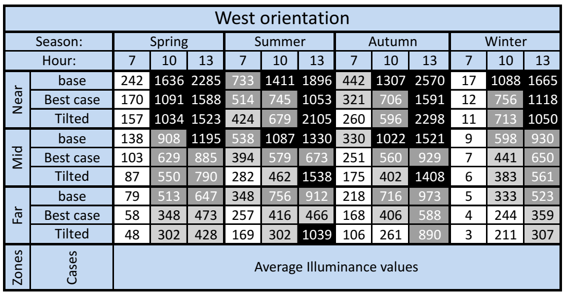
East orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	317	2028	2187	1993	3034	1394	1185	2838	1723	17	1267	1595
	Best case	62	346	380	779	1229	218	419	1382	306	3	231	277
	Tilted	137	875	964	1097	2292	812	474	2172	864	8	546	663
Mid	base	196	1096	1162	2190	2327	1074	1544	2429	1217	9	707	897
	Best case	71	368	402	2177	973	240	763	1071	338	3	248	295
	Tilted	68	389	447	1147	1574	663	454	1385	586	3	257	311
Far	base	113	604	627	2065	1439	764	1470	1517	816	5	387	504
	Best case	56	277	298	1683	669	232	855	735	303	2	188	225
	Tilted	33	190	223	676	993	474	344	857	382	0	126	155
Zones	Cases	Average Illuminance values											

(b) East orientation.



North orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	262	1651	2064	1402	1915	1451	528	1351	1518	17	1049	1457
	Best case	191	1141	1470	1085	1166	671	404	775	840	12	751	997
	Tilted	186	1146	1497	834	1883	1779	339	769	884	12	753	1001
Mid	base	149	910	1087	901	1239	1062	371	1009	1118	9	573	810
	Best case	118	665	835	765	769	485	306	596	633	7	442	582
	Tilted	107	629	809	576	1272	1377	234	540	613	7	417	551
Far	base	84	507	583	517	811	750	233	694	765	5	316	456
	Best case	66	362	441	438	500	358	193	416	439	4	241	319
	Tilted	60	348	443	343	825	962	143	356	402	4	231	305
Zones	Cases	Average Illuminance values											

(c) North orientation.



West orientation													
Season:		Spring			Summer			Autumn			Winter		
Hour:		7	10	13	7	10	13	7	10	13	7	10	13
Near	base	242	1636	2285	733	1411	1896	442	1307	2570	17	1088	1665
	Best case	170	1091	1588	514	745	1053	321	706	1591	12	756	1118
	Tilted	157	1034	1523	424	679	2105	260	596	2298	11	713	1050
Mid	base	138	908	1195	538	1087	1330	330	1022	1521	9	598	930
	Best case	103	629	885	394	579	673	251	560	929	7	441	650
	Tilted	87	550	790	282	462	1538	175	402	1408	6	383	561
Far	base	79	513	647	348	756	912	218	716	973	5	333	523
	Best case	58	348	473	257	416	466	168	406	588	4	244	359
	Tilted	48	302	428	169	302	1039	106	261	890	3	211	307
Zones	Cases	Average Illuminance values											

(d) West orientation.

in all orientations and artificial lighting is still needed in early morning in the south. Artificial lighting is also needed in the Far zone in spring and winter to increase illuminance to reach recommended levels.

In the east orientation, illuminance levels were increased in all Near zones and most of the Mid zones in all seasons when using tilted screens compared with the case of screens without tilting (Table 4.53b). An increase can also be seen in the Far zones in summer and autumn at 10:00 and 13:00.

In the north orientation, tilted screens are able to provide higher average illuminance levels only in the Near zones; in all other zones, the straight screen results are higher except in summer at 10:00 and 13:00 in Table 4.53c.

In the west orientation, tilted screens are not as successful as in the other orientations. Average illuminance values are improved only in few cases: 13:00 in summer and autumn in all zones (Table 4.53d).

Results show that when comparing screens with the best resulting configurations with the same screens tilted 52°, the average illuminance values are increased after tilting screens in near zones of all orientations except the west orientation (Table 4.53). The tables also show that even illuminance values in Mid and Far zones become higher with the use of tilted screens in summer in all times except 7:00, and this can be also noticed in autumn except in the north orientation. However, similar to the previous phases, artificial lighting is still needed in early morning in all zones in spring and winter.

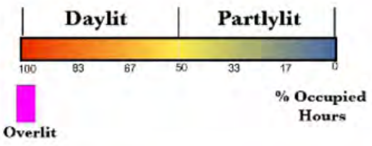
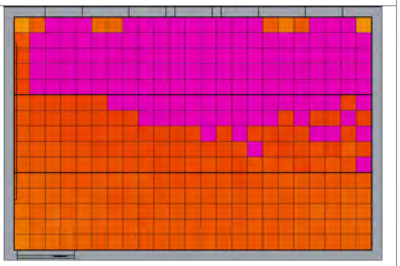
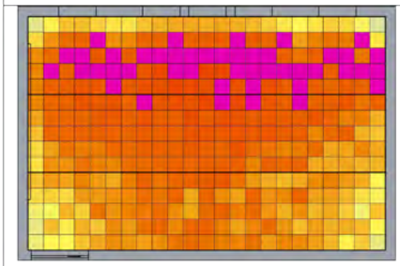
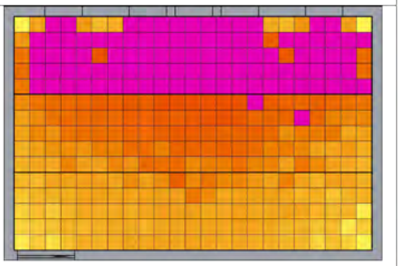
Daylight Availability

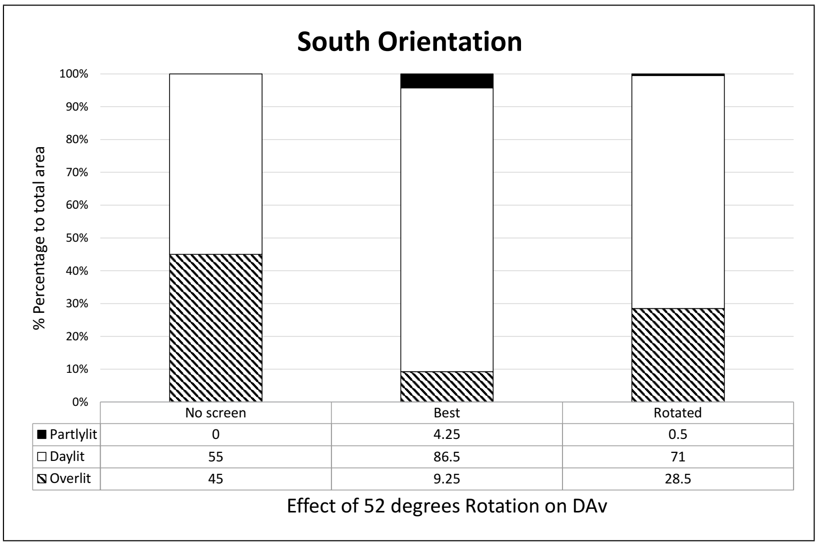
Results of simulation DAv in this experiment are presented in Tables 4.54, 4.55, 4.56 & 4.57 and Figures 4.28, 4.29, 4.30 & 4.31.

In the south orientation, the Overlit area is increased dramatically more than three times compared with the results of non-tilted screens (from 9% to 29%), especially in the Near zone in Table 4.28; however, the Mid and Far zones are not affected and the Overlit area there has not increased. Actually the Daylit area is increased in the Far zone as some Partlylit areas are diminished in the corners. Although the Overlit area increases with the use of tilted screens, it is still much lower than the case with no screen where it is as high as 45% in Figure 4.28.

On the other hand, the Partlylit area is minimised to as low as 0.5%, which is good for the classrooms. More importantly, results show that tilted screens are successful in achieving a Daylit area of 71% out of total area in the south orientation, which is considered acceptable since it is more than 50% of the total area according to the criteria used.

Table 4.54: The effect of screen axial tilting on the distribution of DAv on the classroom plan in the south orientation (windows are located on the top side of the plan).

South Orientation	
Cases:	No screen
	
Best case	Tilted screen
	

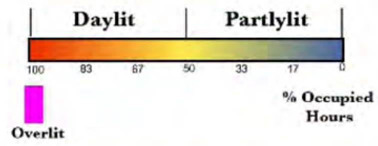
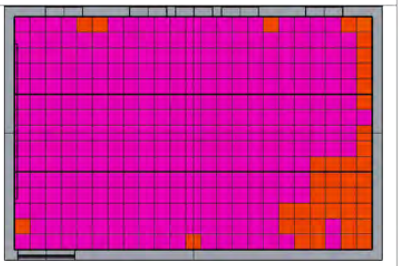
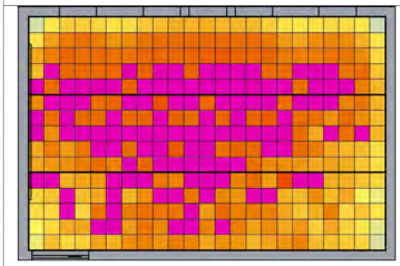
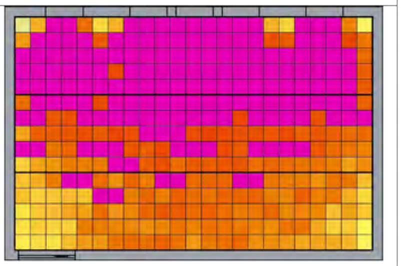


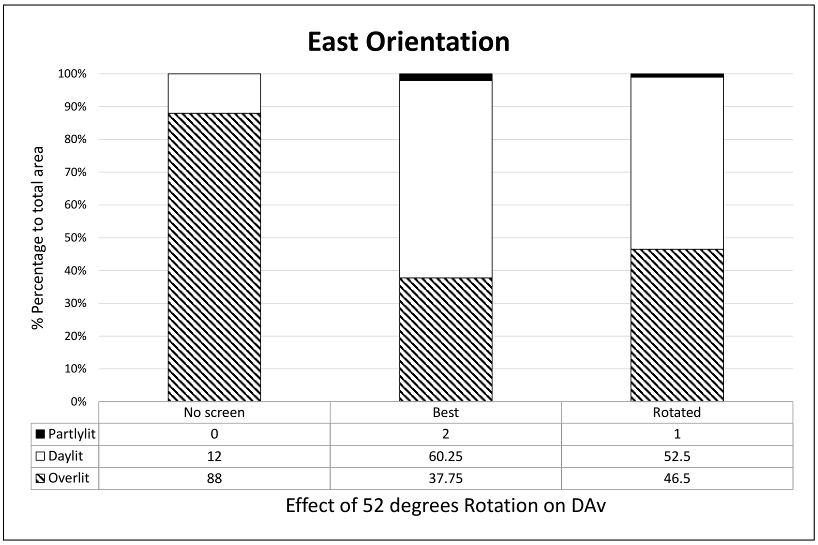
	No screen	Best	Rotated
■ Partlylit	0	4.25	0.5
☐ Daylit	55	86.5	71
▨ Overlit	45	9.25	28.5

Figure 4.28: The effect of screen axial tilting on DAv in the south orientation.

In the east orientation, results show a big increase in Overlit area in the Near zone, whereas in the Far zone the Overlit area is reduced as presented in Table 4.55. Although the Daylit area is reduced, it remains in the acceptable level > 50% with 52.5% Daylit area in Figure 4.29.

Table 4.55: The effect of screen axial tilting on the distribution of DAv on the classroom plan in the east orientation (windows are located on the top side of the plan).

East Orientation	
Cases:	No screen
	
Best case	Tilted screen
	

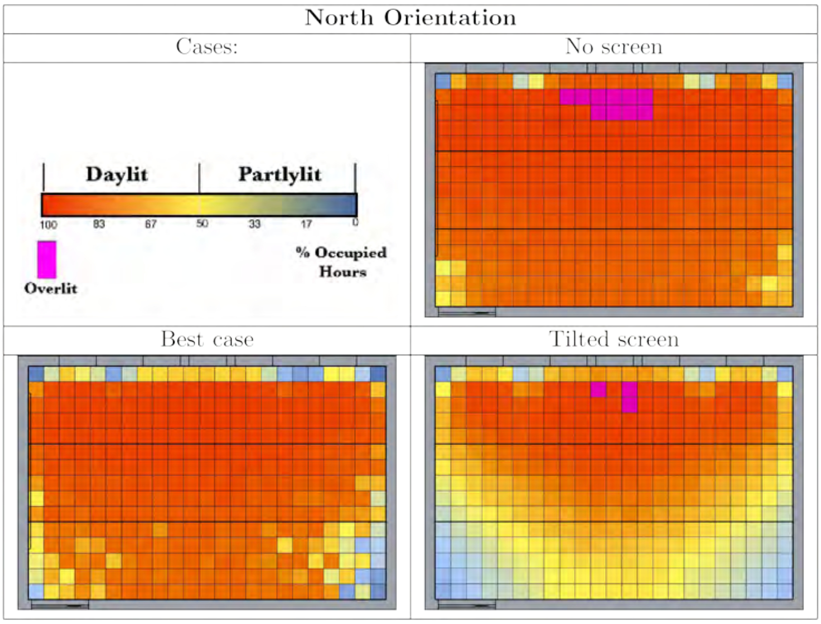


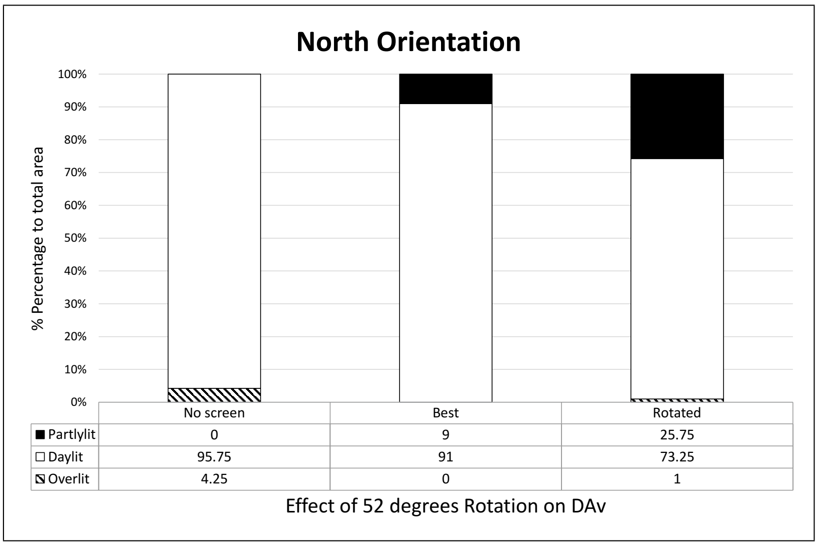
	No screen	Best	Rotated
■ Partlylit	0	2	1
☐ Daylit	12	60.25	52.5
▨ Overlit	88	37.75	46.5

Figure 4.29: The effect of screen axial tilting on DAv in the east orientation.

In the north orientation, the Partlylit area increases and appears in the Far zone in Table 4.56, and the Daylit is reduced to 73.25% in Figure 4.30. It is still however, considered high and acceptable. It can also be noticed that only Overlit area of as low as 1% appeared in the Near zone.

Table 4.56: The effect of screen axial tilting on the distribution of DAv on the classroom plan in the north orientation (windows are located on the top side of the plan).





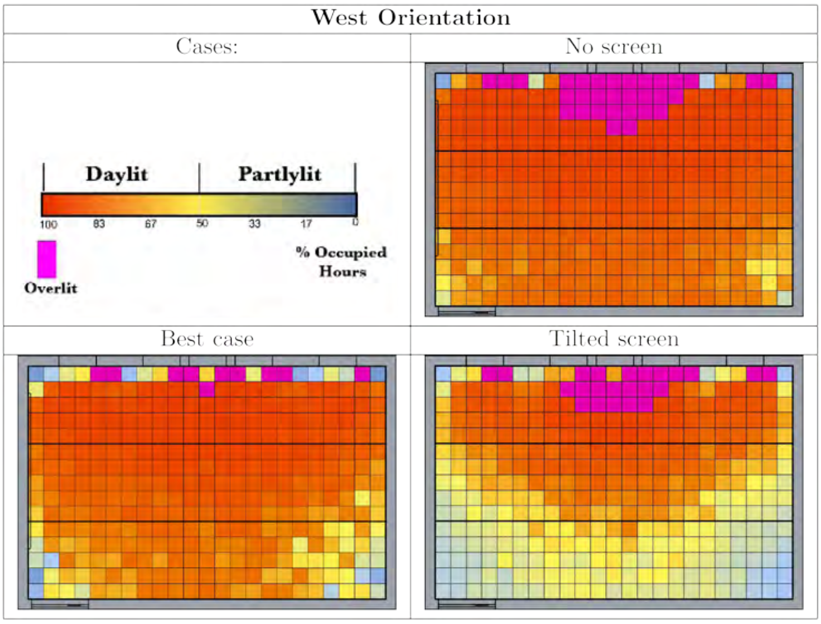
	No screen	Best	Rotated
■ Partlylit	0	9	25.75
☐ Daylit	95.75	91	73.25
▨ Overlit	4.25	0	1

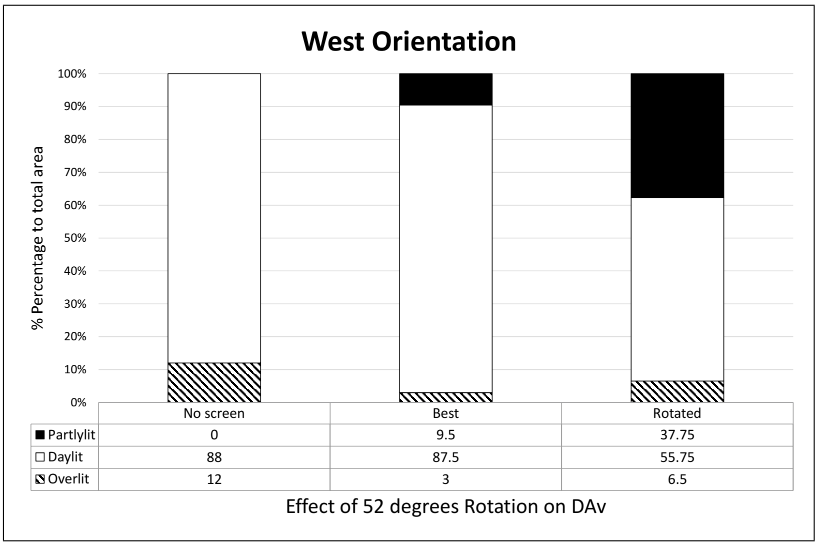
Figure 4.30: The effect of screen axial tilting on DAv in the north orientation.

In the west orientation, the result is similar to the North orientation where the Daylit area is reduced; the Overlit area and Partly lit areas are increased in the

Near zone and Far zone respectively, although, the space still has acceptable levels of Daylit area of more than 55% as shown in Table 4.57 and Figure 4.31.

Table 4.57: The effect of screen axial tilting on the distribution of DAv on the classroom plan in the west orientation (windows are located on the top side of the plan).





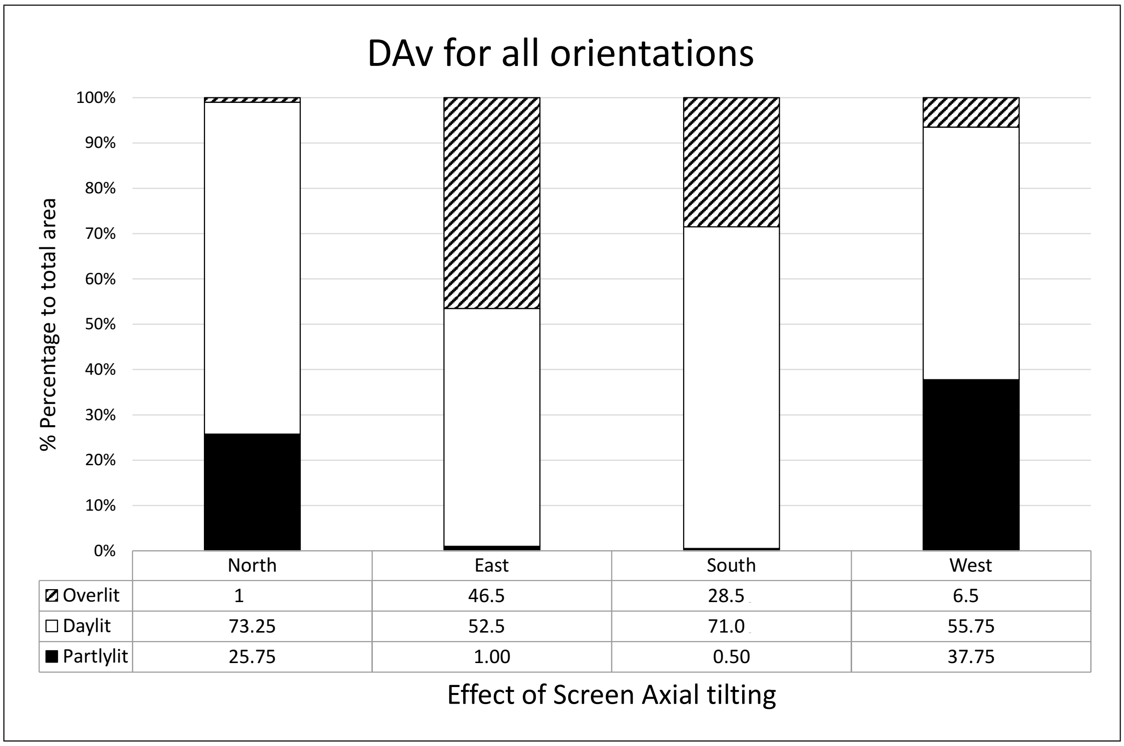
	No screen	Best	Rotated
■ Partlylit	0	9.5	37.75
☐ Daylit	88	87.5	55.75
▨ Overlit	12	3	6.5

Figure 4.31: The effect of screen axial tilting on DAv in the west orientation.

Results of simulating DAv indicate that tilting screens would reduce Daylit area in all orientations and increase Overlit area in all orientations (Figures 4.28, 4.29, 4.30 and 4.31). Achieved Daylit areas however, are above acceptable levels in all orientations (> 50%) according to the criteria of DAv. The resulting Daylit areas are: 52.5%; 71%; 73.25% and 55.75%, in the east, south, north and west orientations respectively.

4.6 Summary and discussion of phase four

Results of phase four are summarised in Figure 4.32 that displays the study findings of the effect of axial tilting of screens on DAv for all main orientations. The figure clearly shows that tilting perforated solar screens by 52° increases Overlit area in all orientations more than the Overlit areas resulted from the best recommended configurations without tilting. However, it also shows that tilting perforated solar screens at the same angle is successful to provide at least 50% of the Daylit area in the classroom.



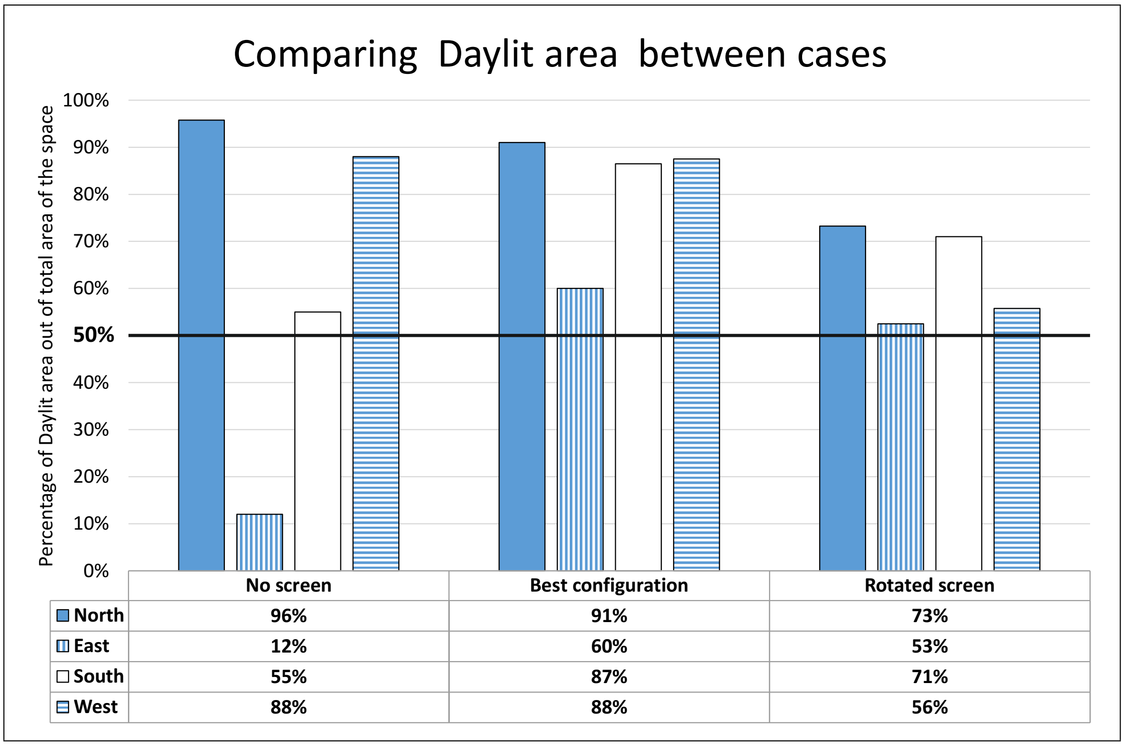
	North	East	South	West
▨ Overlit	1	46.5	28.5	6.5
☐ Daylit	73.25	52.5	71.0	55.75
■ Partlylit	25.75	1.00	0.50	37.75

Figure 4.32: Summary of phase four presenting DAv for all orientations when using tilting screens at 52°.

Since this tilting angle is able to block the view from outside to inside in all privacy breaching scenarios, it appears that this result confirms the research hypothesis that using perforated solar screens is able to provide acceptable levels of interior daylight for the four main orientations and maintain privacy at the same time.

To compare the DAv resulting in this phase with the DAv resulting from the previous phases, Figure 4.33 compares Daylit areas achieved by using the best configuration recommended without axial tilting with the Daylit area resulting by tilting screens 52° using the same configurations of other parameters. It also compares them with the Daylit area achieved when no screen is used to cover windows. The chart has a bold horizontal line to highlight the threshold of 50% of Daylight area, which was used as a criterion for achieving acceptable daylight levels in this study.

The chart shows that using perforated screens is successful in achieving acceptable levels of Daylit areas in all orientations, especially in the east, compared with the case in which no screen is used on the window, where the Daylit area is as low as 12% out of the total space area. It also shows that although Daylit areas are reduced in all orientations when screens are tilted 52°, Daylit areas remain above the minimum level of 50% out of the total floor area.



	No screen	Best configuration	Rotated screen
■ North	96%	91%	73%
▥ East	12%	60%	53%
□ South	55%	87%	71%
▤ West	88%	88%	56%

Figure 4.33: Summary comparing achieved Daylit areas between tilted and un-tilted screens when using the recommended configuration, and the base case with no screen for all orientations.

The final recommended configurations of perforated solar screens are presented in Table 4.58. The table displays the achieved Daylit area according to the CBDM simulation.

Table 4.58: The final achieved Daylit area for each screen configuration that succeeded in maintaining visual privacy and provide acceptable levels of Daylight for each orientation.

	Minimum **Perforation Percentage**	Maximum **Depth Ratio**	Maximum **Cell Size**	Recommended **Aspect Ratio**	Minimum **Tilt Angle**	Achieved **Daylit Area**
North	90%	0.15	2cm	12:1	52°	73%
East	80%	0.75	2cm	4:1	52°	53%
South	90%	0.6	2cm	1:1	52°	71%
West	90%	0.15	2cm	6:1	52°	56%

CHAPTER 5

Concluding Discussion

5.1 Introduction

This research studies the potential of maintaining visual privacy in buildings, while providing acceptable indoor daylight at the same time. The final results of this research show that the research hypothesis is confirmed and using perforated solar screens on windows is able to provide acceptable indoor daylight and maintain visual privacy in classrooms for all main orientations in an area with a hot arid climate. In some cases, the daylighting performance is superior to a case of a window without screens, hence the results are potentially of value to a broader range of building application where privacy concerns are not necessarily applicable. This chapter discusses all the main findings of this research, limitations, recommendations and suggestions for future work.

5.2 Major findings

The major finding in this research is proving using perforated solar screens on windows is able to solve the problem of maintaining privacy, and simultaneously providing acceptable interior daylighting in girls' Schools in Saudi Arabia, and this confirms the hypothesis of this research.

In some cases, using perforated screens with appropriate values for each parameter improves indoor lighting in comparison to the cases without solar screens. This is noticed in improving the illuminance distribution and the spatial ratio between Far and Near zones, and by increasing Daylit area and reducing Overlit area especially in the east orientation. The research results in recommended values for each parameter on each orientation (Table 4.58), which achieved one of the research objectives by providing screen configurations to achieve that.

The research objectives (listed in Chapter 1) have been successfully achieved as follows:

- **Objective 1:** To establish whether using perforated solar screens is able to achieve acceptable interior daylight levels in girls' schools.

  This objective was met by applying perforated solar screens on windows and simulating daylight in the space for the occupied hours over one year and confirming that the resulting Daylit area was obtained for at least half of the studied space for all main cardinal directions.

- **Objective 2:** To establish whether using perforated solar screens is able to maintain privacy for occupants in girls' schools.

  This objective was met by testing the visibility between human subjects and objects behind perforated screens and confirming that with the appropriate configuration, a perforated solar screen can block visibility in all possible scenarios in girls' schools and thus maintaining privacy.

- **Objective 3:** To investigate the parameters of perforated solar screens and evaluate how they affect both the daylight performance and the level of privacy for occupants.

  This objective was met by identifying the parameters to be studied and investigating them one at a time, resulting in recommendations regarding the studied parameters for the cardinal directions.

- **Objective 4:** To recommend values for each parameter of perforated screens that are able to maintain privacy and achieve an acceptable level of daylight at the same time in girls' schools in Saudi Arabia.

  This objective was met by drawing conclusions from the result of all experiments in this research and recommending configurations that provide acceptable indoor daylight and confirming that tilted screens are able to maintain privacy.

These configurations are displayed in Table 4.58, and confirm that the achieved Daylit areas with or without tilting cover more than half of the classroom area in all cardinal directions; the achieved Daylit areas are displayed in Figure 4.33.

Although these recommended configuration applied only in the studied context of girls' schools in Saudi Arabia, the design guide can be used to recommend these values for any location and for any set of variables including the occupancy time of the space. The overall aim of this research (to develop a design guide for identifying configurations of perforated solar screens that is able to maintain privacy and provide acceptable levels of indoor daylighting for a building in a specific location with openings at any known orientation) was met by justifying and clearly presenting the methodology steps one by one to make the research reproducible and therefore maximise its value for influencing future research in the subject.

The research results indicate that depth ratio and perforation percentages are the most effective in increasing the amount of penetrated daylight through perforated solar screens, whereas, the aspect ratio parameter is able to bring only a minor difference, and the cell module size has a minimal effect on daylight performance of screens. Verifying that cell module size of perforated screens has no effect on its performance is a major finding of this research. It means that cell module size can be chosen according to the preference of the designer or the function of the building. For example, when using perforated solar screens in a building where the privacy is an issue, a designer is able to use the smallest module cell size possible according to the available material and machinery to build the screens. The daylight performance of screens would not be affected if the recommended values of depth ratio and perforation percentage for the required orientation is obtained. Similarly, if the view to the outside was integral and solar perforated screens are used to improve indoor daylighting, a designer can choose bigger cell module size and simultaneously keep controlling the oversupply of daylight by obtaining the recommended configurations of other parameters. Table 4.58 can be used to do this in schools in Riyadh, Saudi Arabia, and with the same method used in this research this table can be produced for any location in the world for the required occupancy schedule as long as a weather file of that location is available to be used in CBDM simulation and all other CBDM variables can be prepared.

Axial tilting of screens is proven to have a major role in providing privacy by blocking visibility between viewers from outside and the occupants inside a building. Although tilting screens reduced Daylit areas in all orientations, Daylit areas remained at the acceptable level of indoor daylighting criteria with the configurations that achieved satisfaction of the privacy criteria.

Moreover, experiments conducted in this thesis have helped to produce two papers that were published and presented in two well-known conferences. A paper titled: “Using solar screens in school classrooms in hot arid areas: The effect of different perforated rates on daylighting levels” was published in the proceedings of PLEA2016, the 32^{nd} International conference on Passive and Low Energy Architecture in Los Angeles, California. A second paper titled: “Using solar screens in school classrooms in hot arid areas: The effect of different aspect ratios on daylighting levels” was published in the proceedings of PLEA2017, the 33^{rd} International conference on Passive and Low Energy Architecture in Edinburgh. This thesis has helped contribute to the relevant body of knowledge with these two papers, and future publications will be extracted from this study, on the following possible themes: the effect of depth ratio on the performance of perforated solar screens; the effect of tilting angle on daylighting levels; the effect of cell size on daylighting levels; testing privacy through openings by testing visibility. The final findings of this thesis can also be published in a paper talking about maintaining privacy and improving daylight levels by using perforated solar screens.

5.3 Future suggestions

Another simulation process that could have been used in experiments of daylight simulation in this research is a parametric approach called Genetic Algorithms GA (Renner and Ekárt 2003). GA is a particular class of evolutionary algorithms that uses techniques inspired to evolve a solution for general or specific problems by evolutionary biology such as inheritance, selection, mutation and crossover. It has been proven to be an effective strategy to calculate multiple performance criteria, address multi-objective design problems and finding close to optimum solutions in a short period of time. GA application however, requires extensive mathematical and computer programming knowledge far beyond the domain of most professionals (González and Fiorito 2015). This problem has been solved recently by introducing "Galapagos" an evolutionary solver plug-in for Grasshopper (Rutten 2013). the Galapagos tool is a generic evolutionary solver component that can integrate GA into a highly intuitive solver using a more user-friendly and easy to use tool. Therefore, different optimisation problems can be explored without the need for advanced mathematical and computing skills (González and Fiorito 2015).

Instead of testing values of one parameter at a time, using Galapagos would allow creating a matrix of all possible combinations and testing all options to find an optimum configurations according to the set criteria. The total number of cases would be the outcome of multiplying the number of tested values for each tested parameter with the number of values for other parameters. Thus, there would be a simulation run for every case.

For instance, if this approach was used in phase one of this research the total number of cases in one orientation only would be $9 \times 10 \times 6 \times 10 = 5,400$ cases, because nine variations of perforation percentages were studied: 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10%; ten variations of depth ratio would be studied: 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2, 1.35 and 1.5; six variations of aspect ratio: 12:1, 6:1, 4:1, 2:1, 1:1, 1:2, 1:4, 1:6, 1:10 and 1:20; ten variations of cell module size: 12×12, 8×8, 6×6, 4×4, 3×3 and 2×2.

Thus, 5,400 simulation runs for every orientation would give a total of 21,600 simulation runs for the four main orientations, which is an extraordinarily big number. Using this approach would be nearly impossible with the use of an ordinary computer, considering that each run could take about an average of one to three hours. An option to resolve this limitation was using a supercomputer facility offered by Cardiff University called Raven (*Raven Supercomputer* 2017). The problem with that option however, was that Raven supercomputer uses a Linux operating system instead of Windows, and Grasshopper that controls Galapagos works only in the Windows operating system until the time this thesis was submitted. If a supercomputer using a Windows operating system was available to use or a version of Grasshopper was available to run on a Linux operating system, the author would have used the GA approach. However, the simulation process used in this research by testing one parameter at a time is still valid and used before in relative research. It is adequate to find if the indoor daylight is acceptable or not, and this means that this simulation process can be used to confirm the research hypothesis and achieve the research aim and objectives. Using a GA approach is necessary to find the optimum configuration of screens to provide the best possible indoor daylight levels, and that was not required by the research aim nor the research hypothesis.

If in the future there was an option to conduct GA in a Supercomputer it would be worthy to use that in future similar research. This would allow finding the best configuration of all parameters instead of just finding a successful set of configurations that achieve acceptable levels of indoor daylight similar to this research. In some research, Galapagos was used to perform GA analysis (Brotas and Rusovan 2013; González and Fiorito 2015), but here, the number of parameters and the range of values were much less in comparison with the number of variations in this research. Moreover, in the above-mentioned studies only one orientation was studied in order to reduce simulation time, hence, the total number of simulation runs was a reasonable number and could be done using a high performance personal computer.

Recently, Wagdy (2015) have introduced a new component for Grasshopper called SpeedSim using an approach called Parallel Algorithm to reduce total simulation running time. He used the same approach again in his following papers

(Wagdy and Fathy 2015, 2016; Wagdy et al. 2016). However, Speedsim, is not freely available, neither is it widely used yet and it has not yet been validated. New applications for light simulation are being introduced and developed lately using RADIANCE engine, usually as a plug-in for Grasshopper, namely, Honey-Bee (Roudsari and Waelkens 2015) and Ladybug (Roudsari et al. 2013). Both are freely available and attracting more designers and architectural students but not widely used yet in scientific research. Honey-Bee is under development to include a Parallel Algorithm approach which has not been announced officially yet.

Daylight simulation using CBDM is still under development and some DDPMs are being developed and/or new DDPMs could be introduced in the future. For instance, two new metrics have been introduced lately by Wagdy et al. (2016) called Hourly Spatial Daylight Autonomy H-sDA$_{300}$ and Hourly Spatial Sunlight Exposure H-SE$_{1000}$. These metrics combined hourly illuminance readings from each sensor points with the result of DDPMs metrics of spatial Daylight Autonomy sDA and Annual Sunlight Exposure respectively. However, they have not been validated yet, and it is worth testing or comparing them with actual readings in order to validate them in the future. Despite major advances in this field, much work is still needed to improve and speed up the light simulation process.

This research looked at the privacy aspect and daylight performance of perforated solar screens in school classrooms in hot arid area. Further research can be directed towards the effect of screen parameters on the performance of screens in thermal gain and energy consumption in the same context. This research has been previously undertaken for domestic buildings and not for school buildings, and results would be different for similar reasons as discussed in this research. Moreover, the method used in this research to produce tools to help designers in selecting the appropriate configurations for perforated solar screens can be adapted and used in any other location to produce similar tools as long as a weather data file is available for that location and an occupancy schedule can be constructed and other CBDM variables can be prepared.

5.4 Conclusion

This research has successfully confirmed the research hypothesis that using perforated solar screens would maintain privacy simultaneously with providing acceptable indoor daylight in buildings. It has also achieved the research objective identifying the recommended configuration to achieve an acceptable performance according to the criteria set to assess daylight while maintaining privacy. The research has set recommended values to be used for each parameter of the perforated solar screen on each orientation in school classrooms in the studied context. It also provided tables as tools to be used by architects and designers to select the appropriate value of each parameter according to the required illuminance levels; they can also be used to determine the time at which artificial lighting is needed and in which zone.

Retrofitting existing school buildings in Saudi Arabia by applying perforated solar screens using the recommended configurations identified in this research would benefit 2.18 million girl pupils around Saudi Arabia according to the most recent survey of the Saudi General Authority for Statistics in 2017, occupying about 15,000 public schools. There are 28 Universities in Saudi Arabia that are gender separated; the same configurations can be also applied to retrofit university buildings used by female students. The results of this research can be used also to select configurations for perforated solar screens to use them in boys' school in Saudi Arabia optimise indoor daylight even if maintaining privacy is not required, for example by using 90% perforation without screen axial tilting, which is recommended to maintain privacy. This would benefit 2.22 million boy pupils occupying about another 15,000 public school buildings. This indicates that the outcome of this research could impact and benefit a big part of the population of Saudi Arabia, especially regarding their health, well-being and their productivity.

The overall aim of the study comprising this thesis is to develop a framework for studying the parameters of perforated solar screens to test a hypothesis. For future work, the same framework can be applied to offer more insight on the subject or to conduct a study to optimise indoor daylighting using perforated solar screen for any other location. The required variables to conduct lighting simulation in any location are listed and discussed in this research, e.g. occupancy schedule and the appropriate weather file. Findings of this research have disclosed that perforated screens could enhance indoor lighting in buildings regardless of the usefulness of providing privacy and without affecting the outside view by using bigger cell module size while keeping the depth ratio and perforation percentage at the recommended values. Therefore, the framework developed in this research can be used to improve daylight performance of perforated screens in any place worldwide, even if privacy is not an issue.

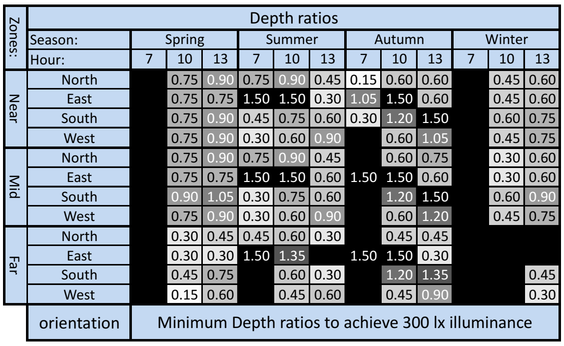
The privacy experiment conducted in this research is novel and has not been done before. Previous research only talked theoretically about the benefits of using perforated solar screens to provide privacy but no one has tested that or/and investigated how the design parameters of the screen would affect that aspect. The way human subjects reacted on describing the Kay pictures they have seen has provided information to the developer of Kay pictures that can help them in the future enhancing of the pictures. For example, the star image was the most detected image; the reason for this could be the fact that the star is the only symmetrical shape between all pictures. The developers of Kay pictures could use the results of this research to study if the human eye react differently to symmetrical pictures by comparing the results of detecting a group of symmetrical pictures against a group of non-symmetrical pictures.

Some of the daylight simulation experiments conducted in this research have not been done before in any context, such as, the effect of cell module size. Some parameters have been investigated only for the energy-saving aspect, or their daylight performance was tested in combination with another parameter, namely, the effect of depth ratio. Some have been investigated using a questionable method to create the variations of that parameter, namely, the opening aspect ratios. The variations selected to test the effect of aspect ratio in previous research have not considered the window dimension and the final dimension of the tested perforated screen after applying the aspect ratio under investigation. The author of this research has questioned the results of using such methods, and developed a procedure to make all the investigated opening aspect ratios resulting in screen dimension identical to the dimension of the window under investigation. The only parameter that has been investigated in an approach similar to that used by the author was the perforation percentage. However, the effect of it (and most parameters) were tested only in the context of living rooms in residential buildings. The author has argued in this research that results would be different for classrooms as they have different layout, window to wall ratio, occupancy schedule and different minimum lighting requirements.

Simulating average illuminance levels in three zones of the space has helped to produce tables in this research to recommend values of the investigated parameter according to the time, zone and orientation based on the results of average illuminances in each zone three times a day. These tables are displayed in the research chapter and copies of them are displayed here as examples.

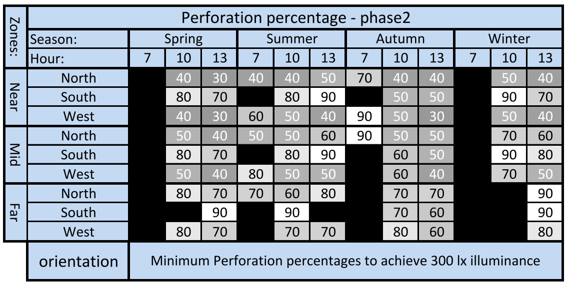
Table 5.1: Minimum recommended depth ratios (a) and perforation percentages (b) to achieve the target illuminance ($300lx$) in all studied cases and zones for specific times throughout the year. (black cells represent cases that $300lx$ cannot be achieved with daylight alone; lighter cells represent higher depth ratios in (a) and lower perforation percentages.)

(a) Minimum recommended depth ratios to achieve acceptable illuminance levels.



Zones:	Depth ratios												
	Season:	Spring			Summer			Autumn			Winter		
	Hour:	7	10	13	7	10	13	7	10	13	7	10	13
Near	North	■	0.75	0.90	0.75	0.90	0.45	0.15	0.60	0.60	■	0.45	0.60
	East	■	0.75	0.75	1.50	1.50	0.30	1.05	1.50	0.60	■	0.45	0.60
	South	■	0.75	0.90	0.45	0.75	0.60	0.30	1.20	1.50	■	0.60	0.75
	West	■	0.75	0.90	0.30	0.60	0.90	■	0.60	1.05	■	0.45	0.75
Mid	North	■	0.75	0.90	0.75	0.90	0.45	■	0.60	0.75	■	0.30	0.60
	East	■	0.75	0.75	1.50	1.50	0.60	1.50	1.50	0.60	■	0.30	0.60
	South	■	0.90	1.05	0.30	0.75	0.60	■	1.20	1.50	■	0.60	0.90
	West	■	0.75	0.90	0.30	0.60	0.90	■	0.60	1.20	■	0.45	0.75
Far	North	■	0.30	0.45	0.45	0.60	0.30	■	0.45	0.45	■	■	■
	East	■	0.30	0.30	1.50	1.35	■	1.50	1.50	0.30	■	■	■
	South	■	0.45	0.75	■	0.60	0.30	■	1.20	1.35	■	■	0.45
	West	■	0.15	0.60	■	0.45	0.60	■	0.45	0.90	■	■	0.30
	orientation	Minimum Depth ratios to achieve 300 lx illuminance											

(b) Minimum recommended perforation percentages to achieve acceptable illuminance levels.



Zones:	Perforation percentage - phase2												
	Season:	Spring			Summer			Autumn			Winter		
	Hour:	7	10	13	7	10	13	7	10	13	7	10	13
Near	North	■	40	30	40	40	50	70	40	40	■	50	40
	South	■	80	70	■	80	90	■	50	50	■	90	70
	West	■	40	30	60	50	40	90	50	30	■	50	40
Mid	North	■	50	40	50	50	60	90	50	50	■	70	60
	South	■	80	70	■	80	90	■	60	50	■	90	80
	West	■	50	40	80	50	50	■	60	40	■	70	50
Far	North	■	80	70	70	60	80	■	70	70	■	■	90
	South	■	■	90	■	90	■	■	70	60	■	■	90
	West	■	80	70	■	70	70	■	80	60	■	■	80
	orientation	Minimum Perforation percentages to achieve 300 lx illuminance											

Using the same method and framework used in this research, similar tables can be produced for any studied space in any location. These tables are very helpful and can be used in the future to develop parametric screens that can change their properties according to the time of the day. The tables can also supply information to help control light fixtures in the studied space. The resulting illuminance tables in this research indicate that in some hours of the day, artificial light is only needed for the Far zone. Using lighting control systems based on the findings displayed in the tables will be very helpful in reducing consumed energy in artificial lighting.

The findings of this research have revealed recommended configurations for perforated solar screens to achieve acceptable levels of indoor daylighting while maintaining privacy, which confirmed the research hypothesis. However, the research did not confirm the optimal configurations to provide the best possible level of indoor daylight. In order find out the optimal configuration, more than 5,000 possible combinations of the configuration need to be simulated as discussed in Section 5.3. The future might reveal solutions to conduct a parametric study using a Generic Algorithm approach in order to achieve this.

References

CL–200A Catalogue, the: (2018). *Konica-Minolta CL–200A Catalogue*. manual. Konica-Minolta. URL: `https://sensing.konicaminolta.us/uploads/cl200a_catalog_eng-wuwp9k4g64.pdf` (visited on 01/24/2018).

3M (2017). *Glass finishes*. 3M Science Applied to life.

Abanomi, Waleed (2005). "Environmental design of prototype school buildings in hot, arid regions with special reference to Riyadh, Saudi Arabia". PhD. Thesis.

Abanomi, Waleed and Phill Jones (2005). "Passive cooling and energy conservation design strategies of school buildings in hot, arid region: Riyadh, Saudi Arabia". In: *Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, pp. 619–630.

Abbasoglu, M Selen and Ugur Ulas Dagli (2009). "Women's visual privacy analysis in traditional Houses and modern apartment block neighbourhoods In Famagusta (North Cyprus)". In: *9th International Postgraduate Research Conference In the Built and Human Environment*.

Abdul-Rahim, Asiah (2008). *Housing from the Islamic Perspective*. Kuala Lumpur , Malaysia.

Abu-Lughod, Janet L (1993). "The Islamic city: Historic myth, Islamic essence, and contemporary relevance". In: *Urban development in the Muslim world*. Ed. by Hooshang Amirahmadi. New York, NY: Routledge, pp. 11–36.

Ahmed, Khaled Galal (2014). "Sustainable community and user-controlled housing processes in Cairo, Egypt:'no-harm'principle as a regulatory mechanism". In: *International Journal of Urban Sustainable Development*, pp. 1–28.

Ajaj, Aiman and Fausto Pugnaloni (2014). "Re-Thinking Traditional Arab Architecture: A Traditional Approach to Contemporary Living". In: *IACSIT International Journal of Engineering and Technology* 6.4, p. 3.

Akbar, Jamel (1989). "Losing interest: blight of the Muslim city". In: *Open House International* 14.3, pp. 28–35.

— (2012). *The Diminishing Role of Windows from Traditional to Modern: The Case of Jeddah, Saudi Arabia*. Report. Newcastle University.

Akbar, Jamel and Besim S Hakim (1992). "Crisis in the Built Environment: The Case of the Muslim City". In: *Middle East Studies Association Bulletin* 26.1, pp. 150–152.

Alawadhi, Esam M (2018). "Double solar screens for window to control sunlight in Kuwait". In: *Building and Environment* 144, pp. 392–401.

Aldossary, Naif Ali (2015). "Domestic Sustainable and Low Energy Design in Hot Climatic Regions". Thesis.

Alitany, Ayman Khalil (2014). "A new strategy of ICT integrated methodologies for 3D documentation : a case study of the projected wooden windows (The Roshans) in the historical city of Jeddah (Saudi Arabia)". Thesis.

Aljofi, E (2005). “The Potentiality of Reflected sunlight through Rawshan screens”. In: *Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece.

— (2006). “Theory of direct sunlight transmission through orthogonal screen cells”. In: *the International Symposium on Renewable Energy: Environment Protection and Energy Solution*. Kuala Lumpur , Malaysia: Malaysian Institute of Energy.

Almansuri, Aisha A, Steve Curwell, and David Dowdle (2010). “Designing a Dwelling Unit in Tripoli-Libya by Using Sustainable Architectural Principles”. In: *2nd International conference on sustainable architecture and urban development*. Amman, Jordan: Faculty of Engineering and Technology, University of Jordan.

Almotairi, T M (1995). “Administration and organizational structure of Local government in the Kingdom of Saudi Arabia.”’ In: *Public Administration in the Kingdom of Saudi Arabia, Institute of Public Administration, Riyadh*, pp. 153–88.

Alnatheer, Othman (2006). “Environmental benefits of energy efficiency and renewable energy in Saudi Arabia’s electric sector”. In: *Energy Policy* 34.1, pp. 2–10.

Alshaibani, Khalid A (2015). “Planning for Daylight in Sunny Regions”. In: *the International Conference on Environment And Civil Engineering ICEACE*. Pattaya, Thailand.

Altman, Irwin (1975). *The environment and social behavior: privacy, personal space, territory, crowding*. Monterey, CA: Brooks/Cole.

— (1977). “Privacy Regulation: Culturally Universal or Culturally Specific?” In: *Journal of Social Issues* 3 (33), pp. 66–84.

Altman, Irwin and Martin M Chemers (1980). “Culture and environment”. In: *basic concepts in environment and behavior series*. London, UK: Cambridge University Press.

Altman, Irwin, Anne Vinsel, and Brian Brown (1981). “Dialectic conceptions in social psychology: An application to social penetration and privacy regulation”. In: *Advances in experimental social psychology*. Vol. 14. Elsevier, pp. 107–160.

Altomonte, Sergio (2009). “Daylight and the Occupant”. In: *the 26th Conference on Passive and Low Energy PLEA2009: Visual and Physio-psychological well-being in built environments*. 22–24 June. Quebec City, Canada, pp. 239–250.

Amer, Mohamed and Ayman Wagdy (2016). “Multivariable Optimization for Zero Over-lit Shading Devices in Hot Climate”. In: *3rd IBPSA-England Conference*. 12-14/09/2016. Newcastle, UK.

Ampatzi, Eleni (2005). “The accuracy of Radiance, the potential and the importance of using the program in the design stage as a tool of reliably accurate lighting simulation”. Msc. in Environmental Design. Thesis.

Archea, John Charles (1984). “Visual access and exposure: An architectural basis for interpersonal behavior”. PhD thesis. Pennsylvania: Pennsylvania State University.

Aries, Myriam B. C., M.P.J. Aarts, and J van Hoof (2015). “Daylight and health: A review of the evidence and consequences for the built environment”. In: *Lighting Research & Technology* 47.1, pp. 6–27.

Asfour, Khalid (1998). “Cultural crisis: cut and paste leads to disaster in the Middle East”. In: *The Architectural Review* 203.1213, pp. 52–60.

Ashmore, Joseph and Paul Richens (2001). “Computer Simulation in Daylight Design: A Comparison”. In: *Architectural Science Review* 44.1, pp. 33–44.

Association Suisse des Electriciens, ASE: the (1989). *Eclairage intérieur par la lumière du jour*. Norm. Swiss Norm SN 418911.

Ayssa, A.Z. (1996). “The traditional Yemeni window and natural lighting”. In: *Renewable Energy* 8.1-4, pp. 214–218.

Bahammam, Ali (1987). “Architectural Patterns of Privacy In Saudi Arabia”. PhD thesis. Montreal, Canada: Mcgill University.

— (1998). “Factors Which Influence the Size of the Contemporary Dwelling: Riyadh, Saudi Arabia”. In: *Habitat International* 22.4, pp. 557–570.

Baker, N A, K Fanchiotti, and E Steemers (1993). *Daylighting in Architecture, A European Reference Book*. London: James and James Ltd. For the Commission of the European Communities.

Barlow, H B (1964). “The physical limits of visual discrimination”. In: *Photophysiology*. Ed. by Giese A C. Vol. 2. New York, NY: Academic Press, pp. 471–491.

Baron, William S. and Gerald Westheimer (1973). “Visual acuity as a function of exposure duration”. In: *Journal of the Optical Society of America* 63.2, pp. 212–219.

Barten, Peter GJ (1992). “Physical model for the contrast sensitivity of the human eye”. In: *Human Vision, Visual Processing, and Digital Display III*. Vol. 1666. International Society for Optics and Photonics, pp. 57–73.

Batool, A and IMK Elzeyadi (2014). “From romance to performance: assessing the impacts of jali screens on energy savings and daylighting quality of office buildings in lahore, Pakistan”. In: *the 30th International PLEA Conference, Ahmedabad, India*. 16–18 December. Ahmedabad, India.

Beadie, Guy et al. (2015). “Refractive index measurements of poly (methyl methacrylate)(PMMA) from 0.4–1.6 μm”. In: *Applied optics* 54.31, F139–F143.

Behrens-Abouseif, Doris (1991). “Mashrabiya”. In: vol. 6. E.J. Brill, pp. 717–720.

Belakehal, A., K. Tabet Aoul, and A. Bennadji (2004). “Sunlighting and daylighting strategies in the traditional urban spaces and buildings of the hot arid regions”. In: *Renewable Energy* 29.5, pp. 687–702.

Bellia, Laura, A. Cesarano, F. Minichiello, and S. Sibilio (2000). “De-Light: a software tool for the evaluation of direct daylighting illuminances both indoors and outdoors comparison with Superlite 2.0 and Lumen Micro 7.1”. In: *Building and Environment* 35.4, pp. 281–295.

Bellia, Laura, Alessia Pedace, and Francesca Fragliasso (2015a). “Dynamic daylight simulations: Impact of weather file’s choice”. In: *Solar Energy* 117.Supplement C, pp. 224–235.

— (2015b). “The impact of the software’s choice on dynamic daylight simulations’ results: A comparison between Daysim and 3ds Max Design®”. In: *Solar Energy* 122, pp. 249–263.

— (2015c). “The role of weather data files in Climate-based Daylight Modeling”. In: *Solar Energy* 112, pp. 169–182.

Bemanian, Mohammadreza, Hamidreza Saremi, Mehran Ahmadnejad, and Hamid Rezai Ghadi (2015). “Visual Privacy Patterns Recognition in Extroverted Houses (Case study: Sari)”. In: *Current World Environment* 10.1, pp. 510–522.

Bennett, Arthur George (1965). “Ophthalmic test types. A review of previous work and discussions on some controversial questions.” In: *The British journal of physiological optics* 22.4, pp. 238–271.

Bennett, Arthur George and Ronald B Rabbetts (1984). *Clinical visual optics*. Vol. 14. London, UK: Butterworths.

Ben-Saleh, Mohammed Abdullah (1998). “The impact of Islamic and customary laws on urban form development in southwestern Saudi Arabia”. In: *Habitat International* 22.4, pp. 537–556.

Benton, C C (1990). “Diminutive Design, Physical Models in Daylighting Education and Practice”. In: *Lighting Design + Application* 20.5, pp. 4–23.

Bhandari, Mahabir, Som Shrestha, and Joshua New (2012). “Evaluation of weather datasets for building energy simulation”. In: *Energy and Buildings* 49.Supplement C, pp. 109–118.

Bingler, S., L. Quinn, and K. Sullivan (2003). *Schools as centers of community: a citizen’s guide for planning and design*. Washington, DC: National Clearinghouse for Educational Facilities;

Bourgeois, D, Christoph Reinhart, and Greg Ward Larson (2008). “Standard daylight coefficient model for dynamic daylighting simulations”. In: *Building Research & Information* 36.1, pp. 68–82.

Boyce, Peter Robert (2004). “Lighting research for interiors: the beginning of the end or the end of the beginning”. In: *Lighting Research & Technology* 36.4, pp. 283–293.

Boyce, Peter Robert, C Hunter, and O Howlett (2003). *The Benefits of Daylighting through windows*. Report. US Department of Energy.

Boyce, Peter Robert, C J Lloyd, N H Eklund, and H M Brandston (1996). “Quantifying the effects of good lighting: the Green Hills Farms project”. In: *Proceedings of the Illuminating Engineering Society of North America Annual Conference*. Cleveland, OH.

Brandt, Th., J. Dichgans, and E. Koenig (1973). “Differential effects of central versus peripheral vision on egocentric and exocentric motion perception”. In: *Experimental Brain Research* 16.5, pp. 476–491.

Brembilla, Eleonora, Nafsika Drosou, and John Mardaljevic (2016). “Real world complexity in reflectance value measurement for climate-based daylight modelling”. In: *Building Simulation & Optimisation (BSO 16)*. Newcastle, UK: IBPSA.

Brembilla, Eleonora, Christina J Hopfe, and John Mardaljevic (2017). “Influence of input reflectance values on climate-based daylight metrics using sensitivity analysis”. In: *Journal of Building Performance Simulation* 0.0, pp. 1–17.

Brembilla, Eleonora, John Mardaljevic, and F Anselmo (2015a). “The effect of the analysis grid settings on daylight simulations with Climate-Based Daylight Modelling”. In: *28th Session of the International Commission on Illumination CIE*. Manchester, UK: CIE.

Brembilla, Eleonora, John Mardaljevic, and Christina J Hopfe (2015b). “Sensitivity Analysis studying the impact of reflectance values assigned in Climate-Based Daylight Modelling”. In: *The 14th International Conference of the International Building Performance Simulation Association*. Hyderabad, India, pp. 1197–1204.

Briggs, Martin S. (1974). *Muhammadan architecture n Egypt and Palestine*. New York: Da Capo Press.

Britannica, The Editors of Encyclopaedia (2012). *Refractive index PHYSICS*. URL: `https://www.britannica.com/science/refractive-index` (visited on 05/12/2016).

British Petroleum, the (2014). *BP Report: Statistical Review of World Energy 2014*. URL: `http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf`.

Brotas, Luisa and Danijel Rusovan (2013). “Parametric daylight envelope”. In: *The 29th Conference on Passive and Low Energy Architecture PLEA2013: Sustainable Architecture for a Renewable Future*. Munich, Germany: PLEA.

Brown, Brian (1972a). “Dynamic visual acuity, eye movements and peripheral acuity for moving targets”. In: *Vision Research* 12.2, pp. 305–321.

— (1972b). “The effect of target contrast variation on dynamic visual acuity and eye movements”. In: *Vision Research* 12.7, pp. 1213–1224.

Bruna, Gilda Collet, Dominique Fretin, Rechilene Mendonça Maia, and Ladislao Pedro Szabo (2008). “Do Muxarabi Ao Brise-Soleil: A Arquitetura Brasileira Ajusta-Se Ao Clima”. In: *Cadernos de Pós-Graduação em Arquitetura e Urbanismo* 7.1.

Bryan, H and S M Autif (2002). “Lighting/Daylighting Analysis: A Comparison”. In: *American Solar Eergy Society Conference*. Reno, Nevada.

Campbell, FW and Gerald Westheimer (1960). “Dynamics of accommodation responses of the human eye”. In: *The Journal of physiology* 151.2, pp. 285–295.

Cannon-Brookes, S W A (1997). “Simple scale models for daylighting design: Analysis of sources of error in illuminance prediction”. In: *Lighting Research & Technology* 29.3, pp. 135–142.

Cantin, F and Cathrine Dubois (2011). “Daylighting metrics based on illuminance, distribution, glare and directivity”. In: *Lighting Research & Technology* 43.3, pp. 291–307.

Chaaban, F B (2008). “Arab Environment, Future Challenges-Air Quality”. In: *the Arab Forum for Environment and Development*. Beirut: AFED ’08, pp. 45–62.

Chauvel, J., B. Collins, R. Dogniaux, and J. Longmore (1982). “Glare from windows: current views of the problem”. In: *Lighting Research & Technology* 14, pp. 31–46.

Chi, Doris A., Eleonora Brembilla, and John Mardaljevic (2017a). “Evaluation of daylighting performance in a retrofitted building facade”. In: *The 33rd PLEA Passive and Low Energy Architecture: Design to Thrive*. 3–5 July. PLEA.

Chi, Doris A., David Moreno, and Jaime Navarro (2017b). “Design optimisation of perforated solar façades in order to balance daylighting with thermal performance”. In: *Building and Environment* 125, pp. 383–400. ISSN: 0360–1323.

— (2017c). “Design optimisation of perforated solar façades in order to balance daylighting with thermal performance”. In: *Building and Environment* 125, pp. 383–400.

— (2018). “Correlating daylight availability metric with lighting, heating and cooling energy consumptions”. In: *Building and Environment* 132, pp. 170–180.

Citherlet, S., J. A. Clarke, and J. Hand (2001). “Integration in building physics simulation”. In: *Energy and Buildings* 33.5, pp. 451–461.

Commission Internationale de l’Eclairage CIE, the (2004). *Ocular lighting effects on human physiology and behaviour*. Report. CIE Publication.

Commission of the European Community, the (1985). *Test Reference Year, Weather data sets for computer simulations of solar energy systems and energy consumption in buildings*. Report. CEC.

Cox, Michael J, Joanne H Norman, and Peter Norman (1999). “The effect of surround luminance on measurements of contrast sensitivity”. In: *Ophthalmic and Physiological Optics* 19.5, pp. 401–414.

Crawley, Drury B (1998). “Which weather data should you use for energy simulations of commercial buildings?/Discussion”. In: *Ashrae Transactions* 104, p. 498.

Crawley, Drury B, Jon W Hand, and Linda K Lawrie (1999). “Improving the weather information available to simulation programs”. In: *Proceedings of Building Simulation IBPSA ’99*. Vol. 2. Kyoto, Japan, pp. 529–536.

Crawley, Drury B et al. (2001). “EnergyPlus: creating a new-generation building energy simulation program”. In: *Energy and Buildings* 33.4, pp. 319–331.

Crisp, VHC, P. J. Littlefair, Cooper I., and G T McKennan (1988). *Daylighting as a passive solar energy option: an assessment of its potential in non-domestic buildings*. Building Research Establishment, Department of the Environment.

Danby, Miles (1993). “Privacy as a Culturally Related Factor in Built Form”. In: *Companion to Contemporary*. Ed. by Ben Farmer and Hentie Louw. London, UK: Routledge, pp. 138–139.

Darke, J. (1982). “The design of public housing: architects’ intentions and users’ reactions”. Sheffield, UK: University of Sheffield.

Day, Linda L. (2000). “Choosing a House: The Relationship between Dwelling Type, Perception of Privacy and Residential Satisfaction”. In: *Journal of Planning Education and Research* 19.3, pp. 265–275.

DeKay, Mark and Brian Brown (2013). *Sun, wind, and light: architectural design strategies*. New York: John Wiley & Sons.

Demer, J L and F Amjadi (1993). “Dynamic visual acuity of normal subjects during vertical optotype and head motion.” In: *Investigative ophthalmology & visual science* 34.6, pp. 1894–1906.

Depaule, J C and J L Arnaud (1985). *A Travers le mur, Collection Alors*. Paris: CCI.

Derksen, Madou et al. (2018). “Pupil mimicry is the result of brightness perception of the iris and pupil”. In: *Journal of Cognition* 1.1, pp. 1–16.

Derkum, Harald (1993). “Effects of various transmission levels in windshields on perception”. In: *Vision in vehicles* 4, pp. 63–68.

Diab, Sahar, Bayan Abu Qadourah, and Riziq Hammad (2017). “Daylight Quality in Healthcare Design, Daylight Measurements Results and Discussion, Case Study: Jordan University Hospital”. In: *Journal of Energy and Power Engineering* 11, pp. 141–149.

Digital Fabrication Lab (2018). URL: `http://sites.cardiff.ac.uk/architecture/about-us/facilities/digital-fabrication-lab/` (visited on 02/05/2018).

Donn, Michael (1999). “Quality assurance simulation and the real world”. In: *Building simulation ’99 : 6th international IBPSA conference*. Ed. by N Nakahara, H Yoshida, M. Udagawa, and J Hensen. Vol. 3. 13-15 September. Kyoto, Japan, pp. 1139–146.

Dubois, Catherine et al. (2015). “Design support tools to sustain climate change adaptation at the local level: A review and reflection on their suitability”. In: *Frontiers of Architectural Research* 4.1, pp. 1–11.

Dubois, Cathrine (1997). *Solar shading and building energy use: A literature review, part I.* Report Report TABK—97/3049. Lund Inst. of Technology, Dept. of Building Science.

Dubois, Cathrine (2000). "A Simple chart to dsgin sunshading devices considering the window solar angle dependent properties". In: *the 3rd ISES Europe Solar Congress: Eurosun*. Copenhagen, Denmark, pp. 19–22.

— (2003). "Shading devices and daylight quality: an evaluation based on simple performance indicators". In: *Lighting Research & Technology* 35.1, pp. 61–76.

Ebrahimpour, Abdulsalam and Mehdi Maerefat (2010). "A method for generation of typical meteorological year". In: *Energy Conversion and Management* 51.3, pp. 410–417.

Education Funding Agency, EFA: the (2013). *Priority School Building Programme PSBP: Facilities Output Specification*. Report. Education Funding Agency EFA.

— (2014). *Daylight Design Guide Rev.02*. Technical Report.

Edward, William Lane (1973). *An Account of the Manners and Customs of the Modern Egyptians*. London: Dover Publications.

Edwards, L. and P. Torcellini (2002). *A Literature Review of the Effects of Natural Light on Building Occupants*. Report. U.S Department of Energy.

Elghazi, Y, A Wagdy, S Mohamed, and A Hassan (2014). "Daylighting driven design: optimizing kaleidocycle facade for hot arid climate". In: *BauSIM*. Aachen, Germany.

Energy Information Administration, the (2012). *The Annual Energy Outlook 2012*. Report. U.S Department of Energy.

— (2014). *Country analysis brief: Saudi Arabia*. Report. U.S Department of Energy.

EnergyPlus (2014). *EnergyPlus thermal simulation program*. URL: `https://energyplus.net/weather` (visited on 10/30/2014).

Erhorne, H, J stoffel, and M Szermanm (1995). "Adeline 2.0—using computer tools to evaluate daylighting and electric lighting applications in buildings". In: *European Conference on Energy-Efficient Lighting*. Newcastle upon-Tyne, England, pp. 25–31.

Erlendsson, Örn (2014). "Daylight Optimization-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy". Thesis.

Erwin, Barbara and Lisa Heschong (2002). "Lighting for Learning". In: *Lightfair International Seminar*. Sanfrancisco, CA: Illuminating Engineer Society North America IESNA, pp. 76–78.

Estes, James M. Jr, Susan Schreppler, and Tonya Newsom (2004). "Daylighting Prediction Software: Comparative Analysis and Application". In: *the 14th Symposium on Improving Building Systems in Hot and Humid Climates,* Richardson, TX, pp. 259–267.

Facey, William (1997). *Back to Earth: Adobe building in Saudi Arabia*. Riyadh: Al-Turath. ISBN: 1900404133.

Fahey, Tony (1995). "Privacy and the Family: Conceptual and Empirical Reflections". In: *Sociology* 29.4, pp. 687–702.

Fasiuddin, M. and I. Budaiwi (2011). "HVAC system strategies for energy conservation in commercial buildings in Saudi Arabia". In: *Energy and Buildings* 43.12, pp. 3457–3466.

Fathy, Hassan (1986). *Natural energy and Vernacular architecture: principles and examples with reference to hot arid climate*. Chicago: University of Chicago.

Feitelson, Eran (1992). “Consumer Preferences and Willingness-to-pay for Water-related Residences in Non-urban Settings: A Vignette Analysis”. In: *Regional Studies* 26.1, pp. 49–68.

Food & Agriculture Organization, the (2017). *Population growth Saudi Arabia 1961-2012*. URL: `https://chronicle.fanack.com/saudi-arabia/population/` (visited on 04/18/2018).

Al-Fouzan, Saleh Abdulaziz (2012). “Using car parking requirements to promote sustainable transport development in the Kingdom of Saudi Arabia”. In: *Cities* 29.3, pp. 201–211.

Francescato, Guido et al. (1979). *Residents' satisfaction in HUD-Assisted Housing: design and management factors*. Washington, DC: Dept. of Housing and Urban Development.

Freewan, A.A.Y. (2014). “Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions”. In: *Solar Energy* 102, pp. 14–30.

Galasiu, Anca D. and Christoph Reinhart (2008). “Current daylighting design practice: a survey”. In: *Building Research& Information* 36.2, p. 15.

Galbraith, Justine (2015). *Optical Properties of Glass: How Light and Glass Interact*. URL: `http://www.koppglass.com/blog/optical-properties-of-glass-how-light-and-glass-interact/` (visited on 05/15/2017).

Gallo, Cettina (1996). “Passive cooling as design methodology: some examples from the past to the present”. In: *Renewable Energy* 8.1—4, pp. 309–314.

Garba, Shaibu Bala (2004). “Managing urban growth and development in the Riyadh metropolitan area, Saudi Arabia”. In: *Habitat International* 28.4. Planning Issues in the Middle East, pp. 593–608.

Georgiou, Michael (2006). “Architectural privacy: A topological approach to relational design problems”. PhD thesis. UCL (University College London).

Ghayeghchi, Maryam Mohammadi (2015). “The Relationship between Privacy and Introversion in Traditional Houses”. In: *Cumhuriyet University Science Journal* 36.4.

GLM 50 product Description, the: (2018). *BOSCH GLM 50 product Description*. manual. BOSCH. URL: `https://www.boschtools.com/us/en/boschtools-ocs/laser-measuring-glm-50-35087-p/` (visited on 01/24/2018).

González, Javier and Francesco Fiorito (2015). “Daylight Design of Office Buildings: Optimisation of External Solar Shadings by Using Combined Simulation Methods”. In: *Buildings* 5.2, p. 560.

Goodman, TM (2009). “Measurement and specification of lighting: A look at the future”. In: *Lighting Research & Technology* 41.3, pp. 229–243.

Graça, Valéria Azzi Collet da, Doris Catharine Cornelie Knatz Kowaltowski, and João Roberto Diego Petreche (2007). “An evaluation method for school building design at the preliminary phase with optimisation of aspects of environmental comfort for the school system of the State São Paulo in Brazil”. In: *Building and Environment* 42.2, pp. 984–999.

Greenlaw, Jean-Pierre (1976). *The coral buildings of Suakin*. Stockfield: Oriel press. ISBN: 0853621586.

Gregor, Thomas (1974). *Mehinaku: the drama of daily life in a Brazilian Indian village*. Chicago, IL: University of Chicago Press.

Grynberg, Anat (1989). *Validation of RADIANCE.* 1575. Lawrence Berkeley Laboratory, Berkeley LBID.

Gugliermeti, F, S Grignaffini, and F bisegna (2001). “Computer simulations, full and scale model measurements as design tools to assess daylight factors in underground open space”. In: *International lighting congress.* Istanbul, Turkey: Istanbul Technical University.

Gugliermetti, F. and F. Bisegna (2006). “Daylighting with external shading devices: design and simulation algorithms”. In: *Building and Environment* 41.2, pp. 136–149.

Hakim, Besim Selim (2013). *Arabic Islamic Cities: Building and Planning Principles.* London, UK: Routledge.

Hall, Irving J, RR Prairie, HE Anderson, and EC Boes (1978). *Generation of a typical meteorological year.* Report. Albuquerque, NM: Sandia Labs.

Halliday, Sandy (2008). *Sustainable construction.* London, UK: Routledge.

Hammad, F. and B. Abu-Hijleh (2010). “The energy savings potential of using dynamic external louvers in an office building”. In: *Energy and Buildings* 42.10, pp. 1888–1895.

Hansen, Veronica Garcia (2006). “Innovative Daylighting Systems For Deep-Plan Commercial Buildings”. Thesis.

Hariri, M (1992). “Design of Rowshan and its importance to the dwelling”. In: *Journal of the Umm-Al-Qura University* 3.5, pp. 175–237.

Harris, C (2006). *Solar screen.* fourth ed. Dictionary of Architecture and Construction. New York: McGraw-Hill books, p. 908.

Al-Hashmi, Ahmed Abdulwahab KHAN and Catherine Semidor (2013). “Virtual Study of the Day-lighting Performance of Rawshan in Residential Buildings of Jeddah”. In: *National Conference on Advancing the Green Agenda - Technology, Practices and Policie.* Dubai, UAE, p. 8.

Hathaway, W. (1995). “Effects of School Lighting on Physical Development and School Performance”. In: *The Journal of Educational Research* 88.4, p. 228.

Al-Hathloul, Saleh (1981). *Cultural conflicts in urban patterns: A Saudi-Arabian case study.* Report. Arab Urban Development Institution.

Heath, G A and MJ Mendell (2002). *DO INDOOR ENVIRONMENTS IN SCHOOLS INFLUENCE STUDENT PERFORMANCE? A REVIEW OF THE LITERATURE.* Report. Ernest Orlando Lawrence Berkeley National Labratory.

Hegazy, Mohammed Amer and Shady Attia (2014). “Investigating the Influence of External Faceades Reflectivity on Daylight Autonomy in Hot Arid Climates”. In: *Building Simulation and Optimization 2014.* London, UK: UCL.

Hegazy, Mohammed Amer, Shady Attia, and J Moro (2013). “Parametric analysis for daylight autonomy and energy consumption in hot climate”. In: *13th Conference of International Building performance Simulation Association.* Chambery, France: IBPSA, pp. 2232–2240.

Al-Hemaidi, Waleed Kassab (2001). “The metamorphosis of the urban fabric in an Arab-Muslim City: Riyadh, Saudi Arabia”. In: *Journal of Housing and the Built Environment* 16.2, pp. 179–201.

Al-Hemmiddi, Nasser (2002). *The evaluation of electrical energy consumption rates elementary school buildings of Riyadh in Saudi Arabia.* Report. Research center, King Saud University.

Heo, Y., R. Choudhary, and G. A. Augenbroe (2012). “Calibration of building energy models for retrofit analysis under uncertainty”. In: *Energy and Buildings* 47.0, pp. 550–560.

Herz Bey, Max (1907). *A descriptive catalogue of the objects exhibited in the National Museum of Arabic Art*. Cairo: prisse d’avennes.

Heschong, Lisa, I. Elzeyadi, and C. Knecht (2002a). *Re-Analysis Report: Daylighting in Schools, Additional Analysis. Tasks 2.2.1 through 2.2.5.* Report. Pacific Gas and Electric Company.

Heschong, Lisa and D Mahone (2003). “Windows and offices: A study of office worker performance and the indoor environment”. In: *California Energy Commission*, pp. 1–5.

Heschong, Lisa, Roger L. Wright, and Stacia Okura (2002b). “Daylighting Impacts on Retail Sales Performance”. In: *Journal of the Illuminating Engineering Society* 31.2, pp. 21–25.

Heschong, Lisa et al. (2012a). *Approved Method: IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE)*. Report LM-83-12. IES-Illuminating Engineering Society.

Heschong, Lisa et al. (2012b). *Approved Methods: IES Spatial Daylight Autonomy sDA and Annual Sunlight Exposure ASE*. LM-83-12. New York, N.Y.: IES - Illuminating Engineering Society.

Heschong-Mahone-Group (1999). *Daylighting in Schools: An Investigation into the Relationship between Daylighting and Human Performance*. Sacramento, CA: Pacific Gas and Electric Company.

High Commission for the Development of Riyadh, the (2016). *High Commission for the Development of Riyadh*. URL: `http://www.arriyadh.com/Eng/Ab-Arriyad/Left/CityInfo/getdocument.aspx?f=/openshare/Eng/Ab-Arriyad/Left/CityInfo/Geographic-Location.doc_cvt.htm` (visited on 11/21/2016).

Hitchcock, R and W Osterhaus (1994). *Superlite User’s Manual*. Berkeley, CA: Lawrence Berkeley Laboratory.

Hixson, Richard F. (1987). *Privacy in a Public Society: Human Rights in Conflict*. New York, NY: Oxford University Press.

Ho, Ming-Chin et al. (2008). “Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms”. In: *Energy and Buildings* 40.10, pp. 1844–1855.

Hobday, Richard (2016). “Myopia and daylight in schools: a neglected aspect of public health?” In: *Perspectives in Public Health* 136.1, pp. 50–55.

Al-Hokail, Sulaiman Abdulrahman (1992). *History of education system in Saudi Arabia*. 5th ed. Riyadh, Saudi Arabia: Ministry of Education, p. 520.

Hong, Tianzhen, S. K. Chou, and T. Y. Bong (2000). “Building simulation: an overview of developments and information sources”. In: *Building and Environment* 35.4, pp. 347–361.

Hopkinson, Ralph Galbraith (1963). *Architectural Physics: Lighting*. London: Her Majesty’s Stationery office.

Hopkinson, Ralph Galbraith, P. Petherbridge, and J. Longmore (1966). *Daylighting*. London, UK: Heinemann, p. 606.

Ibrahim, A (2010). “City of Riyadh: Actions towards sustainability.” In: *the 5th World Urban Forum WUF5*. Rio de Janeiro, Brazil: AFED08.

Al-Ibrahim, Mohammed Hussein (1990). "The criticism of modern architecture in Saudi Arabia". In: *Journal of Architecture and Planning (King Saud University)* 2, pp. 63–80.

IESNA (1997). "1997 IESNA Software Survey". In: *Lighting Design + Application* 11.7, pp. 41–50.

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Report. Geneva, Switzerland: Intern-Governmental Panel on Climate Change, p. 151.

Iversen, Anne (2011). "The effect of different weather data sets and their resolution in climate-based daylight modeling for the location of Copenhagen". In:

Iversen, Anne, Svend Svendsen, and Toke Rammer Nielsen (2013). "The effect of different weather data sets and their resolution on climate-based daylight modelling". In: *Lighting Research & Technology* 45.3, pp. 305–316.

Jackson, A J and I L Bailey (2004). "Visual acuity". In: *Optometry in Practice* 5, pp. 53–68.

Jain, S. and V. Garg (2018). "A review of open loop control strategies for shades, blinds and integrated lighting by use of real-time daylight prediction methods". In: *Building and Environment* 135, pp. 352–364.

Jakubiec, Alstan and Christoph Reinhart (2011). "DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus". In: *The 12th International Conference of Building Simulation*. Sydney, Australia: IBPSA.

Jarvis, Dave and Michael Donn (1997). "Comparison of computer and model simulations of a daylit interior with reality". In: *5th International IBPSA Conference BuildSim97*. Vol. 97, pp. 8–10.

Jensen, J Moeller and H Lund (1995). *Design Reference Year, DRY–a new Danish reference year*. Report. Technical University of Denmark.

Jomah, H A (1992). "The TraditionalProcess of Producing a House in Arabia During the 18th and 19th Centuries, A Case study of Hedjaz". Thesis.

Julian, Warren G. (2006). *Lighting: Basic Concepts*. 6th Edition (Rev). Sydney: USYD, p. 266.

Kaschke, Michael, Karl-Heinz Donnerhacke, and Michael Stefan Rill (2014). "Optics of the Human Eye". In: *Optical Devices in Ophthalmology and Optometry*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, pp. 15–48.

Kay, HAZEL (1983). "New method of assessing visual acuity with pictures". In: *British journal of ophthalmology* 67.2, pp. 131–133.

Kenzari, Bechir and Yasser Elsheshtawy (2003). "The Ambiguous Veil: On Transparency, the Mashrabiy'ya, and Architecture". In: *Journal of Architectural Education* 56.4, pp. 17–25.

Khafaji, O. (1987). "The Provision of school buildings in Saudi Arabia with particular reference to Jeddah". Thesis.

Khodulev, A.B and E. A. Kopylov (1996). *Physically Accurate Lighting Simulation in Computer Graphics Software*. Moscow: Moscow State University.

Al-Khoutani, A. (2001). "The Practicality and Economics of Thermal Insulation Retrofitting for Existing Residential Buildings". Thesis.

Koch-Nielsen, Holger (2002). *Stay cool: A design guide for the built environment in hot climates*. London: James& James. ISBN: 1134276109.

Al-Kodmany, Kheir (1999). “Residential visual privacy: Traditional and modern architecture and urban design”. In: *Journal of Urban Design* 4.3, pp. 283–311.

— (2000). “Women visual privacy in traditional and modern neighborhoods in Damascus”. In: *Journal of Architertural & Planning Research* 4.17, pp. 283–303.

Koenigsberger, O H (1973). *Manual of Tropical Housing, Part1 Climate Design.* London: Longman.

Koks, Don (2006). *Explorations in Mathematical Physics.* New York, NY: Springer-Verlag.

Kosslyn, Stephen M, Thomas M Ball, and Brian J Reiser (1978). “Visual images preserve metric spatial information: evidence from studies of image scanning.” In: *Journal of experimental psychology: Human perception and performance* 4.1, pp. 47–60.

Krüger, Eduardo L. and Adriano Lucio Dorigo (2008). “Daylighting analysis in a public school in Curitiba, Brazil”. In: *Renewable Energy* 33.7, pp. 1695–1702.

Küller, Rikard and Carin Lindsten (1992). “Health and behavior of children in classrooms with and without windows”. In: *Journal of Environmental Psychology* 12.4, pp. 305–317.

Kupritz, Virginia W (2000). “Privacy management at work: a conceptual model”. In: *Journal of Architectural and Planning Research* 17.1, pp. 47–63.

Lagios, Kera, Jeff Niemasz, and Christoph Reinhart (2010). “Animated building performance simulation, linking rhinoceros/grasshopper with radiance/daysim”. In: *SimBuild2010.* New York, NY: IBPSA.

Lalor, Sarah JH, Monika A Formankiewicz, and Sarah J Waugh (2016). “Crowding and visual acuity measured in adults using paediatric test letters, pictures and symbols”. In: *Vision research* 121, pp. 31–38.

Land, MF (1981). “Optics and vision in invertebrates”. In: *Handbook of Sensory Physiology.* Ed. by F Crescitelli. Vol. VII. Berlin, Germany: Springer Verlag, pp. 471–491.

Landolt, E (1899). “Nouveaux opto-types pour la détermination de l’acuité visuelle”. In: *Arch. d’Opht* 19, pp. 465–471.

Lang, Jon T (1987). *Creating architectural theory: The Role of the Behavioral Sciences in Environmental Design.* New York, NY: Van Nostrand Reinhold.

Laouadi, Abdelaziz, Christoph Reinhart, and D Bourgeois (2008). “Efficient calculation of daylight coefficients for rooms with dissimilar complex fenestration systems”. In: *Journal of Building Performance Simulation* 1.1, pp. 3–15.

Larson, Greg Ward and Rob Shakespear (1998). *Rendering with RADIANCE The Art and Science of Lighting Visualization.* San Francisco: Morgan Kaufmann.

— (2003). *Rendering with Radiance the art o lighting visulization.* Revised Edition. Davis, CA, USA: Space& Light, p. 664.

Larson, Greg Ward and Rob Shakespeare (1998). *Rendering with Radiance: the art and science of lighting visualization.* San Francisco, CA: Morgan Kaufmann Publishers. ISBN: 0974538108.

Lea, Hyvärinen, Näsänen RISTO, and LAURINEN PENTTI (1980). “New Visual Acuity Test for Pre-School Children”. In: *Acta Ophthalmologica* 58.4, pp. 507–511.

Lee, E et al. (2012). “Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms”. In: *Building and Environment* 49, pp. 238–244.

Lee, MC et al. (2012). “Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms”. In: *Building and Environment* 49, pp. 238–244.

Li, Danny H. W., Gary H. W. Cheung, and Chris C. S. Lau (2006). “A simplified procedure for determining indoor daylight illuminance using daylight coefficient concept”. In: *Building and Environment* 41.5, pp. 578–589.

Li, Danny H. W. and Joseph C. Lam (2000). “Measurements of solar radiation and illuminance on vertical surfaces and daylighting implications”. In: *Renewable Energy* 20.4, pp. 389–404.

Li, Danny H. W. and Ernest K. W. Tsang (2008). “An analysis of daylighting performance for office buildings in Hong Kong”. In: *Building and Environment* 43.9, pp. 1446–1458.

Lighting Materials for Simulation (2017). URL: `http://lighting-materials.com` (visited on 02/15/2017).

Littlefair, P. J. (1992). “Daylight coefficients for practical computation of internal illuminances”. In: *Lighting Research & Technology* 24.3, pp. 127–135.

Littlefair, P. J. and C. R. T. Lindsay (1990). *Scale models and artificial skies in daylighting studies.* Technical Note 90/3. Building Environmental Performance Analysis Club BEPAC.

Love, J. A. (1993). “Daylighting estimation under real skies: further comparative studies of full-scale and model photometry”. In: *Journal of the Illuminating Engineering Society* 22.2, pp. 61–68.

Love, J. A. and M. Navvab (1989). “A comparison of photometric modeling and computer simulation techniques for daylighting prediction under real sky conditions”. In: *Thermal performance of the exterior envelopes of buildings IV*, pp. 97–107.

— (1991). “Daylighting estimation under real skies: a comparison of full-scale photometry, model photometry, and computer simulation”. In: *Journal of the Illuminating Engineering Society,* 20.1, pp. 140–56.

— (1994). “The vertical-to-horizontal illuminance ratio: a new indicator of daylighting performance”. In: *Journal of the Illuminating Engineering Society* 23.2, pp. 50–61.

Loveland, Joel (2002). “Daylighting and Sustainability”. In: *Environmental Design & Construction* 5.5, p. 28.

Ludvigh, Elek and James W. Miller (1958). “Study of Visual Acuity during the Ocular Pursuit of Moving Test Objects: I. Introduction”. In: *Journal of the Optical Society of America* 48.11, pp. 799–802.

Lynes, J. A. (1968). *Principles of Natural Lighting.* UK: Elsevier Publishing Company, p. 212.

Maamari, F and M Fontoynont (2003). “Analytical tests for investigating the accuracy of lighting programs”. In: *Lighting Research & Technology* 35.3, pp. 225–242.

Al-Maayouf, Mohammed S (2005). “The impact of envelope design on the energy performance for modern houses application in hot, arid regions with special reference to Riyadh, Saudi Arabia.” Thesis.

Mahfouz, Afaf and Ismail Serageldin (1990). “Women y Space in Muslim Societies”. In: *Expressions of Islam in Buildings*, pp. 79–107.

Manaf, Azhani Abd, Zaiton Abdul Rahim, Noor Hanita Abdul Majid, and Spahic Omer (2018). "TOWARDS AN ISLAMIC APPLICATION OF VISUAL PRIVACY PRINCIPLES ON MALAYSIAN TERRACE HOUSING: A CONCEPTUAL FRAMEWORK". In: *PLANNING MALAYSIA JOURNAL* 16.6.

Mangkuto, Rizki A. and Mhd. Akbar Anthony Siregar (2018). "Verification tests of a mirror box type artificial sky without and with building scale model". In: *Frontiers of Architectural Research* 7.2, pp. 151–166.

Mansfield, KP (2008). *British Standard BS 8206-2 Lighting for Buildings-Part 2: Code of Practice for Daylighting*. British Standards Institution.

Al-Mansuree, M (1997). "Womens need in Jeddah housing". In: *Journal of Saudi Architecture* 4.7.

Mardaljevic, John (1995). "Validation of a lighting simulation program under real sky conditions". In: *Lighting Research & Technology* 27.4, pp. 181–188.

— (2000a). "Daylight simulation: validation, sky models and daylight coefficients". PhD thesis. De Montfort University.

— (2000b). "Simulation of annual daylighting profiles for internal illuminance". In: *Lighting Research & Technology* 32.3, pp. 111–118.

— (2001). "The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques". In: *Transactions of the Illuminating Engineering Society* 33.2, pp. 117–134.

— (2002). "Quantification of parallax errors in sky simulator domes for clear sky conditions". In: *Lighting Research & Technology* 34.4, pp. 313–327.

— (2004). "Verification of program accuracy for illuminance modelling: assumptions, methodology and an examination of conflicting findings". In: *Lighting Research & Technology* 36.3, pp. 217–239.

— (2006). "Examples of climate-based daylight modelling". In: *CIBSE National Conference*. London, UK: CIBSE, pp. 21–22.

— (2013). "Daylight, Indoor Illumination, and Human Behavior". In: *Sustainable Built Environments*. Ed. by Vivian Loftness and Dagmar Haase. New York, NY: Springer, pp. 69–111.

— (2015). "Climate Based Daylight Modelling and its discontents". In: *CIBSE Technical Symposium*. 16–17 April. London, UK.

Mardaljevic, John, Marilyne Andersen, Nicolas Roy, and Jens Christoffersen (2012). *Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building*. Report. Velux.

Mardaljevic, John, Lisa Heschong, and E Lee (2009). "Daylight metrics and energy savings". In: *Lighting Research & Technology* 41.3, pp. 261–283.

Mardaljevic, John and George M Janes (2012). "Multiscale Daylight Modeling for Urban Environments". In: *Solar energy at urban scale*. Ed. by Benoit Beckers. Hoboken, NJ: John Wiley & Sons. Chap. 8.

Mardaljevic, John and Nicolas Roy (2016). "The sunlight beam index". In: *Lighting Research & Technology* 48.1, pp. 55–69.

Margulis, Stephen T (2003a). "On the status and contribution of Westin's and Altman's theories of privacy". In: *Journal of Social Issues* 59.2, pp. 411–429.

— (2003b). "Privacy as a social issue and behavioural concept". In: *Journal of social issues* 59.2, pp. 243–261.

Marion, William and Ken Urban (1995). *Users manual for TMY2s: Derived from the 1961–1990 National Solar Radiation Data Base*. Tech. rep. National Renewable Energy Lab., Golden, CO (United States).

Marrickville (2011). “2.6: Acoustic and visual privacy”. In: *Development Control Plan*. Vol. 2. NSW, Australia: New South Wales Government, pp. 537–544.

Marshal, N (1970). “Environmental Components of Orientations Toward Privacy”. In: *Environmental Design Research Association Conference*. Ed. by John Charles Archea and C Eastman. Pittsburgh.

Al-Mayoof, A (2003). *Demonstration of education in the Kingdom of Saudi Arabia: Male and female*. Report. Saudi Ministry of Education.

Mayyasi, A. M., R. P. Beals, A. E. Templeton, and P. N. Jr. Hale (1971). “The Effects Of Ambient Illumination And Contrast On Dynamic Visual Acuity*”. In: *Optometry and Vision Science* 48.10, pp. 844–848.

McGraw, Paul, Barry Winn, and David Whitaker (1995). “Reliability of the Snellen chart”. In: *BMJ* 310.6993, pp. 1481–1482. ISSN: 0959-8138. DOI: `10.1136/bmj.310.6993.1481`. eprint: `https://www.bmj.com/content/310/6993/1481`. URL: `https://www.bmj.com/content/310/6993/1481`.

McNamara, Ann, Alan Chalmers, Tom Troscianko, and Iain Gilchrist (2000). “Comparing real & synthetic scenes using human judgements of lightness”. In: *Rendering Techniques 2000*. Ed. by B. Peroche and H Rushmeier. 26-28/June. Brno, Czech: Springer, pp. 207–218.

Mcneel, Robert and Associates (2016). *Rhinoceros features*. URL: `https://www.rhino3d.com/features` (visited on 01/25/2016).

Merriam Webster (2018). URL: `https://www.merriam-webster.com/dictionary/privacy` (visited on 11/15/2018).

Merry, Sally Engle (1987). “Crowding, Conflict, and Neighborhood Regulation”. In: *Neighborhood and Community Environments*. Ed. by Irwin Altman and Abraham Wandersman. Boston, MA: Springer US, pp. 35–68.

Meteonorm: Global Meteorogical databas, Handbook partII: Theory (2015). URL: `http://www.meteonorm.com/images/uploads/downloads/mn71_theory.pdf` (visited on 04/22/2016).

Miller, James W. (1958). “Study of Visual Acuity during the Ocular Pursuit of Moving Test Objects: II. Effects of Direction of Movement, Relative Movement, and Illumination”. In: *Journal of the Optical Society of America* 48.11, pp. 803–808.

Milling, Ashli et al. (2016). *The redevelopment of the Kay picture test of visual acuity*. Vol. 13, pp. 14–21.

Ministry of Culture, the and Information (2000). *This is our country*. Government Document. Saudi Ministry of Culture and Information MCI.

Ministry of Education website (2015). URL: `https://www.moe.gov.sa/en/PublicEducation/Gov/Pages/AcademicCalendar.aspx` (visited on 03/05/2015).

Ministry of Education, the (2004). *Educational year 2003-2004 projected summary statistics general education*. Government Document.

Ministry of Industry, the and Electricity (1993). *Electricity in the Kingdom of Saudi Arabia: Growth and Development. Annual Report*. Report. Ministry of Industry and Electricity.

— (2002). *Electricity Growth and Development in the Kingdom of Saudi Arabia up to the year 2000*. Report. Ministry of Industry and Electricity.

Al-Mofeez, I. (2007). “Electrical Energy Consumption Pre and Post Energy Conservation Measures: A Case Study of One Story House in Dhahran, Saudi Arabia”. In: *King Saud University, Arch. & Planning* 19.2, pp. 1–12.

Mohamed, Nermine AbdelGelil (2006). “A new Mashrabiyya for contemporary Cairo: Integrating traditional lattic work from Islamic and Japanese cultures”. In: *Journal of Asian Architecture and Building Engieering* 5.1, pp. 37–45.

Mohsenin, Mahsan and Jianxin Hu (2015). “Assessing daylight performance in atrium buildings by using Climate Based Daylight Modeling”. In: *Solar Energy* 119.Supplement C, pp. 553–560.

Monteoliva, J. M., A. Villalba, and A. E. Pattini (2017). “Variability in dynamic daylight simulation in clear sky conditions according to selected weather file: Satellite data and land-based station data”. In: *Lighting Research & Technology* 49.4, pp. 508–520.

Moon, P and D Spencer (1942). “Illumination from a non-uniform sky”. In: *Illuminating Engineering* 37, pp. 707–726.

Moore, Barrington Jr. (2018). *Privacy: Studies in Social and Cultural history*. Vol. 2. New York, NY: Routledge.

Mortada, Hisham (2003). *Traditional Islamic principles of built environment*. London, UK: Routledge.

Mubarak, Faisal A (2004). “Urban growth boundary policy and residential suburbanization: Riyadh, Saudi Arabia”. In: *Habitat international* 28.4, pp. 567–591.

Muhs, Jeff (2000). “Design And Analysis Of Hybrid Solar Lighting And Full Spectrum Solar Energy Systems”. In: *SOLAR Conference*. Madison, WI: American Solar Energy Society.

Nabil, Azza and John Mardaljevic (2005). “Useful daylight illuminance: a new paradigm for assessing daylight in buildings”. In: *Lighting Research & Technology* 37.

— (2006). “Useful daylight illuminances: A replacement for daylight factors”. In: *Energy and Buildings* 38.7, pp. 905–913.

Naghibi, S A (2010). “Privacy in family relations”. In: *Law and family law* 52.

Nations Online Project, the (2018). *Saudi Arabia*. URL: `https://chronicle.fanack.com/saudi-arabia/population/` (visited on 01/10/2018).

Newall, Venetia (1989). “A Moslem Christmas Celebration in London”. In: *The Journal of American Folklore* 102.404, pp. 186–190.

Newell, Patricia Brierley (1995). “Perspectives on privacy”. In: *Journal of Environmental Psychology* 15.2, pp. 87–104.

Nicklas, M. and G. Baily (1997). “Analysis of the Performance of Students in Daylit Schools,” in: *American Solar Energy Society Annual Conference*. Washington, DC.

Numan, M., M. Al-Naim, K. Al-Shaibani, and F. Al-Maziad (2000). “The Impact of Dynamic Cultural Changes on the Design and Energy Performance of Residential Buildings in Saudi Arabia”. In: *Mediterranean Conference for Environment and Solar*. Beirut, Lebanon.

O’Carroll, David C. and Steven D. Wiederman (2014). “Contrast sensitivity and the detection of moving patterns and features”. In: *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 369.1636.

Ochoa, Romulo, Richard Fiorillo, and Cris Ochoa (2014). “Index of refraction measurements using a laser distance meter”. In: *The Physics Teacher* 52.3, pp. 167–168.

Oh, Kyushik and E Lee (2002). “ESTIMATING THE VALUE OF LANDSCAPE VISIBILITY IN APARTMENT HOUSING PRICES”. In: *Journal of Architectural and Planning Research* 19.1, pp. 1–11.

Olgyay, V (1963). *Solar Control (Chapter VII). Desin with Climate.* New Jersey: Princeton University Press.

Oliver, Paul (1990). *Dwellings: The House across the World.* Austin, TX: University of Texas press.

Omer, Spahic (2010a). *Islam and housing.* Kuala Lumpur, Malaysia: A.S Noordeen.

— (2010b). “Some lessons from Prophet Muhammad (SAW) in architecture”. In: *Intellectual Discours* 18.1, pp. 114–140.

Al-Oraier, Fahad (2005). “Thermal analysis of traditional adobe dwellings in Riyadh City, Saudi Arabia”. Thesis.

Osterberg, Gustav (2006). *Topography of the layer of rods and cones in the human retina.* Copenhagen, Denmark: Levin & Munksgaard.

Paccard, Andre (1981). *Le Maroc et l’artisanat traditional islamique dans l’architecture.* Vol. 2. Morocco: Editions Atelier 74.

Paix, D (1982). *The design of buildings for daylighting.* Canberra, Australia: Australian governmentpublishing services.

Palmero-Marrero, A.I. and A.C. Oliveira (2010). “Effect of louver shading devices on building energy requirements”. In: *Applied Energy* 87.6, pp. 2040–2049.

Pastalan, Leon A (1970). “Privacy as an expression of human territoriality”. In: *Spatial behavior of older people.* Ed. by Leon A Pastalan and Daniel H Carson. University of Michigan Press Ann Harbor, pp. 88–101.

Peel, Murray C, Brian L Finlayson, and Thomas A McMahon (2007). “Updated world map of the Köppen-Geiger climate classification”. In: *Hydrology and earth system sciences discussions* 4.2, pp. 439–473.

Perez and Isaac Guedi Capeluto (2009). “Climatic considerations in school building design in the hot-humid climate for reducing energy consumption”. In: *Applied Energy* 86.3, pp. 340–348.

Perez, R. Seals, and J. Michalsky (1993). “All-weather model for sky luminance distribution—Preliminary configuration and validation”. In: *Solar Energy* 50.3, pp. 235–245.

Pesce, A (1976). *Jeddah: Portrait of a City.* London: Falcon Press.

Petrakis, M. et al. (1998). “Generation of a “typical meteorological year” for Nicosia, Cyprus”. In: *Renewable Energy* 13.3, pp. 381–388.

Philby, Harry John (2015). *Encyclopedia Britannica.* URL: `http://www.britannica.com/EBchecked/topic/525348/Saudi-Arabia/45200/Climate` (visited on 04/16/2015).

Phillips, Derek (2000). *Lighting modern buildings.* Oxford: Architectural Press.

Piccoli, B, G Soci, PL Zambelli, and D Pisaniello (2004). “Photometry in the workplace: The rationale for a new method”. In: *Annals of Occupational Hygiene* 48.1, pp. 29–38.

Pirenne, Maurice Henri (1967). *Vision and the Eye.* Vol. 47. Chapman & Hall.

Plympton, P., S. Conway, and K. Epstein (2000). “Daylighting in Schools:Improving Student Performance and Health at a Price Schools Can Afford”. In: *The Ameri-*

can Solar Energy Society Conference. Madison, WI: National Renewable Energy Laboratory.

Poirazis, Harris, Ãke Blomsterberg, and Maria Wall (2008). “Energy simulations for glazed office buildings in Sweden”. In: *Energy & Buildings* 40, pp. 1161–1170.

Al-Qahtany, Ali Muflah (2014). “The development of a consensus-based framework for a sustainable urban planning of the city of Riyadh”. Thesis.

Al-Ragom, F. (2003). “Retrofitting Residential Buildings in Hot Arid Climates”. In: *Energy Conversion and Management* 44, pp. 3209–3219.

Rahim, Zaiton Abdul (2015). “The influence of culture and religion on visual privacy”. In: *Procedia-Social and Behavioral Sciences* 170, pp. 537–544.

Rapoport, Amos (1980). “Cross-Cultural Aspects of Environmental Design”. In: *Environment and Culture*. Ed. by Irwin Altman, Amos Rapoport, and J F Wohlwill. Springer, pp. 7–46.

— (2005). *Culture, Architecture and Design*. Chicago, IL: Locke Scientific.

Raven Supercomputer (2017). URL: `https://www.cardiff.ac.uk/research-equipment/facilities/view/arcca-raven-supercomputing-cluster` (visited on 06/01/2017).

Raynham, PJ (2012). *The Society of Light and Lighting SLL Code for Lighting*. London, UK: CIBSE: The Society of Light and Lighting.

Razali, Noorul Huda Mohd and Anuar Talib (2013). “The concept of privacy and the Malay dwelling interior space planning”. In: *Procedia-Social and Behavioral Sciences* 101, pp. 404–414.

Rea, Mark Stanley (2000). *The IESNA lighting handbook: reference & application*. IESNA Illuminating Engineering Society of North America.

Rea, Mark Stanley and Peter Robert Boyce (1999). “Different sources for different courses under mesopic lighting levels, Vision at low light levels”. In: *4th International Lighting Research Symposium*. Orlando,FL.

Rehman, Shafiqur, Maher A. Bader, and Said A. Al-Moallem (2007). “Cost of solar energy generated using PV panels”. In: *Renewable and Sustainable Energy Reviews* 11.8, pp. 1843–1857.

Reinhart, Christoph (2001). “Daylight availability and manual lighting control in office buildings: simulation studies and analysis of measurement”. Thesis.

— (2002). “Effects of interior design on the daylight availability in open plan offices”. In: *2002 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA, pp. 309–322.

Reinhart, Christoph and Marilyne Andersen (2006). “Development and validation of a Radiance model for a translucent panel”. In: *Energy and Buildings* 38.7, pp. 890–904.

Reinhart, Christoph and Pierre-Felix Breton (2009). “Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim 3.0”. In: *LEUKOS* 6.1, pp. 7–35.

Reinhart, Christoph and Annegret Fitz (2006). “Findings from a survey on the current use of daylight simulations in building design”. In: *Energy and Buildings* 38.7, pp. 824–835.

Reinhart, Christoph and Anca D. Galasiu (2006). “Results of an Online Survey of the Role of Daylighting in Sustainable Design”. In: *NRC-IRC Report* 3.1, pp. 1–25.

Reinhart, Christoph and Sebastian Herkel (2000). “The simulation of annual daylight illuminance distributions: a state-of-the-art comparison of six RADIANCE-based methods”. In: *Energy and Buildings* 32.2, pp. 167–187.

Reinhart, Christoph, Kera Lagios, Jeff Niemasz, and J Alstan Jakubiec (2011). *Diva for Rhino Ver. 2.0.* Computer Program. URL: `www.diva-for-rhino.com`.

Reinhart, Christoph, John Mardaljevic, and Zack Rogers (2006). “Dynamic Daylight Performance Metrics for Sustainable Building Design”. In: *LEUKOS* 3.1, p. 24.

Reinhart, Christoph, Tarek Rakha, and Dan Weissman (2014). “Predicting the Daylit Area—A Comparison of Students Assessments and Simulations at Eleven Schools of Architecture”. In: *LEUKOS* 10.4, pp. 193–206.

Reinhart, Christoph and Oliver Walkenhorst (2001). “Validation of dynamic Radiance based daylight simulations for a test office with blinds”. In: *energy and Buildings* 33.7, pp. 683–97.

Reinhart, Christoph and Jan Wienold (2011). “The daylighting dashboard – A simulation-based design analysis for daylit spaces”. In: *Building and Environment* 46.2, pp. 386–396.

Reis, Antonio Tarcsio and Maria Cristina Lay (2004). “Privacy in the dwelling: attitudes, visual and functional connections”. In: *18th Conference of the International Association for People-Environment Studies (IAPS).* Vienna, Austria.

Renner, Gábor and Anikó Ekárt (2003). “Genetic algorithms in computer aided design”. In: *Computer-Aided Design* 35.8, pp. 709–726.

Robinson (1986). *Daylighting Design and Analysis.* New York: Van Nostrand Reinhold Company.

Rockcastle, Siobhan and Marilyne Andersen (2013). *Annual Dynamics of Daylight Variability and Contrast: a simulation-based approach to quantifying visual effects in architecture.* London: Springer.

Rogers, Zack and David Goldman (2006). *Daylighting metric development using daylight autonomy calculations in the sensor placement optimization tool.* Report. Architectural Energy Corporation.

Roodman, D. M. (1995). *Carbon emissions resume rise: Vital Signs 1995-1996.* London, UK: Earthscan Puplications.

Roudsari, Mostapha Sadeghipour and Anne Waelkens (2015). “A new approach to modeling frit patterns for daylight simulation”. In: *The Symposium on Simulation for Architecture& Urban Design.* Alexandria, VA: Society for Computer Simulation International, pp. 22–27.

Roudsari, Mostapha Sadeghipour, Michelle Pak, Adrian Smith, et al. (2013). “Ladybug: a parametric environmental plug-in for grasshopper to help designers create an environmentally-conscious design”. In: *Proceedings of the 13th international IBPSA conference held in Lyon, France Aug.*

Ruck, N. C. (1989). *Building design and human performance.* New York: Van Nostrand Reinhold, p. 284.

Rushmeier, Holly et al. (2000). “Comparing real and synthetic images: Some ideas about metrics”. In: *Rendering Techniques 2000.* Ed. by B. Peroche and H Rushmeier. 26-28/June. Brno, Czech: Springer, pp. 207–218.

Rutten, David and Robert McNeel (2012). *Grasshopper.* Computer Program. URL: `www.Grasshopper3d.com`.

El-Sabbagh, MK (1982). “On the climate of Saudi Arabia”. In: *Bulletin of Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia* 6, pp. 203–214.

Sabry, Hanan, Ahmed Sherif, and Mahmoud Gad-Elhak (2012a). “Utilization of combined daylighting techniques for enhancement of natural lighting distribution in clear-sky residential desert buildings”. In: *The 28th PLEA Passive and Low Energy Architecture*. Vol. 4. Lima, Peru, p. 3.00.

Sabry, Hanan, Ahmed Sherif, Mahmoud Gad-Elhak, and M. Aly (2014). “Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio”. In: *Solar Energy* 103, pp. 364–377.

Sabry, Hanan, Ahmed Sherif, Mahmoud Gad-Elhak, and Tarek Rakha (2012b). “External Perforated Solar Screen Parameters and Configurations: Daylighting Performance of Screen Axial Rotation and Opening Proportion in Residential Desert Buildings”. In: *14th International Conference in Computing in Civil and Building Engineering*. Moscow, Russia: ISCCBE.

Sabry, Hanan, Ahmed Sherif, and Tarek Rakha (2011). “Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies”. In: *International Conference on Sustainable Design and Construction (ICSDC) 2011*. Ed. by Wai Kiong Oswald Chong and C Hermick. Kansas City, MO: American Society of Civil Engineers, pp. 283–391.

Sabry, Hanan, Ahmed Sherif, S Shawky, and Tarek Rakha (2010). “Assessing the effect of external obstruction parameters on indoor daylighting performance in desert clear sky conditions”. In: *the 16th annual international sustainable development research conference*. Hong Kong.

Samuels, William (2011). “Performance and Permeability: An Investigation of the Mashrabiya for use within the Gibson Desert”. PhD. Thesis.

Al-Sanea, Sami A., M. F. Zedan, and S. N. Al-Hussain (2012). “Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential”. In: *Applied Energy* 89.1, pp. 430–442.

Saudi Consolidated Electrical Company, the (2001). *Electrical Consumption in Riyadh City*. Report. Saudi Consolidated Electrical Company.

Sayer, James R and Eric C Traube (1994). *Factors influencing visibility through motor vehicle windshields and windows: review of the literature*. Report UMTRI–94–20. Transportation Research Institute.

Schaefer, C., G. Bräuer, and J. Szczyrbowski (1997). “Low emissivity coatings on architectural glass”. In: *Surface and Coatings Technology* 93.1, pp. 37–45.

Shach-Pinsly, Dalit, Dafna Fisher-Gewirtzman, and Michael Burt (2011). “Visual Exposure and Visual Openness: An Integrated Approach and Comparative Evaluation”. In: *Journal of Urban Design* 16.2, pp. 233–256.

Sherif, Ahmed, A Faggal, and Rasha Arafa (2010a). “External perforated solar screens for thermal control in desert environments: the effect of perforation percentage on energy loads”. In: *Renewable Energy 2010*. Yokohama, Japan.

Sherif, Ahmed, Hanan Sabry, and Mahmoud Gad-Elhak (2012a). “The impact of changing solar screen rotation angle and its opening aspect ratios on Daylight Availability in residential desert buildings”. In: *Solar Energy* 86.11, pp. 3353–3363.

Sherif, Ahmed, Hanan Sabry, and Tarek Rakha (2010b). “Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions”. In: *Renewable Energy 2010 Conference*. Yokohama, Japan.

Sherif, Ahmed, Hanan Sabry, and Tarek Rakha (2012b). “External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages”. In: *Solar Energy* 86.6, pp. 1929–1940.

Sherif, Ahmed, Abbas El-Zafarany, and Rasha Arafa (2012c). “External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments”. In: *Energy and Buildings* 52.0, pp. 1–10.

— (2013). “Energy Simulation as a Tool for Selecting Window and Shading Configuration in Extreme Desert Environment”. In: *Democratic Transition and Sustainable Communities*. Ed. by Wafaa Nadim. Cairo, Egypt: Shaker Verlag, pp. 446–56.

Sherif, Ahmed et al. (2011). “Balancing the Energy Savings and Daylighting Performance of External Solar Screens: Evaluation of screen opening proportions”. In: *the 27th International Conference on Passive and Low Energy Architecture*. Ed. by M. Bodart and Marilyne Andersen. Vol. 1. Lovain La Neuve, Belgium: Presses Univ. de Louvain, pp. 807–12.

Shishegar, N and M Boubekri (2016). “Natural light and productivity: Analyzing the impacts of daylighting on students’ and workers’ health and alertness”. In: *Proceedings of the International Conference on “Health, Biological and Life Science”(HBLS-16), Istanbul, Turkey*, pp. 18–19.

El-Shorbagy, Abdel-moniem (2010). “Traditional Islamic-Arab house: vocabulary and syntax”. In: *International Journal of Civil & Environmental Engineering IJCEE-IJENS* 10.4, pp. 15–20.

Sidawi, Bhzad (2013). “Understanding the vocabulary of the Islamic architectural heritage”. In: *Global Built Environment Review* 6.2, p. 14.

Sleegers, PJC et al. (2013). “Lighting affects students’ concentration positively: Findings from three Dutch studies”. In: *Lighting Research & Technology* 45.2, pp. 159–175.

Snellen, Herman (1862). *Test-types for the Determination of the Acuteness of Vision*. Utrecht, Netherlands: PW van de Weijer.

Society of Light, the and Lighting (2011). *Lighting Guide 5: Lighting for Education*. Technical Report. London, UK: SSL: CIBSE.

Solar GIS, the (2013). *Validation of Solar GIS GHI and DNI data for the Kingdom of Saudi Arabia*. Report. Geo Model Solar.

Solar-GIS (2010). *Solar GIS website*. URL: `https://solargis.info` (visited on 04/18/2016).

Al-Soliman, T. (1981). “School buildings for boy’s general education in Saudi Arabia: Present functioning, future demand and proposed alternatives under conditions of social change.” Thesis.

— (1994). “The Attributes of change in School Buildings Characteristics, Elements and Performance: A Comparative Study for Buildings Erected Before and after 1980”. In: *King Saud University, Arch.& Planning* 6, pp. 135–177.

— (1995). “School buildings’ designs for government and private schools and their influence on schools’ performance of their functions.” In: *King Saud University, Arch. & Planning* 7, pp. 27–61.

Solt, Judit et al. (2017). “Daylight in the built environment”. In: *Changing perspectives on daylight*. Science/AAAC, pp. 24–32.

Stazi, F., S. Marinelli, C. Di Perna, and P. Munafò (2014). "Comparison on solar shadings: Monitoring of the thermo-physical behaviour, assessment of the energy saving, thermal comfort, natural lighting and environmental impact". In: *Solar Energy* 105, pp. 512–528.

Struyk, Raymond J. (2005). "Housing Policy Issues In A Rich Country With High Population Growth: The Case Of Riyadh, Saudi Arabia". In: *Review of Urban & Regional Development Studies* 17.2, pp. 140–161.

Susilawati, Connie and Muhammed Al Surf (2011). "Challenges facing sustainable housing in Saudi Arabia: a current study showing the level of public awareness". In: *the 17th Pacific Rim Real Estate Society Conference*. 16–19 January. Goldcost, Australia: Bond University.

Szokolay, Steven V (2008). *Introduction to Architectural Science: The Basis of Sustainable Development*. Architectural Press, Elsevier. Oxford, UK.

Taleb, Hanan M. and Steve Sharples (2011). "Developing sustainable residential buildings in Saudi Arabia: A case study". In: *Applied Energy* 88.1, pp. 383–391.

Talib, Kaizer (1984). *Shelter in Saudi Arabia*. London: Academy editions.

Thanachareonkit, Anothai, Jean-Louis Scartezzini, and Marilyne Andersen (2005). "Comparing daylighting performance assessment of buildings in scale models and test modules". In: *Solar Energy* 79.2, pp. 168–182.

Thanachareonkit, Anothai, Jean-Louis Scartezzini, and Robinson (2006). "Comparing the accuracy of daylighting physical and virtual models for complex fenestration systems". In: *The 23rd PLEA International Conference on Passive and Low Energy Architecture*. Geneva, Switzerland: Universite de Geneve, pp. 429–35.

Thapar, Bindia (2012). *Introduction to Indian Architecture*. Tuttle Publishing. ISBN: 1462906427.

Theodorson, Judy (2009). "Daylit Classrooms at 47N, 117W". In: *the 26th Conference on Passive and Low Energy PLEA2009: Visual and Physio-psychological well-being in built environments*. 22–24 June. Quebec City, Canada, pp. 286–290.

Toates, FM (1972). "Accommodation function of the human eye". In: *Physiological reviews* 52.4, pp. 828–863.

Tomah, Ayman Najeed (2011). "Visual privacy recognition in residential areas through amendment of building regulations". In: *Proceedings of the institution of Civil Engineers. Urban Design and Planning*, pp. 1–11.

Tregenza, Peter Roy (1980). "The daylight factor and actual illuminance ratios". In: *Lighting Research & Technology* 12.2, pp. 64–68. ISSN: 0024-3426.

— (1983). "The Monte Carlo method in lighting calculations". In: *Lighting Research & Technology* 15.4, pp. 163–170.

— (1987). "Subdivision of the sky hemisphere for luminance measurements". In: *Lighting Research & Technology* 19.1, pp. 13–14. ISSN: 0024-3426.

— (1994). "Daylighting computation: Radiosity method using triangular patches". In: *International Journal of Lighting Research & Technology* 26.1, pp. 1–7. ISSN: 1365-7828.

— (2017). "Uncertainty in daylight calculations". In: *Lighting Research & Technology* 49.7, pp. 829–844.

Tregenza, Peter Roy and Isobel M Waters (1983). "Daylight coefficients". In: *Lighting Research & Technology* 15.2, pp. 65–71.

— (1984). "Predicting daylight from cloudy skies". In: *Energy and Buildings* 6.3, pp. 261–266.

Tsangrassoulis, Aris, Mat Santamouris, and D. Asimakopoulos (1996). “Theoretical and experimental analysis of daylight performance for various shading systems”. In: *Energy and Buildings* 24.3, pp. 223–230.

Al-Twaijri, A. (2002). *The impact of Energy conservation Programs on the Long-Term Plan of Electricity in the Kingdom of Saudi Arabia*. Report. World Energy Council.

Ubbelohde, M Susan and Christian Humann (1998). *Comparative Evaluation of Four Daylighting Software Programs*. Report. American Council for an Energy-Efficient Economy (ACEE) Summer Study on Energy Efficiency in Buildings.

Ubbelohde, M Susan, S J Weidt, and J Johnson (1989). *Daylighting Software Evaluation Project Report*. Report. Regional Daylighting Center, University of Minnesota.

U.S Geological Survey, the (2016). *Earthshots: Satellite Images of Environmental Change*. URL: `http://earthshots.usgs.gov/earthshots/Riyadh` (visited on 05/11/2016).

Versage, Rogerio, Ana Paula Melo, and Roberto Lamberts (2010). “Impact of Different Daylighting Simulation Results on The Prediction of Total Energy Consumption”. In: *4th National Conference of IBPSA-USA: SimBuild*. Vol. 4. 11-13 Aug. New York, NY: International Building Performance Simulation Association IBPSA, pp. 1–7.

Vogt, Adolf Max (2000). *Le Corbusier, the noble savage: toward an archaeology of modernism*. MIT Press. ISBN: 0262720337.

Vyas, D (2005). “Traditional Indian architecture-the future solar buildings”. In: *International Conference on Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, pp. 19–21.

Wagdy, Ayman (2015). *SpeedSim-for-DIVA software*. URL: `https://www.aymanwagdy.com/#!speedsim/cjg9` (visited on 01/08/2017).

Wagdy, Ayman and Fatma Fathy (2015). “A parametric approach for achieving optimum daylighting performance through solar screens in desert climates”. In: *Journal of Building Engineering* 3, pp. 155–170.

— (2016). “A Parametric Approach for Achieving Daylighting Adequacy and Engergy Efficiency by Using Solar Screens”. In: *The 32nd PLEA International Conference on Passive and Low Energy Architecture*. Los Angeles, CA.

Wagdy, Ayman, Fatma Fathy, and Sergio Altomonte (2016). “Evaluating the daylighting performance of dynamic façades by using new annual climate-based metrics”. In: *The 32th PLEA Passive and Low Energy Architecture: Cities, Buildings, People: Towards Regenerative Environments*. Ed. by Pablo La Roche and Marc Schiler. Vol. 2. 11-13 July. PLEA 2016, pp. 941–947.

Waldram, Percy J (1909). “The measurement of illumination; daylight and artificial: with special reference to ancient light disputes”. In: *The Journal of the Society of Architects* 3, pp. 131–40.

— (1925). “The Natural and Artificial Lighting of Buildings”. In: *Journal of The Royal Institute of British Architects RIBA* 32.13, pp. 405–26.

— (1950). *A measuring diagram for daylight illumination*. London, UK: Batsford Ltd.

Walsh, John William Tudor (1961). *The science of daylight*. UK: Macdonald& Co.

Watkins, R, G J Levermore, and J B Parkinson (2013). “The design reference year – a new approach to testing a building in more extreme weather using UKCP09 projections". In: *Building Services Engineering Research and Technology* 34.2, pp. 165–176.

WeatherBank-INC. (2010). *WeatherBank,INC. website.* URL: `http://www.weatherbank.com` (visited on 04/15/2016).

Weather-Source (2017). *Weather Source website.* URL: `https://weathersource.com/` (visited on 05/05/2017).

Webb, Ann R. (2006). "Considerations for lighting in the built environment: Non-visual effects of light". In: *Energy and Buildings* 38.7, pp. 721–727.

Westin, Alan F and Oscar M Ruebhausen (1967). *Privacy and freedom.* Vol. 1. New York, NY: Atheneum.

Wilcox, Stephen and William Marion (2008). *Users manual for TMY3 data sets.* Report.

Wong, Nyuk Hien and Agustinus Djoko Istiadji (2004). "Effect of external shading devices on daylighting penetration in residential buildings". In: *Lighting Research & Technology* 36.4, pp. 317–330.

World Bank, the (2017). *Saudi Arabia Report.* URL: `http://data.worldbank.org/country/saudi-arabia` (visited on 04/16/2017).

Worldmark Encyclopedia of Nations, the (2007). *Saudi Arabia.* URL: `http://www.encyclopedia.com/places/asia/arabian-peninsula-political-geography/saudi-arabia#LOCATION_SIZE_AND_EXTENT` (visited on 01/10/2018).

WSA website (2018). URL: `http://www.cardiff.ac.uk/architecture/about-us/facilities/environmental-lab/sky-dome/` (visited on 02/05/2018).

www.cct–uk.com (2018). URL: `http://www.cct-uk.com/fb700.htm` (visited on 02/05/2018).

www.integra.jp/en (2007). URL: `www.integra.jp/en` (visited on 05/15/2015).

www.lighting-technologies.com (2017). URL: `www.lighting-technologies.com` (visited on 05/05/2015).

El–Zafarany, Abbas, Ahmed Sherif, and Rasha Arafa (2013). "Energy Efficiency of External Perforated Window Solar Screens in Desert Environments: Effect of Screen Surface Reflectance". In: *AEI 2013 Building Solutions for Architectural Engineering.*

Appendix A: Published work.

plea 2016

Los Angeles July 11-13

Cities, Buildings, People:
Towards Regenerative
Environments

PLEA 2016: 32nd International Conference on Passive and Low Energy Architecture

Edited by:
Pablo La Roche and Marc Schiler

PLEA 2016 Los Angeles – 32nd International Conference on Passive and Low Energy Architecture.
Cities, Buildings, People: Towards Regenerative Environments

USING SOLAR SCREENS IN SCHOOL CLASSROOMS IN HOT ARID AREAS:

THE EFFECT OF DIFFERENT PERFORATION RATES ON DAYLIGHTING LEVELS

AHMAD KOTBI[1,2], ELENI AMPATZI[1]

[1]Welsh School of Architecture, Cardiff University, Cardiff, UK
[2]College of Architecture & Planning, King Saud University, Riyadh, Saudi Arabia

ABSTRACT: Hot arid areas are endowed with an abundance of clear skies. Thus, the solar energy available can significantly raise the temperature of interior spaces and also result in an uncomfortable visual environment due to glare and poor uniformity ratios. This paper focuses on a special case of girls' schools in Saudi Arabia, where the privacy issue is critical due to socio-cultural and religious beliefs. Most windows in girls' schools are covered by dark opaque film to maintain privacy. This window treatment brings the need for electric lights, which makes schools huge consumers of energy considering the peak time operational hours and the large number of schools. This paper looks at how different perforation rates affect the performance of screens by simulating 10 different ratios from 10% to 90% and a base case without a screen. First, the effect was tested on average illuminance levels, and then on Daylight Availability by using the Daylight Dynamic Performance Metrics approach (DDPM). The results specify the minimum perforation rate to provide the required average illuminance in each orientation and give a tool to decide perforation rates according to the required percentage of daylit area in contexts similar to the studied space.

Keywords: Daylight, Solar Screens, Schools, Privacy, Daylight Availability, Daylight Dynamic Performance Metrics.

INTRODUCTION

Hot arid areas are endowed with an abundance of clear skies. Thus, the solar energy available can significantly raise the temperature of interior spaces and also result in an uncomfortable visual environment due to glare and poor uniformity ratios [1]. A shading device called a "Mashrabiya" has been traditionally used in some of these areas. Mashrabiyas are fixed in front of windows to control solar penetration, a concept that is now being broadly adopted in solar screens [2], but have also a social function of maintaining privacy which is an important issue in Islamic cultures [3]. The dual purpose of this device explains the spread of its use around the world wherever Muslims exist, from Moorish Spain in the West through North Africa and the Middle East to India in the East [4].

The privacy issue for women is important in Saudi Arabia as the country follows an Islamic law, which means women should be covered in the presence of unrelated men. Following the same law, women wear a black robe called an "Abaya", which they can only remove at women-only events, their houses or in buildings occupied by women only, such as girls' schools. In the latter environments, it is common practice for the windows to be completely covered by black opaque coatings or non-transparent curtains to maintain privacy.

These treatments are known to have an effect on the occupants' health, wellbeing and efficiency due to lack of adequate daylight and access to external views [5, 6]. Using perforated screens could be a solution for this situation to maintain privacy and at the same time improve interior daylight conditions. Although there are many solutions during the design process such as using courtyards, this research focuses on retrofitting existing buildings.

The performance of perforated screens is affected by many parameters and previous studies have summarised these to be: perforation rate, depth ratio, shape, reflectivity of colour, aspect ratio of openings, tilt and rotation angles [7]. This paper is a part of an ongoing research that examines the parametric design of perforated screens for both enhancing interior daylight levels and maintaining privacy in typical girls' classrooms in a hot arid area.

OBJECTIVE

The objective of this paper is to define optimum perforation rates for solar screens in order to optimise interior daylighting for each main orientation in the context of schools in hot arid areas. Different perforation rates are later going to be studied in relation to privacy as the next step to this research.

Previous studies have already investigated the effect of different parameters of perforated screens on daylight in living rooms in residential spaces, namely, perforation rate, depth ratio, axial rotation [2, 7, 8]. However, results would be different for educational spaces, due to different illuminance requirements, different window to wall ratio, space size, dimensions and hours of occupancy when compared with residential spaces.

SIMULATION

The experiment is conducted using virtual simulation using the following software: "Rhinoceros" often abbreviated as 'Rhino' which is used to build the 3D model, it is a 3D modelling tool with the capability to create and analyse complex geometry. "DIVA-for-Rhino" often abbreviated as 'DIVA' stands for "Design Iterate Validate Adapt" [9], is an environmental analysis plug-in for Rhinoceros-3D and is used as an interface for the simulation engines: Radiance and Daysim [10], and it performs a daylight analysis on an existing architectural model [11]. "Radiance", developed by GregWard at Lawrence Berkely National Laboratory, works with the ray trace backward technique for the precise daylight calculations on which most of the daylighting software tools are based [12], and It has previously been validated [13, 14]. Daysim calculates the annual performance in the form of Daylight Autonomy that represents the percentage of occupancy hours where daylight achieved the target illuminance [15] it also has been validated based on physical measurments [10, 16]. "Grasshopper-3D" developed by David Rutten at Mcneel & Associates [17], is used in this study with Rhino to produce 3D models of solar screens with different perforation rates, Grasshopper is a generic algorithm editor allowing the user to perform parametric modelling extension for Rhino. Parametric modelling refers to the automated parameter based generation of 3D elements [18]. In this study, screens are automatically drawn based on author's defined algorithms and can be altered by changing parameters within the algorithm according to the required result. Grasshopper can also be used with DIVA to control and increase the workflow of simulation runs and export results [19]. The DIVA component in Grasshopper is used in this study to control DIVA-for-Rhino and export results to "Ms-EXCEL".

The location of analysis is Riyadh, which lies on Latitude 24.7, Longitude 46.80 and elevated 612 m above sea level. The weather data file for Riyadh is used for simulation, obtained from the U.S Department of Energy [20]. The weather data contains a generated Typical Meteorological Year "TMY"; it contains 12 Typical Meteorological Months "TMM" selected from recorded data for about 23 years [21]. The data to produce this file was recorded in King Khaled Airport in Riyadh.

The simulated sky condition was set as 'clear sky with sun' as this is the typical sky in such climate. The weather in Riyadh is very hot as it is surrounded by deserts; the average daily maximum temperature is 41°C in summer and can reach 50°C in extreme cases. In winter, the average daily temperature is 14°C, and the minimum temperature can reach -2°C in extreme cases. The external illuminance in such climate can reach up to 100,000 lx in Summer [22].

Simulation parameters are presented in (Table 1), an ambient division of 1000 was recommended to avoid resulting in high brightness variation [23-25]. Ambient accuracy is chosen to be 0.1, being adequate since the smallest opening was not less than 0.005m [7]. The ambient bounces are the number of times the light hits any plane and it is recommended to be 6 [23, 24]. However, only for the first stage of the analysis presented here, the ambient bounces is chosen to be 3 instead of 6 to reduce the extremely long processing time resulted by the complexity of screen geometry. This has been justified previously by comparing results of identical simulation models using different ambient bounces [25]. The experiment is repeated for the four main orientations.

Table 1: Utilized Radiance Simulation Parameters.

Ambient bounces	Ambient divisions	Ambient sampling	Ambient resolution	Ambient accuracy
6	1000	20	300	0.1

ARCHITECTURAL PARAMETERS

The simulated space (Fig. 2&3) and the indoor parameters represent an average classroom in Riyadh [N24.63°, E46.72°] the capital of Saudi Arabia. The typology used is based on 11 classrooms that the researcher visited and monitored in summer 2015 [26], with the dimensions slightly adjusted to allow the space to be divided into three zones with the same number of measuring points 'zones distinction explained below'. A typical classroom has five windows, the dimensions of windows are also adjusted from 1.25×0.75m to 1.2×0.72m in order to have the ability to be divided equally for further investigation (cell size, aspect ratio and depth ratio). (Table 2) presents the assumed parameters for the modelled classroom and the reflectance values of indoor surfaces as recommended by Illuminating Engineering society [23]. Four streets surround most schools in Riyadh, and there is a scarcity of trees since it is a desert environment. Therefore, external obstructions are ignored in simulation, the external walls were assumed to have beige colour with a reflectance of 35%.

Table 2: parameters of the simulated classroom and screen

Space parameters	
Dimensions	4.50m × 6.90m × 3.00m
Working Level	+0.75m
Surfaces reflectance	
Interior walls	50%
Exterior walls	35%
Ceiling	80%
floor	20%
furniture	50%
White Board	90%
Solar screen	70%
Windows parameters	
Window to wall ratio "WWR"	21%
Number of windows	5
Dimensions	0.72m × 1.20m
Sill height	1.15m
Transmission	88%
Solar screen parameters	
Cell size	0.06m × 0.06m
Depth	0.045m
Depth ratio	0.75
Reflectance	70%

SCREEN PERFORATION

Since the focus of this paper is on perforation rates, other screen parameters remain fixed and assumed as follows:

- Horizontal to Vertical aspect ratio of 1:1
- Module size was 6×6 cm. (Fig. 1)
- Depth ratio of 75% 'module size / depth'
- Colour reflectance: 70%.

Each window is divided into a 6×6cm module, which gives 240 perforation. The perforation rate is calculated considering the module grid and each hole were concentric with it. (Fig. 3) represents examples of two screens, with 50% and 90% perforation rates.

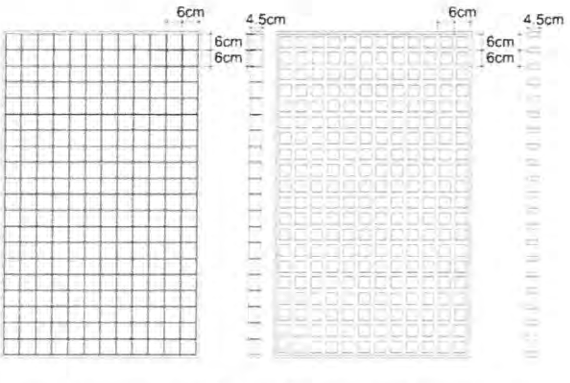


Figure 1: screen module, an elevation and a section of an example of 50% perforation rate on the right and 90% perforation rate on the left.

METHODOLOGY

Experiments are conducted in two stages. First, daylight illuminance levels at specific times and days are analysed using measuring points spread on a reference plane to calculate interior illuminance at each point.

The Illumination Engineering Society recommends the height of the working plane to be just above the highest regular task in the space, which is for classrooms, reading and writing on desks [23]. Therefore, the working plane is set at 0.75m height (Fig. 2), just above the top of pupils' desks as measured in an actual classroom in Riyadh [26]. The reference plane has 345 measuring points evenly distributed in a 0.3×0.3m grid, and divided equally into three zones, each zone having 115 measuring points, zones are named according to the distance from the window (Near zone, Mid zone, Far zone) as explained in (Fig. 3). The 0.3×0.3 grid is chosen as the minimum recommended distance to improve accuracy [23]. This method was used before in similar related studies [2, 25].

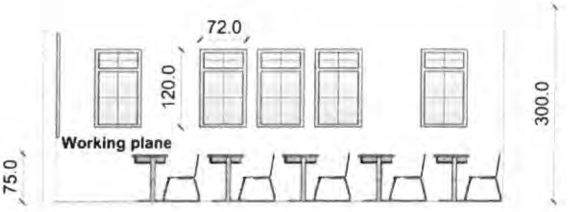


Figure 2: Base case classroom section showing windows and height of working plane.

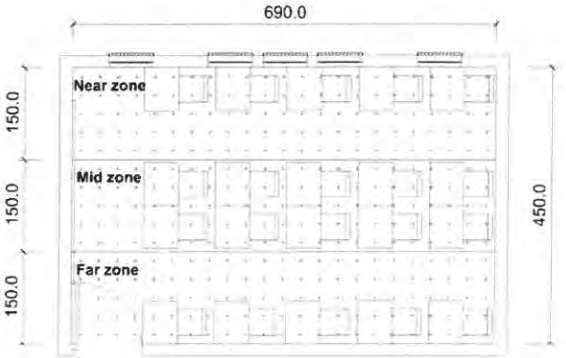


Figure 3: Base case classroom plan and zones.

In the second phase, the effect of different perforation rates on the annual performance is tested by using Dynamic Daylight Performance Metrics "DDPM". These metrics evaluate daylighting performance based on time series of illuminance or luminance levels within a space. These time series cover the occupancy hours in a calendar year and are based on external, annual solar radiation data for the building site [15]. These metrics include Daylight Autonomy "DA", Useful Daylight Illuminance "UDI" and "Daylight Availability". "DA" which is defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone, and then categorize the space according to that into two criteria: 'Daylit area' and 'Partly Daylit area'. Daylit area is the area achieving the required threshold for at least half of the occupied time, whereas, areas that fail to achieve the required threshold are considered Partly lit area [10]. "UDI" uses upper and lower threshold of 100lx and 2000lx to determine illuminance within a useful range [27]. "Daylight Availability" however, was developed to combine both "DA" and "UDI". When using this metric, the space is categorized into three classifications, according to the daylight availability criterion. "Daylit" areas are the areas receiving adequate daylight for at least half of the occupancy time, "Partlylit" areas are the areas receiving adequate daylight for less than half of the occupancy time, "Overlit" areas are the areas receiving ten times or more of the adequate daylight for at least 5% of the occupancy time [24]. The 5% criterion was selected according to British Standards [28].

The standard adequate illuminance for a reading and/or writing task is 500lx [29], however, it is very difficult to depend on daylight solely to achieve this level without causing glare. Therefore, the adequate illuminance level was set to 300lx since the aim was to reduce the use of artificial light as possible [23, 30].

The occupancy times are chosen from a typical school year in Saudi Arabia, which has 36 weeks a year i.e. 180 days with a total of 1080 hours, school year often starts in mid-September until mid-June in two semesters, each one has one half-term break

PHASE I: AVERAGE ILLUMINANCE

In this phase, average interior illuminance of the 115 measuring points for each zone is calculated for the "no screen" case and nine other cases from 90% to 10% perforation rate, by simulating 3 specific times in four specific days under a clear sky condition. These days are chosen to be spread between each season (summer, autumn, winter, spring) and being a school day in a typical school year in Saudi Arabia. The simulated times were selected to be (07:00, 09:30, 12:00), considering the fact that school hours in Saudi Arabia start from 6:45 to 12:30 due to the hot ambient temperatures in the afternoon hours. The simulation process is repeated for the four main orientations (East, North, West and South). Most similar experiments have used only three orientations: North, South and either East or West, given that the sun path is symmetrical; therefore, the result of 09:00 and 15:00 in the West would be the same as the result of 15:00 and 09:00 on the East respectively [8]. This was not applicable in this study since the selected hours for the simulation were (07:00, 09:30, 12:00), thus, not symmetrical between East and West.

The average illuminance was calculated for each zone excluding measuring points with more than >5000lx, because including these points would bias the average values although they stand for less than 0.5% of the measuring points [25]. Then, the average illuminance of each case in each zone is displayed in a table for each orientations (Table 3, 4, 5&6). That allows producing a table for the recommended perforation rate for each case (Table 7).

RESULTS OF PHASE I

The results show that using perforating screens in most cases maintains the percentage between readings of average illuminance in Near, Mid and Far zones. Thus, maintain the light distribution and uniformity within the space. The only exception was noon in summer for all orientations (Table 3,4,5&6), and 7:00 in winter and spring for East orientation, (Table 4). In the later cases, percentage of average illuminance in Far and Mid zones are reduced with the use of solar screens, thus less daylight uniformity.

Table 3: Average Illuminance for each case in the three zones of the South orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

South Orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	181	240	626	151	301	369	214	512	521	116	365	467
	90%	110	135	368	86	176	208	86	300	345	70	215	265
	80%	102	120	330	77	151	182	74	261	304	63	188	230
	70%	92	108	296	68	133	155	63	217	257	54	157	193
	60%	86	93	261	59	111	130	52	179	215	46	129	156
	50%	84	89	245	57	102	118	48	158	186	44	116	141
	40%	71	75	205	44	77	86	34	105	130	33	81	97
	30%	66	65	185	40	62	69	27	76	90	29	64	72
	20%	61	59	167	35	50	55	22	53	58	25	49	53
	10%	57	55	153	31	43	46	18	37	40	22	39	41
Mid	no screen	211	312	832	356	454	572	429	820	873	172	584	767
	90%	92	128	355	206	224	286	107	465	556	76	298	406
	80%	78	107	231	86	190	241	91	390	478	67	255	344
	70%	65	90	241	74	153	195	73	324	408	54	200	280
	60%	53	73	189	61	119	152	57	256	327	42	161	216
	50%	52	67	179	45	108	139	51	227	282	38	143	197
	40%	37	46	118	30	66	81	31	131	177	24	84	110
	30%	30	33	85	23	46	56	20	76	102	19	53	69
	20%	23	26	61	16	29	33	12	40	51	11	31	38
	10%	20	21	48	12	19	22	7	19	22	8	19	21
Far	no screen	260	424	1327	344	750	927	382	1121	1045	238	963	1098
	90%	75	119	311	278	251	345	118	599	693	72	355	527
	80%	63	100	253	76	208	284	99	503	597	61	301	438
	70%	52	82	202	62	168	226	76	405	503	48	235	350
	60%	40	63	156	52	127	172	59	313	413	36	179	268
	50%	40	61	149	38	119	159	56	281	347	34	168	245
	40%	24	36	83	21	62	82	29	149	218	19	85	124
	30%	18	25	61	16	41	53	17	85	121	12	52	71
	20%	13	17	35	9	21	26	8	37	53	7	25	33
	10%	10	12	26	6	12	14	4	13	16	4	12	14

Table 4: Average Illuminance for each case in the three zones of the East orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

East Otientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	806	482	619	777	449	255	1133	385	218	2061	458	242
	90%	483	274	372	579	286	144	519	226	121	1247	289	137
	80%	421	237	338	506	244	129	432	192	109	972	244	120
	70%	348	200	297	424	205	115	364	164	98	811	211	107
	60%	282	160	273	349	165	99	305	138	87	531	175	93
	50%	248	142	256	294	149	95	283	121	81	465	157	89
	40%	164	96	217	203	98	78	198	82	66	261	104	71
	30%	111	72	195	135	74	69	98	65	61	277	75	64
	20%	67	53	179	83	54	63	33	47	63	96	53	56
	10%	37	42	167	45	40	58	21	36	50	38	39	51
Mid	no screen	1078	787	790	907	746	331	659	642	286	1220	755	324
	90%	687	424	324	594	446	136	339	326	114	930	443	131
	80%	585	351	275	512	367	115	284	272	96	874	380	112
	70%	488	287	234	436	301	97	229	221	79	713	315	94
	60%	303	222	187	354	232	78	183	175	64	657	245	76
	50%	345	196	168	307	210	71	159	157	58	622	216	68
	40%	216	112	110	204	118	47	93	88	39	286	124	45
	30%	135	70	79	138	71	36	55	59	30	188	77	36
	20%	68	39	63	80	40	27	25	33	27	205	40	25
	10%	23	21	50	30	21	21	10	18	18	18	20	19
Far	no screen	1028	1173	1219	816	1036	457	564	1057	377	535	1004	456
	90%	691	544	283	538	565	129	297	394	104	305	568	131
	80%	592	450	235	476	468	108	255	328	88	261	473	105
	70%	497	359	189	408	375	88	211	258	71	220	392	85
	60%	325	274	143	345	287	69	168	199	55	181	303	67
	50%	353	253	140	297	263	64	147	185	53	158	273	64
	40%	229	127	80	211	134	37	85	94	30	105	142	37
	30%	145	74	55	144	78	26	55	58	22	71	82	28
	20%	74	32	38	82	35	17	26	27	17	40	36	16
	10%	19	14	27	29	14	13	7	11	10	16	14	11

Table 5: Average Illuminance for each case in the three zones of the North orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

North Orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	213	247	617	144	240	279	116	282	281	105	256	277
	90%	131	137	369	81	146	171	81	204	191	62	168	179
	80%	114	123	337	71	132	155	78	195	179	57	156	166
	70%	100	108	300	64	120	144	73	183	169	51	146	151
	60%	83	95	271	57	111	131	70	174	155	46	135	141
	50%	78	89	260	54	102	127	65	167	149	42	128	136
	40%	59	72	229	45	93	114	61	159	136	36	115	121
	30%	48	63	197	39	82	102	59	148	127	33	111	112
	20%	39	55	175	36	75	94	57	144	122	30	102	106
	10%	34	50	102	33	72	90	55	142	119	28	99	102
Mid	no screen	330	334	791	190	281	312	111	263	296	135	271	300
	90%	157	142	333	74	119	138	49	132	149	54	119	139
	80%	133	117	279	64	102	119	44	119	134	46	106	122
	70%	109	97	233	52	88	101	37	105	118	38	90	104
	60%	85	79	180	41	72	84	32	90	106	30	74	88
	50%	80	71	166	38	67	80	28	87	99	28	69	82
	40%	47	46	115	24	49	63	22	74	84	20	51	65
	30%	34	36	84	19	37	46	19	62	71	15	42	52
	20%	21	25	64	14	30	37	16	56	64	11	36	45
	10%	14	19	40	12	25	32	14	51	60	9	31	40
Far	no screen	533	473	1223	240	355	388	129	283	309	169	324	349
	90%	165	137	288	64	111	126	36	102	115	43	106	121
	80%	137	112	237	51	92	106	30	89	100	37	89	102
	70%	111	92	185	43	76	86	24	77	85	28	73	85
	60%	86	70	148	32	61	71	20	64	73	23	60	70
	50%	82	67	141	31	56	67	20	63	69	21	57	67
	40%	43	37	101	18	43	50	13	45	51	14	38	50
	30%	30	29	56	13	25	32	11	38	41	9	29	34
	20%	15	17	38	8	19	23	8	32	35	6	22	26
	10%	8	12	22	6	15	18	7	30	31	5	19	22

Table 6: Average Illuminance for each case in the three zones of the West orientation, highlighting cells (black) with ≥300lx, (grey) between 200lx and 299lx.

West orientation													
Seoson		Summer			Autumn			Winter			Spring		
Time		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	no screen	215	268	619	195	274	263	149	240	231	211	277	240
	90%	143	171	367	136	183	148	115	161	131	170	188	134
	80%	135	158	334	127	169	134	110	150	119	162	178	120
	70%	125	145	302	120	159	117	105	141	102	156	166	108
	60%	115	133	265	112	145	101	100	130	90	150	156	96
	50%	110	128	249	107	140	96	98	128	83	147	152	88
	40%	100	113	205	97	127	78	92	115	68	140	136	74
	30%	92	105	185	92	116	68	88	108	61	136	128	65
	20%	87	97	167	89	112	60	87	103	51	133	123	58
	10%	83	94	156	84	107	55	85	99	47	130	120	53
Mid	no screen	252	299	842	219	304	358	216	255	317	289	293	315
	90%	135	141	351	117	147	150	155	124	135	215	147	129
	80%	119	122	300	107	133	128	147	109	115	208	135	111
	70%	109	106	239	94	115	106	141	96	95	199	117	92
	60%	97	90	198	85	101	84	134	85	75	191	105	76
	50%	93	85	181	84	94	78	133	81	70	190	100	68
	40%	78	64	115	67	75	51	124	64	45	180	82	45
	30%	69	55	85	61	68	39	120	55	34	175	71	35
	20%	65	47	63	57	58	28	119	48	24	170	64	26
	10%	60	42	50	55	55	22	115	44	18	169	60	21
Far	no screen	259	343	1332	230	332	517	202	286	451	287	314	431
	90%	105	118	316	92	121	147	111	98	128	225	116	122
	80%	92	103	252	82	103	126	107	86	109	216	102	102
	70%	80	86	205	74	88	100	101	71	86	209	86	82
	60%	72	70	157	66	74	79	97	60	68	161	73	64
	50%	69	67	150	64	70	72	97	58	63	203	72	61
	40%	54	45	82	51	51	42	90	40	36	196	50	35
	30%	48	35	58	46	41	31	87	33	27	191	44	26
	20%	42	28	37	42	34	18	85	27	16	189	37	17
	10%	40	23	27	40	30	12	83	24	11	187	32	12

Table 7: Minimum recommended perforation rate to achieve target illuminance in all studied cases and zones. Lighter shade specifies higher perforation rate.

Minimum Perforation Rate													
Orientation		Summer			Autumn			Winter			Spring		
		7	09:30	12	7	09:30	12	7	09:30	12	7	09:30	12
Near	N			70									
	E	70		80	60			60			50		
	S			80					90	80			
	W			70									
Mid	N			90									
	E	50	80	90	50	70		90	90		50	70	
	S			90					70	60			80
	W			80									
Far	N												
	E	50	70		60	70			80		90	60	
	S			90			90		60	50		80	70
	W			90									

All screens on the West and North orientations reduced the illuminance sharply since there is no direct sun (Table 5&6), considering the fact that simulation times did not include afternoon hours when the direct Sun hits western façade.

The results also show that some cases provide average illuminance of more than 1200 lx without knowing if the area is considered as 'Overlit' or 'Daylit', which explains the necessity for the next phase to clearly understand the situation, using 'Daylight Availability' one of the Dynamic Daylight Performance Metrics "DDPM".

PHASE II: DAYLIGHT AVAILABILITY

In this stage, the daylight availability distribution is analyzed to compare the "no screen" case with different cases of perforation rates in the four main orientations.

Each one of the 345 measuring point presents a square with a color scale according to the percentage of the occupied hours that achieve the required threshold. The higher the percentage the lighter the square is. Each table represents one orientation, a plan of each case is presented and the total area of the plan is divided into three areas: 'Daylit', 'Partlylit' and 'Overlit'. Finally, the percentage of each area to the total space is presented in charts to compare cases for each orientations.

RESULTS OF PHASE II

The results show a linear increase of the 'Partlylit' area and decrease of the 'Overlit' area for East and South orientations when decreasing the perforation rate (Fig. 4,5). It appears that 'Overlit' area is reduced in all orientations with the use of solar screens, which means using solar screens would reduce direct sunlight penetration.

For the East orientation, 80% perforation rate achieves more 'Daylit' area than other rates in the East orientation, 90% & 70% perforation rates also provide acceptable 'Daylit' area of about 60% of total area (Fig. 4) and (Table 8).

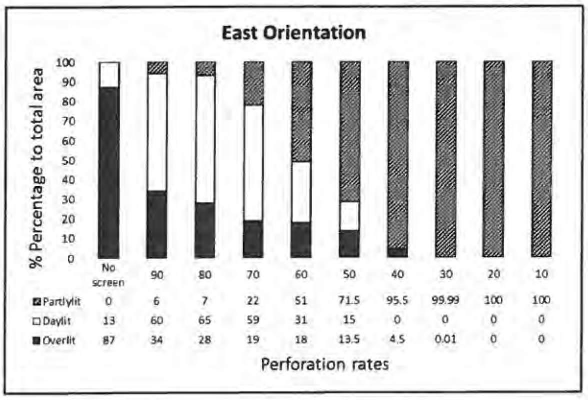


Figure 4: Daylight availability distribution relative to total area for the East orientation.

In the South Orientation, 90% perforation rate achieves better daylight availability than other rates, 70% perforation rate also achieves acceptable result of 41.5% 'Daylit' area of the total area (Fig. 5) and (Table 9).

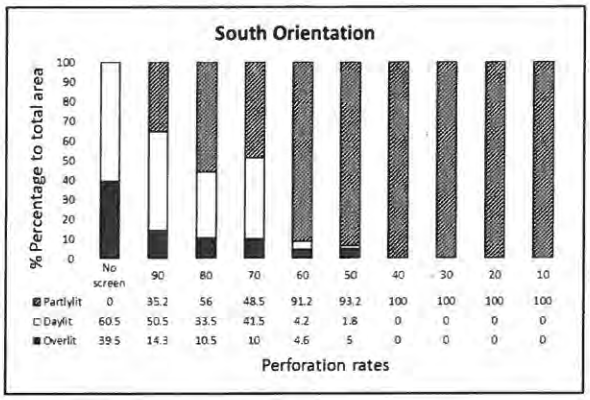
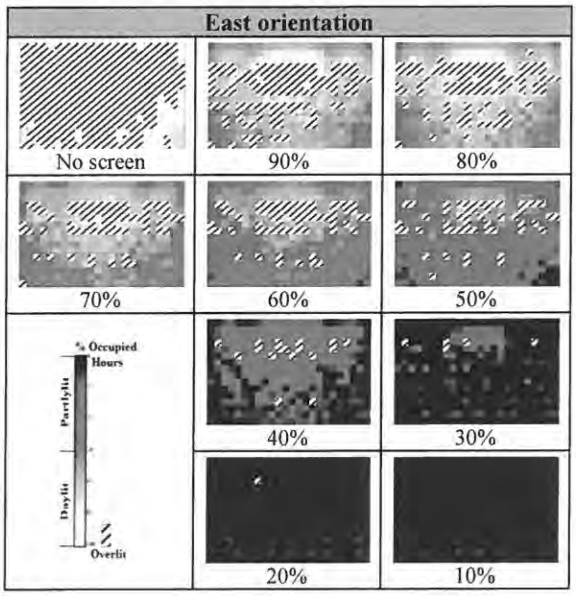


Figure 5: Daylight availability distribution relative to total area for the South orientation.

Table 8: Daylight Availability distribution on the classroom plan for each case on Eastern orientation.



For the North and West orientation, there were no issues of 'Overlit' spaces since there is no direct sunlight, however, all screens have sharply reduced the daylight availability, and all cases fail to achieve acceptable 'Daylit' area. Even 90% rate barely achieves 3% 'Daylit' area in North and 4% in West. (Table 10) shows a comparison between the 'no screen' case and 90% rate case; the transition between the two cases is not gradual like it is found in East and South orientations.

Table 9: Daylight Availability distribution for each case on Southern orientation.

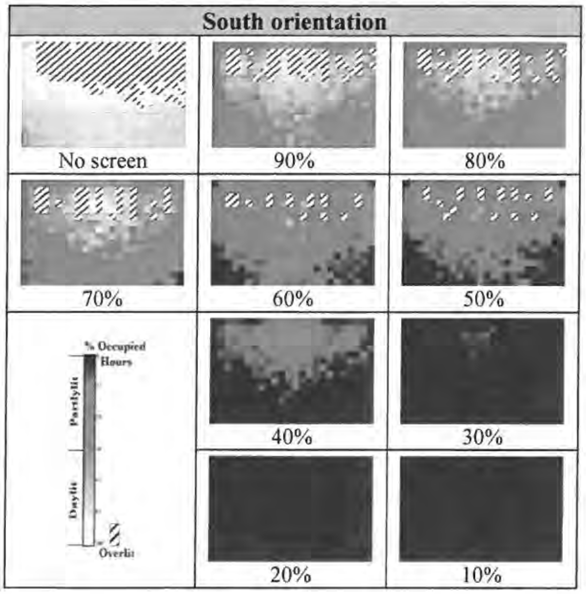
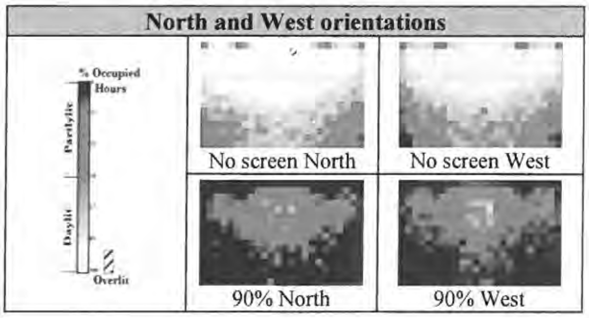


Table 10: Daylight Availability distribution for No screen and 90% cases on North and West orientations.



DISCUSSION

The simulation of a range of perforation rates for a solar screen demonstrates that the perforation rate is related to the orientation of the window and the time of the day. In the East and South orientations, there is a linear reduction of Overlit area with the use of solar screens. In the west orientation however, there are no Overlit areas as would be expected especially in summer, which is explained by the fact that the school day in this context finishes at 12:30 before the direct sun can hit the western façade. The results indicate that 70%, 80% and 90% perforation rate would achieve acceptable 'Daylit' area in the East orientation, and 90% & 70% in the South orientations. However, there is no evidence on which perforation could maintain privacy in classrooms; further investigation is needed to test the effect of perforation rate on maintaining privacy of schools occupants.

In the West and North orientations, there was a dramatic reduction of 'Daylit' areas between the 'no screen' case and the 90% rate screen. Other parameters could be the reason for that gap, for example, using less depth ratio 'module size / depth of screen' could provide better daylight for a screen with the same perforation rate. Hence, further investigation is needed for other parameters such as depth ratio, aspect ratio, cell size and axial rotation.

CONCLUSION

In conclusion, the result of this experiment provides a table (Table 5) that could be used as a tool to help architects to decide minimum perforation rate needed for different orientation and times for school classrooms in similar spaces at the same context. Moreover, (Fig. 4&5) would be useful to help architects to choose a perforation rate for solar screens according to the required percentage of 'Daylit' area to achieve illuminance level of 300 lux.

ACKNOWLEDGEMENTS

This research is supported by a scholarship from King Saud University. I thank the Saudi Deputy Minister of Education for valuable help in collecting preliminary data. I also thank Jakubiec, A., Reinhart, C., Hosney, A. and Fathy, F. for their help in DIVA and Grasshopper software use.

REFERENCES

1. Julian, W., (2006). *Lighting: Basic Concepts*. 6th Edition (Rev) ed. Sydney: USYD.
2. Sabry, H., A. Sherif and T. Rakha, (2011). Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies. In *International Conference on Sustainable Design and Construction (ICSDC)*. Kansas City, Missouri, March 23-25.
3. Fathy, H., (1986). *Natural energy and Vernacular architecture: principles and examples with reference to hot arid climate*. Chicago: University of Chicago.
4. Alitany, A., (2014*)*. A new strategy of ICT integrated methodologies for 3D documentation : a case study of the projected wooden windows (The Roshans) in the historical city of Jeddah *(Saudi Arabia). Departament d'Expressió Gràfica Arquitectònica*. Barcelona, Spain, Universitat Politècnica de Catalunya.
5. Veitch, J., (2005). Light, lighting, and health: issues for consideration. *LEUKOS*, 2(2): p. 85-96.
6. Webb, A., (2006). Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings*, 38(7): p. 721-727.

7. Sabry, H., et al., (2014). Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio. *Solar Energy,* 103: p. 364-377.
8. Sherif, A., H. Sabry and T. Rakha, (2010). Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions. In *Renewable Energy*. Yokohama, Japan, June 27 – July 2.
9. Jakubiec, J. A. and C. F. Reinhart, (2011). DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus. In *Building Simulation-12th Conference of International Building Performance Simulation Association*. Sydney, November 14-16.
10. Reinhart, C. F. and O. Walkenhorst, (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings,* 33(7): p. 683-697.
11. Reinhart, C. F., et al., (2011). Diva for Rhino Ver. 2.0. [Online], Available: www.diva-for-rhino.com [10 October 2015].
12. Reinhart, C. and A. Fitz, (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings,* 38(7) : p. 824-835.
13. Mardaljevic, J., (1995). Validation of a lighting simulation program under real sky conditions. *Lighting Research and Technology,* 27(4): p. 181-188.
14. Reinhart, C. F. and S. Herkel, (2000). The simulation of annual daylight illuminance distributions: a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings,* 32(2): p. 167-187.
15. Reinhart, C., J. Mardaljevic and Z. Rogers, (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS* 3(1): p. 24.
16. Reinhart, C. and P. Breton, (2009). Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim 3.0. *LEUKOS,* 6(1): p. 7-35.
17. Rutten, D. and R. McNeel, (2012). Grasshopper. *Generative modeling for Rhino*. [Online], Available: www.grasshopper3d.com [29 October 2015].
18. Erlendsson, Ö., (2014). Daylight Optimization-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy. *School of Architecture and the built environmnet* Stockholm, Royal Institute of Technology. 111.
19. Lagios, K., J. Niemasz and C. Reinhart, (2010). Animated building performance simulation (abps)-linking rhinoceros/grasshopper with radiance/daysim. In *SimBuild,* New York, NY, August 11-13.
20. DOE., (2015). *Weather data file for Riyadh Saudi Arabia [online*]: U.S Department of Energy. Available: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=SAU/cname=Saudi%20Arabia [14 October 2015].
21. Hall, I. J., et al., (1978). Generation of a typical meteorological year. San Diego, CA, Sandia Labs., Albuquerque, NM (USA).
22. Alshaibani, K., (2015). Planning for Daylight in Sunny Regions. *In International Conference on Environment And Civil Engineering (ICEACE'2015*), Pattaya, Thailand, August 8-9.
23. IES, D., (2012). Approved Methods: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).
24. Reinhart, C. and J. Wienold, (2011). The daylighting dashboard – A simulation-based design analysis for daylit spaces. *Building and Environment,* 46(2): p. 386-396.
25. Sherif, A., H. Sabry and T. Rakha, (2012). External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages. *Solar Energy,* 86(6): p. 1929-1940.
26. Kotbi, A. and E. Ampatzi, (2016). Using Mashrabiya to Enhance Daylight and maintain privacy in Girls' Schools in Saudi Arabia. In *9th conference of Saudi Students in UK*, Birmingham UK, Scientific Society for Saudi Students in UK, February 13-14.
27. Nabil, A. and J. Mardaljevic, (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings,* 38(7): p. 905-913.
28. BSI, B. E., (2007). 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London, UK, British Standards Institution.
29. Phillips, D. (2000). *Lighting modern buildings*. Oxford: Architectural Press.
30. Heschong, L. and H. M. Group (2012). Daylight Metrics. *PIER Daylighting Plus Research Program*. California, California Energy Commission.

Organized by

CAL POLY POMONA

USC

CAL POLY
SAN LUIS OBISPO

PLEA
SUSTAINABLE ARCHITECTURE + URBAN DESIGN

PLEA 2017 EDINBURGH
Design to Thrive

USING SOLAR SCREENS IN SCHOOL CLASSROOMS IN HOT ARID AREAS: THE EFFECT OF DIFFERENT ASPECT RATIOS ON DAYLIGHTING LEVELS

Ahmad Kotbi[1], Eleni Ampatzi[2] and Huw Jenkins[3]

[1] Welsh School of Architecture, Cardiff University, Cardiff, UK, kotbiag@cf.ac.uk;
[2] Welsh School of Architecture, Cardiff University, Cardiff, UK, ampatzia@cf.ac.uk;
[3] Welsh School of Architecture, Cardiff University, Cardiff, UK, jenkinsh@cf.ac.uk

Abstract: Hot arid areas are endowed with an abundance of clear skies. Thus, the solar energy available can significantly raise the temperature of interior spaces and also result in an uncomfortable visual environment. External perforated solar screens have been used to control solar penetration through windows. Such screens can also serve a social function, that of maintaining privacy. This paper focuses on a special case of girls' schools in Saudi Arabia, where the privacy issue is critical due to socio-cultural and religious beliefs. Windows in girls' schools facing public spaces are typically covered by dark opaque film to maintain privacy. This window treatment results in overreliance on artificial lighting, and in a corresponding increase in energy use. The performance of screens can be affected by many parameters, namely: perforation rate, depth ratio, shape, reflectivity of colour, aspect ratio of openings. This paper looks at how different Aspect ratios affect the performance of screens by simulating a range of cases of different aspect ratios, using the Daylight Dynamic Performance Metrics approach (DDPM). Results recommend using 1:1 aspect ratio for the south orientation whereas using different aspect ratios for the North and West orientations provide better daylight levels in the studied context.

Keywords: Daylight, Perforated Solar Screens, Schools, windows, Daylight Dynamic Performance Metrics.

Introduction

Areas with hot arid desert climate are characterised by an abundance of clear skies. Thus, the available solar radiation can significantly increase the temperature of interior spaces and result in uncomfortable visual environments due to discomfort glare and poor uniformity ratios (Julian, 2006). Fixed external solar screens can control solar penetration in spaces whilst improve the visual and thermal comfort of the users of such spaces (Harris, 2006). These screens follow the general principles of a shading device that has been traditionally used in hot arid areas, called "Mashrabiya". The Mashrabiya has always had a social function to serve, that of maintaining privacy which is of importance to the Islamic cultures (Fathy, 1986). This dual purpose, explains the widespread use of these devices around the world wherever Muslims exist, from Moorish Spain in the West through North Africa and the Middle East to India in the East (Alitany, 2014). The same principle is used in contemporary architecture to shade facades. Using such perforated solar screens is also proven to reduce energy consumption (Sabry et al, 2014).

The issue of providing privacy for women is significant in Saudi Arabia as the country follows an Islamic regulation, which dictates that women should be covered in the attendance of unrelated men. Following the same regulation, women have to wear "Abaya", a dark robe which they can only take off when inside their houses or in buildings occupied only by women, such as girls' schools. To maintain privacy in girls' schools, it is common for windows to be completely covered by black opaque coatings or non-transparent curtains. Figure 1 shows an example of current situation from a site visit by the main author (Kotbi and Ampatzi 2015).

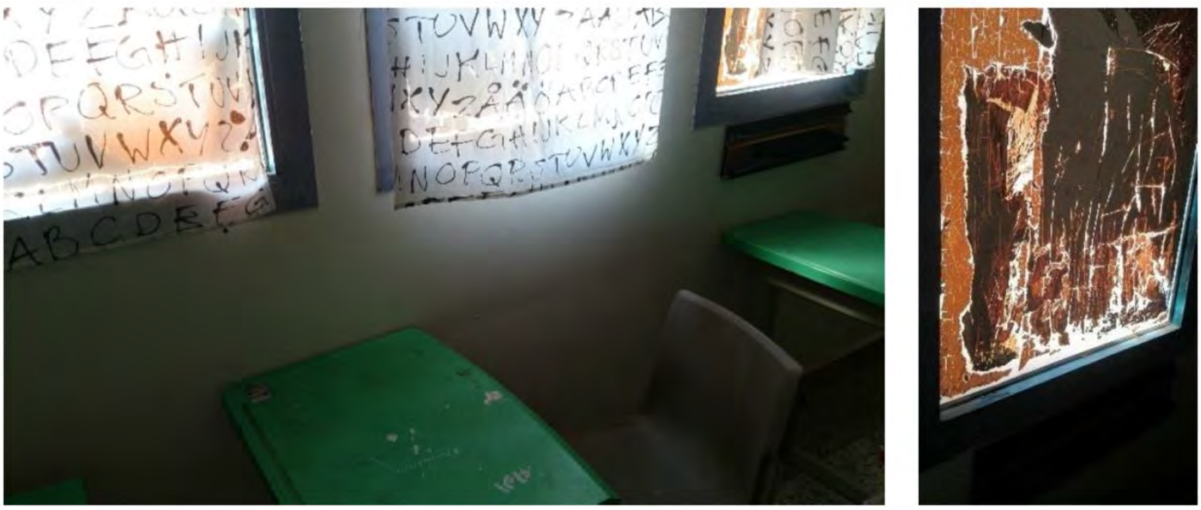


Figure 1: an example chowing using black opaque film to cover windows

It is well known that such treatments could affect the occupants' wellbeing and productivity, especially students in schools (Erwin, Heschong, 2002), due to the lack of access to external views and adequate natural light (Webb, 2006). These window treatments require exclusive use of artificial lighting, and as a result, girls' schools in Saudi Arabia became significant energy consumers, considering also the numbers of schools and the fact that they all operate during peak hours (Abanomi, Jones, 2005). Considering the characteristics and function of perforated solar screens, it is likely that they are an effective alternative solution to the window treatments currently in place in girls' schools in Saudi Arabia. This research focuses on adopting such screens as a retrofit strategy for existing buildings used as schools, therefore, other solutions that could be effectively integrated in the design process were not considered, such as organising teaching spaces around internal courtyards.

The performance of perforated solar screen can be controlled by different parameters, previous studies have summarized the key parameters affecting the performance of perforated solar screens to: perforation rate, depth ratio, cell shape, colour reflectance, aspect ratio of openings, tilt and rotation angles. The authors have already investigated the effect of perforation rate on daylighting in the same context (Kotbi and Ampatzi 2016), Sherif et al. (2012) also studied the perforation rate in residential living rooms. Aljofi (2005) have looked at the effect of the cell shape and colour reflectance of the screen on daylight distribution in a general context. The latter study concluded that a light colour and a rectangular shape result to improved daylight distribution in comparison to darker materials or round openings. In the context of a residential living room, Sherif et al. (2012) have examined the effect of depth ratio its effect on energy consumption for cooling, heating and lighting , Sabry et al. (2011) have studied the effect of screen rotation angle on daylight . Regarding aspect ratios, Sherif et al. (2013) have investigated the effect of opening aspect ratios on daylighting and on energy consumption for residential living rooms. However, no previous research known to the authors have investigated the effect of aspect ratio on the daylight performance in classrooms.

Objective

This paper is a part of ongoing research that examines the parametric design of perforated screens for both enhancing interior daylight levels and maintaining privacy in typical girls' classrooms in a hot arid area. The objective of this paper is to examine optimum aspect ratios for perforated solar screens to enhance daylighting inside classrooms in hot arid areas for the four main orientations (North, South, East and West). This perspective is considered to be novel, as no other research focusing on this aspect and context is known to the authors.

Methodology

A validated virtual simulation approach is used for this experiment. A 3D base-case classroom was modelled, representing a typical classroom with five windows. This typology is based on a physical survey conducted previously by the authors for 11 classrooms (Kotbi and Ampatzi 2015). In this study, nine perforated solar screens each with different aspect ratio are modelled. In a previous study the optimum perforation rate for solar screens for the same context has been studied (Kotbi and Ampatzi 2016), hence the recommended perforation rate for each orientation is used here. The depth ratio used for each orientation is set according to an optimisation exercise conducted as part of the overall research (unpublished at the time of writing). Other parameters were fixed to control the result. All fixed parameters are listed in Table 1.

The aspect ratio is defined as the ratio between the horizontal width (H) and vertical length (V) of the cell H:V. Screens with four aspect ratios with horizontal direction (2:1, 4:1, 6:1, 12:1) and four with vertical direction 1:2, 1:4, 1:10, 1:20 are examined and compared with a 1:1 square cell. A 6 cm module cell size was used as the basis for creating screens with different aspect ratios. Figure 2 shows examples of different cases.

Table 1: Parameters of simulated solar screens

Module size for cells	6 x 6cm	Depth Ratio	0.15 North, West; 0.6 South; 0.75 East
Colour reflectance	70%	Perforation rate	90% North, West, South ; 80% East

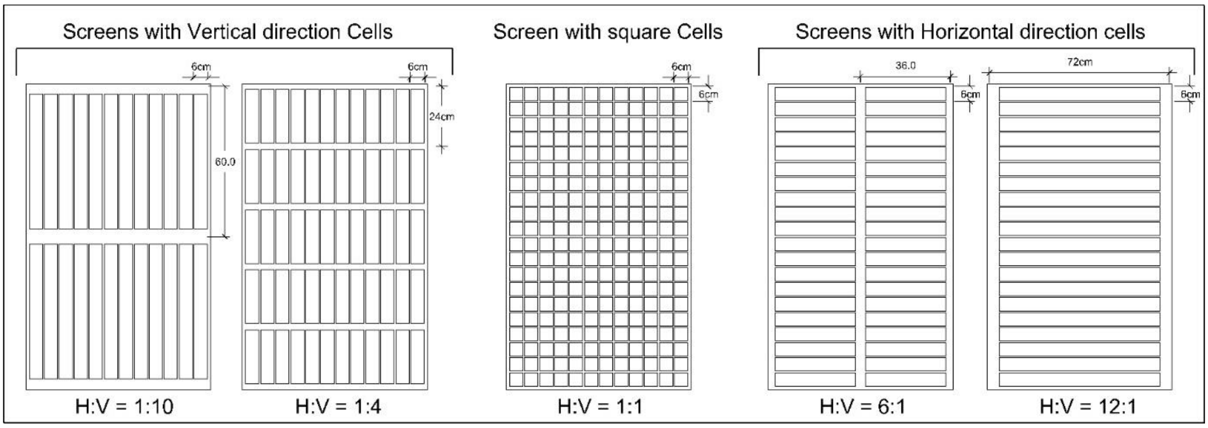


Figure 2: Examples of screens with different aspect ratios

These cases are tested for the four main orientations using the Dynamic Daylight Performance Metrics (DDPMs). These metrics evaluate daylighting performance based on a time series of illuminance levels within a space. The time series cover the occupancy schedule in a calendar year, and based on annual solar radiation data included in the weather data file used in the simulation (Reinhart et al, 2006). The DDPM includes many metrics such as Daylight Autonomy (DA), useful Daylight Illuminance (UDI) and Daylight Availability (DAv). The

DA represents the percentage of occupied hours of the year when at least the minimum required illuminance is achieved; following from that, the space is divided as either 'Daylit' and 'Partly lit' area. Daylit is characterised as the area that has achieved the required illuminance level for at least half of the occupancy hours, while Partly lit area is the area that did not achieve that illuminance level (Reinhart, Walkenhorst, 2001). The UDI uses the lower and upper thresholds of 100lx and 2000lx accordingly to determine illuminance within a useful range, UDI also represents area with oversupply of daylight (more than 2000lx) (Nabil, Mardaljevic, 2006). The problem with the DA is that it does not account for the area with oversupply of daylight in the results, which is usually accompanied with visual and thermal discomfort especially in such climate. "DAv" however, combines both "DA" and "UDI". When using Daylight Availability metric, the space is divided into three categories: 'Daylit' area, 'Partly lit' area and 'Overlit' area, which is the area receiving more than ten times the required illuminance for at least 5% of the occupancy hours (Reinhart, Wienold, 2011). The 5% criterion was selected according to British Standards (BSI, 2007).

Architectural parameters

The dimensions of the base case classroom are 6.90m x 4.50m Figure 3. The dimensions of each of the windows are 0.72m x 1.2m Figure 4. The assumed indoor parameters and reflectance values are presented in Table2. Most schools in Riyadh are surrounded by four streets at least 20m wide and all classrooms are not in a ground floor, hence external obstructions are ignored in these simulations.

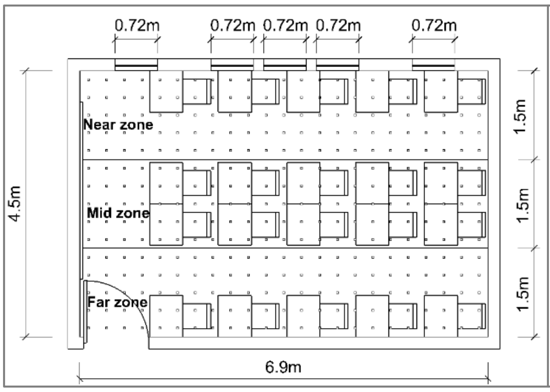


Figure 3: plan of the simulated classroom

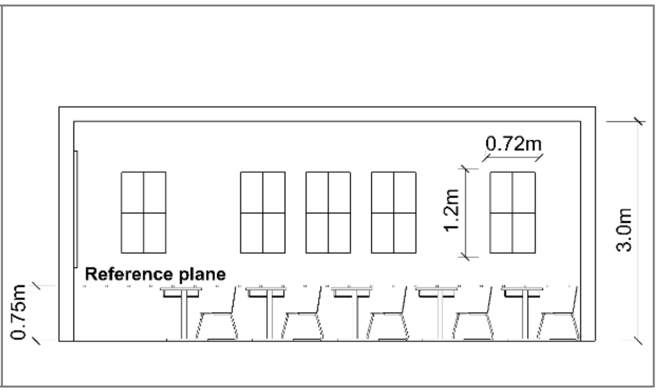


Figure 4: section of the simulated classroom

Table 2: Parameters of simulated classroom

Space parameters		**Windows parameters**	
Dimensions	4.50m X 6.9m X 3.0m	WWR	21%
Working level	+0.75m	No. of Windows	5
Surface Reflectance		Dimensions	0.72m x 1.2m
Interior walls	50%	Sill height	1.15m
Exterior walls	35%	Glass Transmission	88%
Ceiling	80%	**Solar Screens parameters**	
Floor	20%	Cell size	6cm x 6cm
Furniture	50%	Perforation Rates	N&W&S: 90%, E: 80%
White board	90%	Depth ratios	N&W: 0.15, E: 0.75, S: 0.6
Solar screens	70%	Screen reflectance	70%

Simulation process

To conduct the virtual simulation three software tools were used. The software “Rhinoceros”, which is a 3D modelling tool, was used to build geometries of the modelled classroom and perforated screens with different configurations. “DIVA” is a plug-in for ‘Rhinoceros’ (Jakubiec, Reinhart, 2011) and is used as an interface for the simulation engines “Radiance” and “Daysim”. Both software engines are broadly used for backward-tracing daylighting analysis and have been previously validated by comparing simulation results with physical measurements (Reinhart, Breton, 2009). “Grasshopper”, a generic algorithm editor that works as a parametric modelling extension for Rhinoceros (Rutten, McNeel, 2012), was used to produce the variation of solar screens according to the required parameters. “Grasshopper” was also used with “DIVA” to control the simulation runs and export the results.

The location is Riyadh (24.7°N, 46.8°E). The weather data file for Riyadh was obtained from the U.S Department of Energy (DOE, 2015). Weather files represent a Typical Meteorological Year “TMY” and are generated using recorded data including global solar radiation from around 23 years (Hall et al, 1978). The sky condition setup in this study was “clear sky with sun” as this is a typical sky condition in this climate (Al-Abbadi et al, 2002).

Simulation parameters used for Radiance simulation engine are presented in Table 3. The “ambient bounces” represents the number of times the light is allowed to hit and bounce from any plane in the simulated scene, and the recommended value is at least 6 to account for complicated configuration such as perforated screens (IES, 2012). The “ambient divisions” parameter determines the number of sample rays sent out from a surface point. It is recommended to be set at as high as 1000 to avoid high brightness variation (Reinhart, Wienold, 2011). An ambient sampling parameter greater than zero determines the number of extra rays that are sent in sample areas with a high brightness gradient. The combination of “ambient accuracy” ”, “ambient resolution” and the maximum scene dimension gives a measure of how fine the luminance distribution is distributed, according to this formula: [(Maximum scene dimension × ambient accuracy) / ambient resolution] (Larson, Shakespeare, 2004). Hence, setting the “ambient accuracy” at 0.1 and “ambient resolution” at 300 with a maximum scene dimension of 100m means that the smallest cell in simulated perforated screens can be as small as 3cm because (100m × 0.1)/300 = 0.03m.

Table 3: Utilized Radiance Simulation Parameters

Ambient bounces	Ambient divisions	Ambient sampling	Ambient	Ambient accuracy
6	1000	20	300	0.1

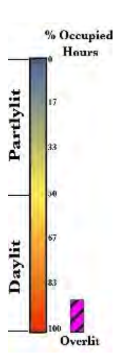
A grid of measuring sensors is used as a reference plane to plot the metrics’ data. The reference plane is recommended to be on the highest plane where regular task is performed in the space (IES, 2012). In the case of a classroom, the reference plane is set on pupils desks at 0.75m height Figure 4. There are in total 345 measuring points on the reference plane, spread evenly on a 0.3mx0.3m grid, this grid is the minimum recommended grid to improve accuracy (IES, 2012).

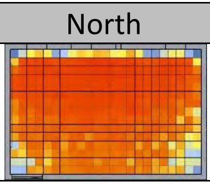
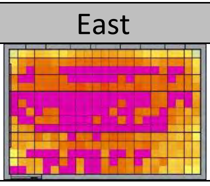
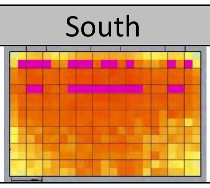
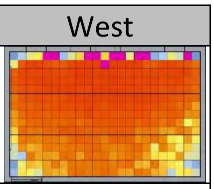
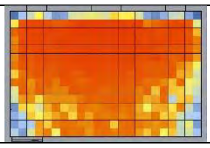
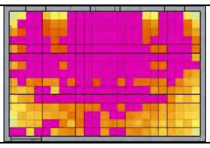
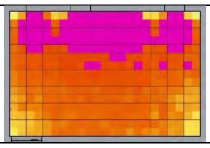
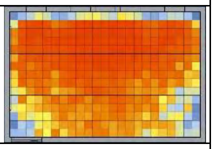
To simulate DAv, we need to set a required illuminance threshold and provide an occupancy schedule. The standard adequate illuminance for a reading and/or writing task is 500lx (Phillips, 2000), however, it is problematic to depend on daylight solely to achieve this level without causing discomfort glare (Mardaljevic et al, 2009). Therefore, the required illuminance threshold was set to 300lx since the aim was to reduce the use of artificial light as much as possible (Heschong et al, 2012). The occupancy schedule is created using a typical school year in Saudi Arabia, which has 180 days in 36 weeks, with a total of 1080 hours, the school year starts on mid-September until mid-June in two semesters, each term has one half term break. The school day starts at 6:30 and ends at 13:30 to avoid the hot afternoon hours as much as possible.

Results

Each of the 345 measuring points is represented by a coloured square on the classroom plan to show daylight availability distribution. The colour of each square indicates the percentage of time achieving 300lx out of total occupancy time according to a colour scale ranges from Blue 0% to Red 100%. Squares in magenta colour represent Overlit conditions. Table 4 compares DAv distribution for the best and worst case for each orientation. The percentage of Daylit area of the total classroom area is then calculated for each case in each orientation. The graph in Figure 5 displays Daylit areas for all cases. Cases achieved more than 50% daylit area is considered adequate to achieve acceptable daylight performance (Sherif et al, 2012).

Table 4: Comparison between daylight availability distribution of best and worst case for each orientation

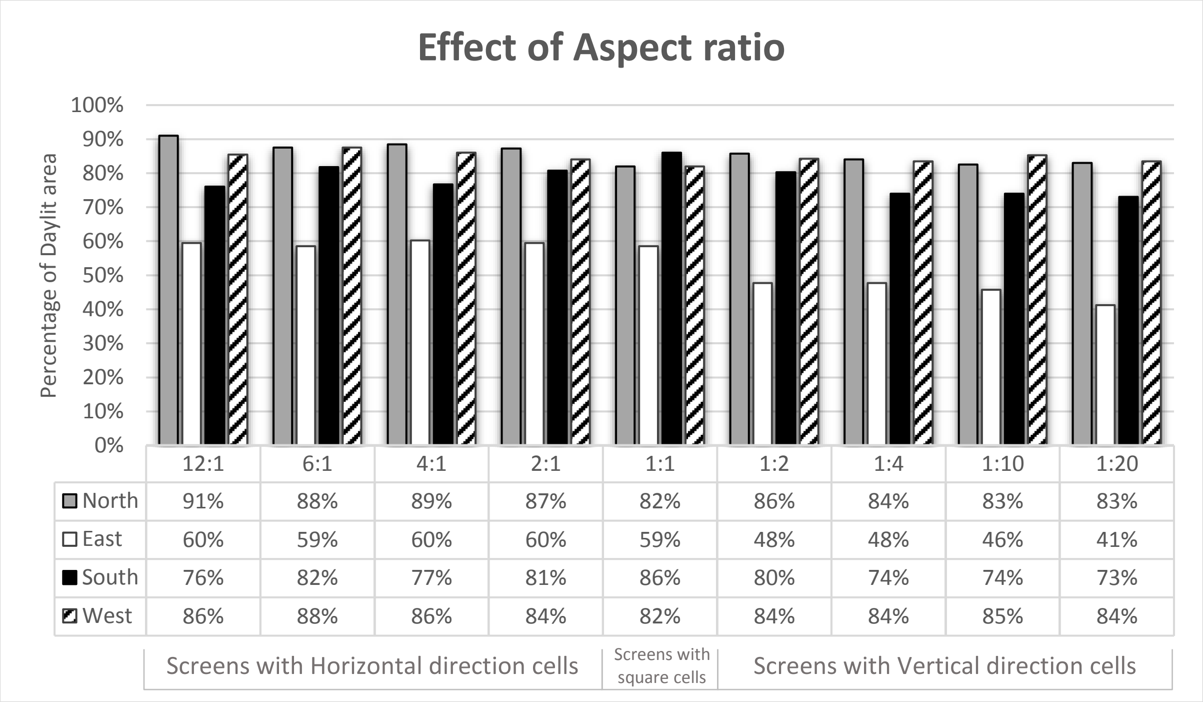
Legend


	North	East	South	West
Best Case				
H:V	12:1	4:1	1:1	6:1
Daylit area	91%	60%	86%	88%
Worst Case				
H:V	1:1	1:20	1:10	1:1
Daylit area	82%	41%	73%	82%

Results in Figure 5 show that using screens with horizontal direction cells could provide more daylit area in the studied context for all main orientations except South orientation, and screens with vertical direction provide also more daylit area than screens with square cells for the North and West orientations. In the South Orientation the optimum aspect ratio is 1:1 with square cells, using other aspect ratio for Southern orientation could reduce the daylight performance of the solar screen.

Discussion and Conclusion

To provide more daylit area, results of this study recommend using different aspect ratio than 1:1 in the North and West facades, and using 1:1 aspect ratio in the South. For the East orientation, results recommend using only screens with horizontal direction cells. Most cases of aspect ratios in all main orientations achieved adequate level of daylighting performance providing daylit area of more than 50% of total space. Only the screens with vertical direction in the East orientation failed to achieve adequate daylit areas as shown in Figure 5, in these cases, overlit areas occupied about half of the total area of the classroom Table 4. It must be noticed that the result of West façade reflects the occupation schedule used in this context as the school day finishes early. Which differs from studies of residential spaces where occupation schedule extend until sunset.



	12:1	6:1	4:1	2:1	1:1	1:2	1:4	1:10	1:20
▒ North	91%	88%	89%	87%	82%	86%	84%	83%	83%
□ East	60%	59%	60%	60%	59%	48%	48%	46%	41%
■ South	76%	82%	77%	81%	86%	80%	74%	74%	73%
▨ West	86%	88%	86%	84%	82%	84%	84%	85%	84%

Figure 5: percentage of Daylit area for all cases

Results of previous studies by the authors recommended using 90% perforation rate in North, West and South facades, 80% in the East facades. It also recommended depth ratio of 0.15 in North and West Facades, 0.6 in West facades, 0.75 in East Façade. Results of this experiment proved that using the recommended results by the authors in previous studies could achieve adequate daylight performance when using any aspect ratio, except for East façade where screens with vertical direction did not achieve adequate daylit levels. Hence, architects could use different aspect ratios according to the required daylit area provided using the chart in Figure 5.

References

Abanomi, W., Jones, P. (2005). Passive cooling and energy conservation design strategies of school buildings in hot, arid region: Riyadh, Saudi Arabia. In: *Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, 19-21 May 2005.

Al-Abbadi, N.M., Alawaji, S.H., Bin Mahfoodh, M.Y., Myers, D.R., Wilcox, S., Anderberg, M. (2002). Saudi Arabian solar radiation network operation data collection and quality assessment. *Renewable Energy,* 25(2), 219-234.

Alitany, A.K. (2014). *A new strategy of ICT integrated methodologies for 3D documentation : a case study of the projected wooden windows (The Roshans) in the historical city of Jeddah (Saudi Arabia).* PhD. Universitat Politècnica de Catalunya.

Aljofi, E. (2005). The Potentiality of Reflected sunlightthrough Rawshan screens. In: *Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, 19-21 May 2005.

BSI, B.E. (2007). *15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.*

DOE, (2015). *Weather data file for Riyadh Saudi Arabia*. [Online]Available from:
http://apps1.eere.energy.gov/region=2_asia_wmo_region_/country=Saudi%20Arabia
[Accesed:14/10/2015]

Erwin, B., Heschong, L. (2002). Lighting for Learning. In: *Lightfair International Seminar*. Sanfrancisco, CA, 5 June 2002.

Fathy, H. (1986). *Natural energy and Vernacular architecture: principles and examples with reference to hot arid climate.* Chicago: University of Chicago.

Hall, I.J., Prairie, R., Anderson, H., Boes, E. (1978). *Generation of a typical meteorological year.*(SAND-78-1096C; CONF-780639-1).

Harris, C. (2006). *Solar screen,* fourth ed. New York: McGraw-Hill books.

Heschong, L., Group, H.M. (2012). *Daylight Metrics*. [Online] Available from: http://www.energy.ca.gov/2012publications/CEC-500-2012-053/CEC-500-2012-053.pdf [Access:14/2/2016].

IES, D.M.C. (2012). *Approved Methods: IES Spatial Daylight Autonomy sDA and Annual Sunlight Exposure.*

Jakubiec, J.A., Reinhart, C.F. (2011). DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus. In*: Conference of International Building Performance Simulation Association*, Sydney, Australia, 14-16 November 2011.

Kotbi, A., Ampatzi, E. (2015). Using Mashrabiya to enhance daylighting and privacy in girls' schools in Saudi Arabia. a poster in In: *the 6th Daylight Symposium,* London, UK, 2-3 September.

Kotbi, A.G., Ampatzi, E. (2016). Using solar screens in school classrooms in hot arid areas: the effect of different perforation rates on daylighting levels. In: *32th PLEA conference on Passive and Low Energy Architecture,* Los Angeles, CA, 11-13 July 2016.

Larson, G.W., Shakespeare, R. (1998). *Rendering with Radiance: the art and science of lighting visualization*. Sanfrancisco: Morgan Kaufmann Publishers.

Mardaljevic, J., Heschong, L., Lee, E. (2009). Daylight metrics and energy savings. *Lighting Research and Technology,* 41(3), 261-283.

Nabil, A., Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings,* 38(7), 905-913.

Phillips, D. (2000). *Lighting modern buildings,* Oxford: Architectural Press.

Reinhart, C., Breton, P.F. (2009). Experimental Validation of Autodesk 3ds Max 2009 and Daysim *LEUKOS,* 6(1), 7-35.

Reinhart, C.F., Mardaljevic, J., Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS,* 3(1), 24.

Reinhart, C.F., Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings,* 33(7), 683-697.

Reinhart, C.F., Wienold, J. (2011). The daylighting dashboard –A simulation-based design analysis for daylit spaces. *Building and Environment,* 46(2), 386-396.

Rutten, D., McNeel, R. (2012). *Grasshopper*. www.Grasshopper3d.com. [14/12/2015].

Sabry, H., Sherif, A., Gadelhak, M., Aly, M. (2014). Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio. *Solar Energy,* 103, 364-377.

Sabry, H., Sherif, A.H., Rakha, T. (2011). Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies. In: *International Conference on Sustainable Design and Construction (ICSDC) 2011*, Kansas city MO, 23-25March.

Sherif, A., El-Zafarany, A., Arafa, R. (2012). External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments. *Energy and Buildings,* 52(0), 1-10.

Sherif, A., El Zafarany, A., Arafa, R. (2013). Evaluating the energy performance of external perforated solar screens: Effect of screen rotation and aspect ratio. In: *SB13 Sustainable Building 2013*, Singapore, 9-10 September.

Sherif, A., Sabry, H., Rakha, T. (2012). External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages. *Solar Energy,* 86(6), 1929-1940.

Sherif, A., Sabry, H., Gadelhak, M. (2012). The impact of changing solar screen rotation angle and its opening aspect ratios on Daylight Availability in residential desert buildings. *Solar Energy,* 86(11), 3353-3363.

Webb, A.R. (2006). Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings,* 38(7), 721-727.

Appendix B: Risk assessment.

Risk Assessment WSA

1. General Information

Department	ARCHI	**Building**	Bute Building	**Room number**	0.41 (Artificial sky)
Assessor	Ahmad Kotbi	**Date of Assessment**	21/11/2017	**Assessment number**	

2. Brief Description of procedure/activity including location and duration

The experiment will take place inside the artificial sky in room number (0.41) in the basement of Bute Building. 20 subjects will be recruited. 3-5 subjects will participate in each session covering a day of the experiment. The experiments will take 4-6 days in total. The researcher will have one assistant for each session. The experiment is planned to take place in a week starting from 11November 2017.

A box will be attached to a tilted table. It will have the ability to be tilted and will have LED lamps installed in it. An image will be placed inside the box. One side of the box will be covered by a perforated screen that can also be tilted from 0 to 90 degree.

Three screens and six images will be used in the experiments.

Participants will be asked whether the image behind the screen is recognizable while the assistant tilts the screen very slowly. The researcher will then record the tilting angle of the screen. A mirror will be fixed at the end of the dome and used to compensate for distance shortages when testing long distances as the dome is not wide enough.

Participants will be subjected to a quick visual acuity test first so that anyone with visual acuity results below normal vision standards will be excluded from the rest of the experiment.

3. Assessment

What are the hazards	**Who might be harmed**	**Existing controls**	**Likelihood of risk**	**Current risk level**	**What further action is necessary? Inc. by whom and when**	**Future risk level**
Medical emergency	Participants and Researcher	First Aid kit is provided in the building	Low	Low	Inform the participants about the location of the first aid kit.	
Travel	NA	NA	NA	NA	NA	
Fieldwork	NA	NA	NA	NA	NA	

Fire	Participants and Researcher	Following the local procedure in case of fire alarm.	Low	Low	The researcher would show participants the floor plans and fire exit doors at the beginning of each session.	
Noise Manual handling	Building users	Closing doors	Low	Low	The artificial sky is already isolated. The researcher will make sure that the door is closed.	
Stress	Participants and Researcher		Low	Low	Researcher will assure participants that they can withdraw from experiment at any time without giving any reason if not comfortable.	
Slips/trips/falls	Participants and Researcher	Signs are used to inform for hazards as necessary	Low	Low	Researcher and his assistant will make sure there are no slip/trip hazards during the experiment, secure any wires and use signs if required.	
Head injury entering the dome	Researcher, assistant and participants	Entrance is padded and has a sign to watch heads when enrering.	Medium	Low	Researcher will inform participants to take care ant watch their head when entering the dome	
Electrical	Researcher and his assistant	Only tested equipment used in University buildings.	Low	Low	Only LED lamps powered by batteries will be used and tested inside the built box. The electrical equipment are already tested.	
Display screen	NA	NA	NA	NA	NA	
Lone working	NA	NA	NA	NA	NA	

Machinery/equipment	Researcher	No one is allowed to operate the sky-dome but a staff member.	Low	Low	A staff member will be always present during the experiment and will be operating the skydome.	
Breaking mirror	Researcher and his assistant and participants	The mirror will be installed one time and will not be touched til the end of experiment.	Low	Low	Researcher will take care when installing the mirror at the end of the dome with the help of his assistant. No participants will go near the mirror at any time.	
Recruiting subjects not known to the school, holding an event in the school.	Building users	Due regard given to the 'Prevent duty' policy	Low	Low	List of names of participants will be submitted for all participants before entering the building, proof id will be checked to match the names. Sing in and out times will be registered for participants. However names will not relate to the questionnaire sheets as they are anonymous.	
Constructing the structure	The researcher	It will be under control supervised by Dan, who is experienced and responsible for the workshop in bute building	Low	Low	Installing the LED lamps will be supervised by Huw Jenkins. He is experienced and responsible for the artificial sky dome and most lighting equipment for students.	
Environmental impact	NA	NA	NA	NA	NA	

[1] Risk assessment guidance notes version 4/March 2017/reviewed annually

Appendix C: Ethics approval form.

EC1706.319

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

WS

Tick one box: ☐ STAFF ■ PHD/MPHIL

Title of project: Testing visibility through perforated screens

Name of researcher(s): Ahmad Kotbi

Name of principal investigator: Eleni Ampatzi, Huw Jenkins

Contact e-mail address: kotbiag@cf.ac.uk

Date: 20/6/2017

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)		X	
	• People with learning difficulties		X	
	• Patients (NHS approval is required)		X	
	• People in custody		X	
	• People engaged in illegal activities		X	
	• Vulnerable elderly people		X	
	• Any other vulnerable group not listed here		X	
• When working with children: I have read the Interim Guidance for Researchers Working with Children and Young People (http://www.cardiff.ac.uk/archi/ethics_committee.php)				X

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	X		
• Will you tell participants that their participation is voluntary?	X		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	X		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	X		
• Will you give participants the option of omitting questions they do not want to answer?	X		
• If the research is observational, will you ask participants for their consent to being observed?			X
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?	X		

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		X	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		X	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?				X
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants			X
	• allow the participants the option of anonymity for all or part of the information they provide			X

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (http://www.cf.ac.uk/osheu/index.html)	X

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		X	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		X	

---

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

Prevent Duty	**YES**	
Has due regard be given to the 'Prevent duty', in particular to prevent anyone being drawn into terrorism? https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/445916/Prevent_Duty_Guidance_For_Higher_Education__England__Wales_.pdf http://www.cardiff.ac.uk/publicinformation/policies-and-procedures/freedom-of-speech	X	

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information. The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A **The Project** (provide all the information listed below in a separate attachment)

1. Title of Project
2. Purpose of the project and its academic rationale
3. Brief description of methods and measurements
4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria
5. Consent and participation information arrangements - please attached consent forms if they are to be used
6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them
7. Estimated start date and duration of project

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Researcher's declaration (tick as appropriate)	
• I consider this project to have **negligible ethical implications** (*can only be used if none of the grey areas of the checklist have been ticked*).	
• I consider this project research to have **some ethical implications**.	
• I consider this project to have **significant ethical implications**	

Signature	**Name**	**Date**
Researcher or MPhil/PhD student	Ahmad G. Kotbi	27/6/2017
Signature	**Name**	**Date**
Lead investigator or supervisor	Eleni Ampatzi	27/6/2017

Advice from the School Research Ethics Committee

STATEMENT OF ETHICAL APPROVAL

This project had been considered using agreed Departmental procedures and is now approved

Signature Robert Davis **Name** ROBERT DAVIS **Date** 29/06/17

Chair, School Research Ethics Committee

Appendix D: Prevent duty guidelines.

HM Government

Prevent Duty Guidance:
for higher education institutions in England and Wales

This sector specific guidance for higher education institutions in England and Wales subject to the Prevent duty is additional to, and is to be read alongside, the general guidance contained in the Revised Prevent Duty Guidance issued on 16th July 2015.

Higher education

1. Section 26(1) of the Counter-Terrorism and Security Act 2015 ("the Act") imposes a duty on "specified authorities", when exercising their functions, to have due regard to the need to prevent people from being drawn into terrorism. Certain higher education bodies ("Relevant Higher Education Bodies", or "RHEBs") are subject to the section 26 duty. RHEBs' commitment to freedom of speech and the rationality underpinning the advancement of knowledge means that they represent one of our most important arenas for challenging extremist views and ideologies. But young people continue to make up a disproportionately high number of those arrested in this country for terrorist-related offences and of those who are travelling to join terrorist organisations in Syria and Iraq. RHEBs must be vigilant and aware of the risks this poses.

2. Some students may arrive at RHEBs already committed to terrorism; others may become radicalised whilst attending a RHEB due to activity on campus; others may be radicalised whilst they are at a RHEB but because of activities which mainly take place off campus.

Higher education specified authorities

3. The higher education institutions specified in Schedule 6 to the Act fall into two categories:

- the governing body of qualifying institutions within the meaning given by section 11 of the Higher Education Act 2004.
- private higher education institutions that are not in receipt of public funding from the Higher Education Funding Council for England (HEFCE) or the Higher Education Funding Council Wales (HEFCW) but have similar characteristics to those that are. This includes governing bodies or proprietors of institutions not otherwise listed that have at least 250 students, excluding students on distance learning courses, undertaking courses of a description mentioned in Schedule 6 to the Education Reform Act 1988 (higher education courses).

4. Most of these institutions already have a clear understanding of their Prevent related responsibilities. Institutions already demonstrate some good practice in these areas. We do not envisage the new duty creating large new burdens on institutions and intend it to be implemented in a proportionate and risk-based way.

5. Compliance with the Prevent duty requires that properly thought through procedures and policies are in place. Having procedures and policies in place which match the general expectations set out in this guidance will mean that institutions are well placed to comply with the Prevent duty. Compliance will only be achieved if these procedures and policies are properly followed and applied. This guidance does not prescribe what appropriate decisions would be - this will be up to institutions to determine, having considered all the factors of the case.

6. We would expect RHEBs to be delivering in the following areas.

External Speakers and Events

7. In order to comply with the duty all RHEBs should have policies and procedures in place for the management of events on campus and use of all RHEB premises. The policies should apply to all staff, students and visitors and clearly set out what is required for any event to proceed.

8. The RHEB clearly needs to balance its legal duties in terms of both ensuring freedom of speech and academic freedom, and also protecting student and staff welfare. Although it predates this legislation, Universities UK produced guidance in 2013 to support institutions to make decisions about hosting events and have the proper safeguards in place: http://www.universitiesuk.ac.uk/highereducation/Pages/Externalspeakersinhighereducationinstitutions.aspx

9. The Charity Commission also produced guidance on this matter in 2013: https://www.gov.uk/government/publications/charities-and-terrorism and https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/351342/CT-5.pdf

10. Encouragement of terrorism and inviting support for a proscribed terrorist organisation are both criminal offences. RHEBs should not provide a platform for these offences to be committed.

11. Furthermore, when deciding whether or not to host a particular speaker, RHEBs should consider carefully whether the views being expressed, or likely to be expressed, constitute extremist views that risk drawing people into terrorism or are shared by terrorist groups. In these circumstances the event should not be allowed to proceed except where RHEBs are entirely convinced that such risk can be fully mitigated without cancellation of the event. This includes ensuring that, where any event is being allowed to proceed, speakers with extremist views that could draw people into terrorism are challenged with opposing views as part of that same event, rather than in a separate forum. Where RHEBs are in any doubt that the risk cannot be fully mitigated they should exercise caution and not allow the event to proceed.

12. We would expect RHEBs to put in place a system for assessing and rating risks associated with any planned events, which provides evidence to suggest whether an event should proceed, be cancelled or whether action is required to mitigate any risk. There should also be a mechanism in place for assessing the risks associated with any events which are RHEB-affiliated, funded or branded but which take place off-campus and for taking swift and appropriate action as outlined in paragraph 11.

13. Additionally, institutions should pay regard to their existing responsibilities in relation to gender segregation, as outlined in the guidance produced in 2014 by the Equality and Human Rights Commission: http://www.equalityhumanrights.com/sites/default/files/publication_pdf/Guidance%20for%20universities%20and%20students%20unions%2017-07-14.pdf

14. RHEBs should also demonstrate that staff involved in the physical security of the institution's estate have an awareness of the Prevent duty. In many instances, this could be achieved through engagement with the Association of University Chief Security Officers (AUCSO). Where appropriate and legal to do so, an institution should also have procedures in place for the sharing of information about speakers with other institutions and partners.

15. But managing the risk of radicalisation in RHEBs is not simply about managing external speakers. Radicalised students can also act as a focal point for further radicalisation through personal contact with fellow students and through their social media activity. Where radicalisation happens off campus, the student concerned may well share his or her issues with other students. Changes in behaviour and outlook may be visible to university staff. Much of this guidance therefore addresses the need for RHEBs to have the necessary staff training, IT policies and student welfare programmes to recognise these signs and respond appropriately.

Partnership

16. In complying with this duty we would expect active engagement from senior management of the university (including, where appropriate, vice chancellors) with other partners including police and BIS regional higher and further education

Prevent co-ordinators. We would expect institutions to seek to engage and consult students on their plans for implementing the duty.

17. Given the size and complexity of most institutions we would also expect RHEBs to make use of internal mechanisms to share information about Prevent across the relevant faculties of the institution. Having a single point of contact for operational delivery of Prevent related activity may also be useful.

18. We would expect institutions to have regular contact with the relevant Prevent co-ordinator. These co-ordinators will help RHEBs comply with the duty and can provide advice and guidance on risk and on the appropriate response. The contact details of these co-ordinators are available on the Safe Campus Communities website: www.safecampuscommunities.ac.uk.

Risk assessment

19. RHEBs will be expected to carry out a risk assessment for their institution which assesses where and how their students might be at risk of being drawn into terrorism. This includes not just violent extremism but also non-violent extremism, which can create an atmosphere conducive to terrorism and can popularise views which terrorists exploit. Help and support will be available to do this.

20. We would expect the risk assessment to look at institutional policies regarding the campus and student welfare, including equality and diversity and the safety and welfare of students and staff. We would also expect the risk assessment to assess the physical management of the university estate including policies and procedures for events held by staff, students or visitors and relationships with external bodies and community groups who may use premises, or work in partnership with the institution.

Action Plan

21. With the support of co-ordinators, and others as necessary, any institution that identifies a risk should develop a Prevent action plan to set out the actions they will take to mitigate this risk.

Staff Training

22. Compliance with the duty will also require the institution to demonstrate that it is willing to undertake Prevent awareness training and other training that could help the relevant staff prevent people from being drawn into terrorism and challenge extremist ideas which risk drawing people into terrorism. We would expect appropriate members of staff to have an understanding of the factors that make people support terrorist ideologies or engage in terrorist-related activity. Such staff should have sufficient training to be able to recognise vulnerability to being drawn into terrorism, and be aware of what action to take in response. This will include an understanding of when to make referrals to the Channel programme and where to get additional advice and support.

23. We would expect the institution to have robust procedures both internally and externally for sharing information about vulnerable individuals (where appropriate to do so). This should include appropriate internal mechanisms and external information sharing agreements where possible.

24. BIS offers free training for higher and further education staff through its network of regional higher and further education Prevent co-ordinators. This covers safeguarding and identifying vulnerability to being drawn into terrorism and can be tailored to suit each institution or group of individuals.

Welfare and pastoral care/chaplaincy support

25. RHEBs have a clear role to play in the welfare of their students and we would expect there to be sufficient chaplaincy and pastoral support available for all students.

26. As part of this, we would expect the institution to have clear and widely available policies for the use of prayer rooms and other faith-related facilities. These policies should outline arrangements for managing prayer and faith facilities (for example an oversight committee) and for dealing with any issues arising from the use of the facilities.

IT policies

27. We would expect RHEBs to have policies relating to the use of their IT equipment. Whilst all institutions will have policies around general usage, covering what is and is not permissible, we would expect these policies to contain specific reference to the statutory duty. Many educational institutions already use filtering as a means of restricting access to harmful content, and should consider the use of filters as part of their overall strategy to prevent people from being drawn into terrorism.

28. To enable the university to identify and address issues where online materials are accessed for non-research purposes, we would expect to see clear policies and procedures for students and staff working on sensitive or extremism-related research. Universities UK has provided guidance to help RHEBs manage this, which available at http://www.universitiesuk.ac.uk/highereducation/Pages/OversightOfSecuritySensitiveResearchMaterial.aspx

Student unions and societies

29. Institutions should have regard to the duty in the context of their relationship and interactions with student unions and societies. They will need to have clear policies setting out the activities that are or are not allowed to take place on campus and any online activity directly related to the university. The policies should set out what is expected from the student unions and societies in relation to Prevent including making clear the need to challenge extremist ideas which risk drawing people into terrorism. We would expect student unions and societies to work closely with their institution and co-operate with the institutions' policies.

30. Student unions, as charitable bodies, are registered with the Charity Commission and subject to charity laws and regulations, including those that relate to preventing terrorism. Student Unions should also consider whether their staff and elected officers would benefit from Prevent awareness training or other relevant training provided by the Charity Commission, regional Prevent co-ordinators or others.

Monitoring and enforcement

31. The Secretary of State will appoint an appropriate body to assess the bodies' compliance with the Prevent duty. A separate monitoring framework will be published setting out the details of how this body will undertake monitoring of the duty.

Appendix E: The Questionnaire.

Data Sheet,

Participant Details

Participant no.: 12 Date: 21/11 Time: 12:47

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: S no. of Children: — no. of Children in School: —

no. of girls : — no. of girls in school —

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 5° Image no.: 2

Tilt angle (Screen-3): 9° Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 25° Image no.: 6

Tilt angle (Screen-3): 35° Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 33° Image no.: 5

Tilt angle (Screen-3): 43° Image no.: 2

Data Sheet,

Participant Details

Participant no.: 2 Date: 21.11.17 Time: 01:15 Pm

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: D no. of Children: 2 no. of Children in School: 2

no. of girls : — no. of girls in school —

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 4

Tilt angle (Screen-2): 10 Image no.: 4

Tilt angle (Screen-3): 12 Image no.: 5

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 14 Image no.: 1

Tilt angle (Screen-3): 35 Image no.: 3

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 17 Image no.: 2

Tilt angle (Screen-3): 42 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 03 Date: 22 / 11 Time: 12 : 00

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 3 no. of Children in School: 2

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 6 Image no.: 6

Tilt angle (Screen-3): 17 Image no.: 5

Case-2

Tilt angle (Screen-1): X Image no.: 3

Tilt angle (Screen-2): 24 Image no.: 3

Tilt angle (Screen-3): 37 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 32 Image no.: 1

Tilt angle (Screen-3): 49 Image no.: 2

Data Sheet,

Participant Details

Participant no.: 4 Date: 22/~~9~~11/17 Time: 10:30

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 3 no. of Children in School: 2

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 4

Tilt angle (Screen-2): 5 Image no.: 4

Tilt angle (Screen-3): 11 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: ~~2~~ 1

Tilt angle (Screen-2): 11 Image no.: ~~2~~ 1

Tilt angle (Screen-3): 37 Image no.: 6

Case-3

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 38 Image no.: 5

Tilt angle (Screen-3): 45 Image no.: 2

Data Sheet,

Participant Details

Participant no.: 5 Date: 22/11/17 Time: 10:50

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☐ No Gender: ☐ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 3 no. of Children in School: 1

no. of girls : 3 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 6° Image no.: 5

Tilt angle (Screen-3): 13° Image no.: 6

Case-2

Tilt angle (Screen-1): X Image no.: 4

Tilt angle (Screen-2): 27 Image no.: 4

Tilt angle (Screen-3): 32 Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 26 Image no.: 2

Tilt angle (Screen-3): 45 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 06 Date: 22.11.17 Time: 11:16

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 3 no. of Children in School: 3

no. of girls : 2 no. of girls in school 2

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 3

Tilt angle (Screen-2): 5 Image no.: 3

Tilt angle (Screen-3): 13 Image no.: 4

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 24 Image no.: 1

Tilt angle (Screen-3): 35 Image no.: 6

Case-3

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 40 Image no.: 5

Tilt angle (Screen-3): 45 Image no.: 2

Data Sheet,

Participant Details

Participant no.: 07 Date: 22 Nov 17 Time: 11:40

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 2 no. of Children in School: 1

no. of girls : 2 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 12 Image no.: 5

Tilt angle (Screen-3): 14 Image no.: 6

Case-2

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 15 Image no.: 2

Tilt angle (Screen-3): 32° Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 4

Tilt angle (Screen-2): 27 Image no.: 4

Tilt angle (Screen-3): 50 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 0 9 Date: 22 Nov 17 Time: 1:15 pm

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 1 no. of Children in School: 1

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 7° Image no.: 2

Tilt angle (Screen-3): 11° Image no.: 1

Case-2

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): Image no.: 5

Tilt angle (Screen-3): 37° Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 33 Image no.: 6

Tilt angle (Screen-3): 47° Image no.: 3

Data Sheet,

Participant Details

Participant no.: 09 Date: 22.11.2017 Time: 1:50 pm

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 1 no. of Children in School: 1

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 11° Image no.: 5

Tilt angle (Screen-3): 13° Image no.: 6

Case-2

Tilt angle (Screen-1): X Image no.: 3

Tilt angle (Screen-2): 24° Image no.: 3

Tilt angle (Screen-3): 40° Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 26 Image no.: 2

Tilt angle (Screen-3): 47° Image no.: 1

Data Sheet,

Participant Details

Participant no.: 10 Date: 23/11/2017 Time: 10:30

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 1 no. of Children in School: 1

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 3

Tilt angle (Screen-2): 6 Image no.: 3

Tilt angle (Screen-3): 10 Image no.: 4

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 25° Image no.: 1

Tilt angle (Screen-3): 29° Image no.: 2

Case-3

Tilt angle (Screen-1): X Image no.: ~~8~~ 5

Tilt angle (Screen-2): 6 Image no.: ~~8~~ 5

Tilt angle (Screen-3): 45 Image no.: ~~8~~ 6

Data Sheet,

Participant Details

Participant no.: 11 Date: 23/11/2017 Time: ____________

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☐ No Gender: ☐ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 1 no. of Children in School: 1

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 5 Image no.: 1

Tilt angle (Screen-3): 10 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 27° Image no.: 6

Tilt angle (Screen-3): 35° Image no.: 5

Case-3

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 336 Image no.: 4

Tilt angle (Screen-3): 16 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 12 Date: 23/11/2017 Time: 12:15

Conservative environment background (Middle Eastern/ Muslim): ☒ Yes ☐ No Gender: ☐ M ☒ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☒ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: Single no. of Children: / no. of Children in School: /

no. of girls : / no. of girls in school /

Recorded Results

Case-1

Tilt angle (Screen-1): √ Image no.: 5

Tilt angle (Screen-2): 10 Image no.: 5

Tilt angle (Screen-3): 13 Image no.: 6

Case-2

Tilt angle (Screen-1): λ Image no.: ~~4~~ ~~3~~ 3

Tilt angle (Screen-2): 23 Image no.: ~~4~~ 5

Tilt angle (Screen-3): 38 Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 31 Image no.: 2

Tilt angle (Screen-3): 52 Image no.: 4

Data Sheet,

Participant Details

Participant no.: 13 Date: 23-11-2017 Time: 12:30

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: Single no. of Children: 0 no. of Children in School: 0

no. of girls : 0 no. of girls in school 0

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): X Image no.: 3

Tilt angle (Screen-3): 10 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 25 Image no.: 5

Tilt angle (Screen-3): 36 Image no.: 2

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 22 Image no.: 6

Tilt angle (Screen-3): 46 Image no.: 2

Data Sheet,

Participant Details

Participant no.: 14 Date: 23-11-17 Time: 1:15

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 2 no. of Children in School: 1

no. of girls : 1 no. of girls in school 0

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 8 Image no.: 1

Tilt angle (Screen-3): 12 Image no.: ~~2~~ 6

Case-2

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 30 Image no.: 5

Tilt angle (Screen-3): 35 Image no.: 3

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 34 Image no.: 2

Tilt angle (Screen-3): 48 Image no.: 4

Data Sheet,

Participant Details

Participant no.: 15 Date: 23.11.17 Time: 13:35

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: S no. of Children: 0 no. of Children in School: –

no. of girls : – no. of girls in school –

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 3

Tilt angle (Screen-2): 4 Image no.: 3

Tilt angle (Screen-3): 11 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 20 Image no.: ~~3~~5

Tilt angle (Screen-3): 31 Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 26 Image no.: 6

Tilt angle (Screen-3): 45 Image no.: 4

Data Sheet,

Participant Details

Participant no.: 16 Date: 27 Nov 17 Time: 11:00 am

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☒ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 2 no. of Children in School: 2

no. of girls : 2 no. of girls in school 2

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 5

Tilt angle (Screen-2): 12 Image no.: 5

Tilt angle (Screen-3): 10 Image no.: 1

Case-2

Tilt angle (Screen-1): X Image no.: 4

Tilt angle (Screen-2): 30 Image no.: 4

Tilt angle (Screen-3): 38 Image no.: 2

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 32 Image no.: 8

Tilt angle (Screen-3): 45 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 17 Date: 2711 Time: 11:40

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☑ No Gender: ☐ M ☑ F

Age: ☐ Below 25yrs ☑ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: single no. of Children: X no. of Children in School: X

no. of girls : X no. of girls in school X

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 9 Image no.: 1

Tilt angle (Screen-3): 12 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 29 Image no.: 6

Tilt angle (Screen-3): 37 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 35

Tilt angle (Screen-2): 38 Image no.: 35

Tilt angle (Screen-3): 51 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 18 Date: 27/11/2017 Time: 12:00 PM

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: Married no. of Children: 2 no. of Children in School: 1

no. of girls : 2 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): 2 Image no.: 6

Tilt angle (Screen-2): 5 Image no.: 6

Tilt angle (Screen-3): 12 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 28 Image no.: 2

Tilt angle (Screen-3): 42 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 36 Image no.: 1

Tilt angle (Screen-3): 49 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 19 Date: 28.11.2017 Time: 9:40

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: Married no. of Children: 2 no. of Children in School: 2

no. of girls : 1 no. of girls in school 1

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 5 Image no.: 6

Tilt angle (Screen-3): 10 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 22 Image no.: 1

Tilt angle (Screen-3): 37 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 24 Image no.: 2

Tilt angle (Screen-3): 50 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 20 Date: 28-11-2017 Time: 11:15 A.M.

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☑ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

Marital Status: Single no. of Children: ______ no. of Children in School: ______

no. of girls : ______ no. of girls in school ______ eye test 4 mistakes

Recorded Results

Case-1

Tilt angle (Screen-1): ✓ Image no.: 2

Tilt angle (Screen-2): X Image no.: 2

Tilt angle (Screen-3): 9 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 15 Image no.: 1

Tilt angle (Screen-3): 33 Image no.: 5

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 37 Image no.: 6

Tilt angle (Screen-3): 41 Image no.: 3

Data Sheet,

Participant Details

Participant no.: 21 Date: 28/11/17 Time: 12:00

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

Marital Status: M no. of Children: 3 no. of Children in School: 2

no. of girls : 2 no. of girls in school 2 Eye test ✓

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 10 Image no.: 6

Tilt angle (Screen-3): 12 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 25 Image no.: 1

Tilt angle (Screen-3): 38 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 22 Image no.: 2

Tilt angle (Screen-3): 52 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 22 Date: 28/11/17 Time: 12:25

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☑ Below 25yrs ☐ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: 0 no. of Children in School: 0

no. of girls : 0 no. of girls in school 0 eye test mistakes:________

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): X Image no.: 2

Tilt angle (Screen-3): 10 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 22 Image no.: 1

Tilt angle (Screen-3): 38 Image no.: 4

Case-3

Tilt angle (Screen-1): 1 Image no.: 6

Tilt angle (Screen-2): 32 Image no.: 3

Tilt angle (Screen-3): 47 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 23 Date: 28/11/17 Time: 14:00

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☑ No Gender: ☐ M ☑ F

Age: ☐ 18-24yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: ________ no. of Children in School: ________

no. of girls : ________ no. of girls in school ________ eye test mistakes: ________

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): X Image no.: 1

Tilt angle (Screen-3): 10 Image no.: 1

Case-2

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 20 Image no.: 6

Tilt angle (Screen-3): 30 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 21 Image no.: 2

Tilt angle (Screen-3): 43 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 24 Date: 29/11/17 Time: 12:20

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☑ 18-24yrs ☐ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: 0 no. of Children in School: 0

no. of girls : 0 no. of girls in school 0 eye test mistakes:________

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 10° Image no.: 6

Tilt angle (Screen-3): 10° Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 19 Image no.: 2

Tilt angle (Screen-3): 36° Image no.: 5

Case-3

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 35 Image no.: 1

Tilt angle (Screen-3): 50 Image no.: 4

Data Sheet,

Participant Details

Participant no.: 25 Date: 29/11/18 Time: 13:00

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☐ M ☑ F

Age: ☑ 18-24yrs ☐ 25-29yrs ☐ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: / no. of Children in School: /

no. of girls : / no. of girls in school / eye test mistakes: /

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 10 Image no.: 3

Tilt angle (Screen-3): 12 Image no.: 2

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 26 Image no.: 4

Tilt angle (Screen-3): 35 Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 39 Image no.: 5

Tilt angle (Screen-3): 50 Image no.: 6

Data Sheet,

Participant Details

Participant no.: 26 Date: 28,11 2017 Time: 1.10

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☒ No Gender: ☒ M ☐ F

Age: ☐ 18-24yrs ☐ 25-29yrs ☒ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: 0 no. of Children in School: 0

no. of girls : 0 no. of girls in school 0 eye test mistakes:_______

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): X Image no.: 3

Tilt angle (Screen-3): 12 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 30 Image no.: 5

Tilt angle (Screen-3): 34 Image no.: 1

Case-3

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 30° Image no.: 4

Tilt angle (Screen-3): 40 Image no.: 2

Data Sheet,

Participant Details

Participant no.: 27 Date: 29/11/17 Time: 13:00

Conservative environment background (Middle Eastern/ Muslim): ☑ Yes ☐ No Gender: ☑ M ☐ F

Age: ☐ 18-24yrs ☐ 25-29yrs ☑ 30-34yrs ☐ 35-39yrs ☐ 40+ yrs

no. of Children: 3 no. of Children in School: 2

no. of girls : 0 no. of girls in school 0 eye test mistakes: ______

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 1

Tilt angle (Screen-2): 8 Image no.: 1

Tilt angle (Screen-3): 11 Image no.: 3

Case-2

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 22 Image no.: 2

Tilt angle (Screen-3): 37 Image no.: 4

Case-3

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 31 Image no.: 6

Tilt angle (Screen-3): 60 Image no.: 5

Data Sheet,

Participant Details

Participant no.: 28 Date: 29/11/17 Time: 14:25

Conservative environment background (Middle Eastern/ Muslim): ☐ Yes ☐ No Gender: ☐ M ☐ F

Age: ☐ 18-24yrs ☐ 25-29yrs ☐ 30-34yrs ☑ 35-39yrs ☐ 40+ yrs

no. of Children: 3 no. of Children in School: 3

no. of girls : 1 no. of girls in school 1 eye test mistakes: ✓

Recorded Results

Case-1

Tilt angle (Screen-1): X Image no.: 6

Tilt angle (Screen-2): 11 Image no.: 5

Tilt angle (Screen-3): 17 Image no.: 6

Case-2

Tilt angle (Screen-1): X Image no.: 2

Tilt angle (Screen-2): 30 Image no.: 3

Tilt angle (Screen-3): 31 Image no.: 2

Case-3

Tilt angle (Screen-1): x Image no.: 1

Tilt angle (Screen-2): 40 Image no.: 4

Tilt angle (Screen-3): 44 Image no.: 1

Appendix F: Permission to use KAY pictures.

Re: Using Kay pictures in a study

Ahmad Kotbi

Sun 10/06/2018 02:45

Sent Items

To: Kay Pictures <contact@kaypictures.co.uk>;

1 attachments (5 MB)

chapter3.pdf;

Dear Hazel,

Sorry for my late response, I was conducting the experiment and I wrote it up in my chapters so I could send it to you to show you some details of what I am doing.

I used Kay pictures instead of Letters because I did not want subjects to use their imagination in guessing the letter that they see even if they saw part of it. I made sure that subjects have not seen any of the KAY pictured before, and also not having an optometry background as they might be familiar with KAY pictures.

I am placing pictures with size 6/24 and place them at 6m away. My argument that a subject with a normal vision can easily identify a KAY picture size 6/24 from 6m away, and if the subject could not identify the picture then the screen was the reason and it succeeded in lowering visibility and thus provide privacy.

Please find attached two chapters that KAY pictures were mentioned in the thesis (they were too big to be sent in one message, I will send one now and the other will follow). Currently I am just writing my thesis. when I use KAY pictures in papers for publishing, I will send a copy to you.

Please do not hesitate to contact me for any more information.

Best Regards,
Ahmad

From: Kay Pictures <contact@kaypictures.co.uk>
Sent: 21 May 2018 12:53:39
To: Ahmad Kotbi
Subject: Re: Using Kay pictures in a study

Dear Ahmad,

Thanks for your email. Your study sounds very interesting.

We are intrigued why you decided to use pictures rather than letter vision test to indicate the window visibility level? Also, what is your visual acuity criteria for deciding if the window has sufficient privacy?

We are happy in principle for you to use images of our test in your thesis and any publications, but we would like to see a copy of the experiment samples you use prior to publication.

Please can you email this to us, and we will respond very quickly. I can't foresee any issue.

Best wishes

Hazel Kay

Kay Pictures Ltd
Unit 39 (2nd Floor), Silk Mill Business Park
Brook Street
Tring
HP23 5EF
Tel: + 44 (0) 1442 823507
Fax: + 44 (0) 8701 236191
Email: contact@kaypictures.co.uk
Web: http://www.kaypictures.co.uk
Web: http://www.kayfunpatch.com
Twitter: http://twitter.com/kaypictures
Twitter: http://twitter.com/kayfunpatch

On 18 May 2018, at 17:00, Ahmad Kotbi <KotbiAG@cardiff.ac.uk> wrote:

> Dear Kay pictures representative,
>
> I am a PhD candidate in Architecture in the Welsh school of Architecture in Cardiff University. My project is about windows in buildings and maintaining privacy.
>
> I am planning to conduct an experiment regarding testing privacy levels through windows in buildings. I have bought a set of crowded Kay pictures from your website, I am planning to use them to test human subjects whether they can recognize the pictures when looking through different types of windows to test which window succeeded to maintain privacy by preventing subjects from recognizing the kay picture behind it.
> I would like please to ask for your permission to use them in my experiment and present samples of them in my thesis and maybe published papers (with credits to Kaypictures).
>
> Please do not hesitate to ask for any more information.
>
> Best Regards,
> Ahmad

Re: Using Kay pictures in a study

Kay Pictures <contact@kaypictures.co.uk>

Sat 23/06/2018 08:52

To: Ahmad Kotbi <KotbiAG@cardiff.ac.uk>;

Dear Ahmad,

Thank you for the additional information. I was very interested to learn about the problem itself and the way you plan to investigate the effectiveness of any solutions.
We spent some time discussing how the windows in the school might be obscured and what level of opacity would be considered sufficient.
I hope my late reply hasn't impacted on your experiments. As I mentioned in my first email, we have no problem with you using the Kay Picture Test optotypes in the way you have described and in publishing samples of your experiments that show the optotypes.

I hope you will send your conclusions in due course, as we are keen to know more.

Best wishes
Hazel

Kay Pictures Ltd
Unit 39 (2nd Floor), Silk Mill Business Park
Brook Street
Tring
HP23 5EF
Tel: + 44 (0) 1442 823507
Fax: + 44 (0) 8701 236191
Email: contact@kaypictures.co.uk
Web: http://www.kaypictures.co.uk
Web: http://www.kayfunpatch.com
Twitter: http://twitter.com/kaypictures
Twitter: http://twitter.com/kayfunpatch

On 10 Jun 2018, at 02:50, Ahmad Kotbi <KotbiAG@cardiff.ac.uk> wrote:

> Dear Hazel,
>
> Following my previous email. Please find attached the second chapter
>
> Best Regards,
> Ahmad
>
> ---
>
> **From:** Kay Pictures <contact@kaypictures.co.uk>
> **Sent:** 21 May 2018 12:53:39
> **To:** Ahmad Kotbi
> **Subject:** Re: Using Kay pictures in a study
>
> Dear Ahmad,
>
> Thanks for your email. Your study sounds very interesting.

We are intrigued why you decided to use pictures rather than letter vision test to indicate the window visibility level? Also, what is your visual acuity criteria for deciding if the window has sufficient privacy?

We are happy in principle for you to use images of our test in your thesis and any publications, but we would like to see a copy of the experiment samples you use prior to publication.

Please can you email this to us, and we will respond very quickly. I can’t foresee any issue.

Best wishes
Hazel Kay

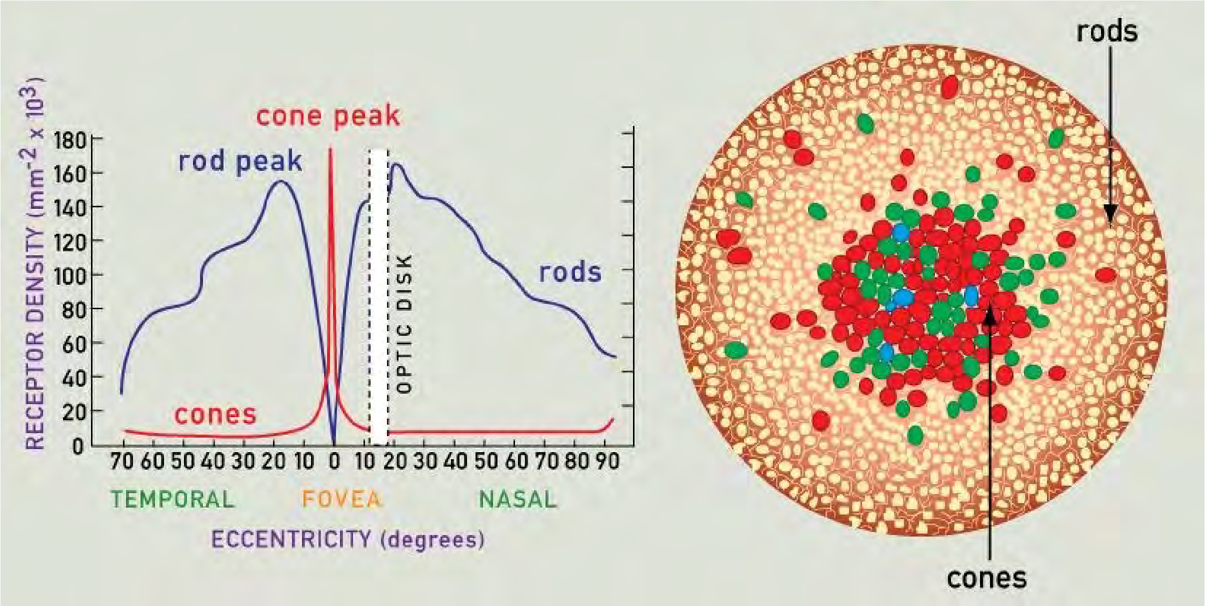
Kay Pictures Ltd
Unit 39 (2nd Floor), Silk Mill Business Park
Brook Street
Tring
HP23 5EF
Tel: + 44 (0) 1442 823507
Fax: + 44 (0) 8701 236191
Email: contact@kaypictures.co.uk
Web: http://www.kaypictures.co.uk
Web: http://www.kayfunpatch.com
Twitter: http://twitter.com/kaypictures
Twitter: http://twitter.com/kayfunpatch

On 18 May 2018, at 17:00, Ahmad Kotbi <KotbiAG@cardiff.ac.uk> wrote:

> Dear Kay pictures representative,
>
> I am a PhD candidate in Architecture in the Welsh school of Architecture in Cardiff University. My project is about windows in buildings and maintaining privacy.
>
> I am planning to conduct an experiment regarding testing privacy levels through windows in buildings. I have bought a set of crowded Kay pictures from your website, I am planning to use them to test human subjects whether they can recognize the pictures when looking through different types of windows to test which window succeeded to maintain privacy by preventing subjects from recognizing the kay picture behind it.
> I would like please to ask for your permission to use them in my experiment and present samples of them in my thesis and maybe published papers (with credits to Kaypictures).
>
> Please do not hesitate to ask for any more information.
>
> Best Regards,
> Ahmad

<Chapter10.pdf>

Appendix G: Licensed images.


cone peak
rod peak
RECEPTOR DENSITY (mm^{-2} x 10^3)
180
160
140
120
100
80
60
40
20
0
cones
rods
OPTIC DISK
70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90
TEMPORAL
FOVEA
NASAL
ECCENTRICITY (degrees)
rods
cones

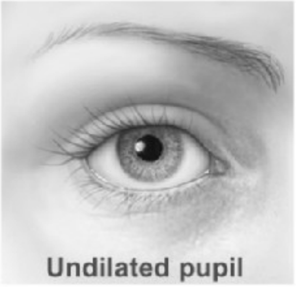
   - "Work" means the literary and/or artistic work offered under the terms of this License including without limitation any production in the literary, scientific and artistic domain, whatever may be the mode or form of its expression including digital form, such as a book, pamphlet and other writing; a lecture, address, sermon or other work of the same nature; a dramatic or dramatico-musical work; a choreographic work or entertainment in dumb show; a musical composition with or without words; a cinematographic work to which are assimilated works expressed by a process analogous to cinematography; a work of drawing, painting, architecture, sculpture, engraving or lithography; a photographic work to which are assimilated works expressed by a process analogous to photography; a work of applied art; an illustration, map, plan, sketch or three-dimensional work relative to geography, topography, architecture or science; a performance; a broadcast; a phonogram; a compilation of data to the extent it is protected as a copyrightable work; or a work performed by a variety or circus performer to the extent it is not otherwise considered a literary or artistic work.
   - "You" means an individual or entity exercising rights under this License who has not previously violated the terms of this License with respect to the Work, or who has received express permission from the Licensor to exercise rights under this License despite a previous violation.
   - "Publicly Perform" means to perform public recitations of the Work and to communicate to the public those public recitations, by any means or process, including by wire or wireless means or public digital performances; to make available to the public Works in such a way that members of the public may access these Works from a place and at a place individually chosen by them; to perform the Work to the public by any means or process and the communication to the public of the performances of the Work, including by public digital performance; to broadcast and rebroadcast the Work by any means including signs, sounds or images.
   - "Reproduce" means to make copies of the Work by any means including without limitation by sound or visual recordings and the right of fixation and reproducing fixations of the Work, including storage of a protected performance or phonogram in digital form or other electronic medium.
2. Fair Dealing Rights. Nothing in this License is intended to reduce, limit, or restrict any uses free from copyright or rights arising from limitations or exceptions that are provided for in connection with the copyright protection under copyright law or other applicable laws.
3. License Grant. Subject to the terms and conditions of this License, Licensor hereby grants You a worldwide, royalty-free, non-exclusive, perpetual (for the duration of the applicable copyright) license to exercise the rights in the Work as stated below:
   - to Reproduce the Work, to incorporate the Work into one or more Collections, and to Reproduce the Work as incorporated in the Collections; and,
   - to Distribute and Publicly Perform the Work including as incorporated in Collections.

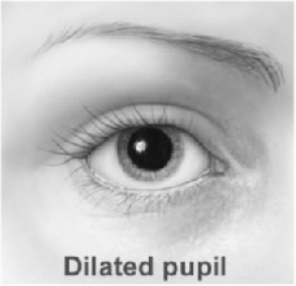
   The above rights may be exercised in all media and formats whether now known or hereafter devised. The above rights include the right to make such modifications as are technically necessary to exercise the rights in other media and formats, but otherwise you have no rights to make Adaptations. Subject to 8(f), all rights not expressly granted by Licensor are hereby reserved, including but not limited to the rights set forth in Section 4(d).
4. Restrictions. The license granted in Section 3 above is expressly made subject to and limited by the following restrictions:
   - You may Distribute or Publicly Perform the Work only under the terms of this License. You must include a copy of, or the Uniform Resource Identifier (URI) for, this License with every copy of the Work You Distribute or Publicly Perform. You may not offer or impose any terms on the Work that restrict the terms of this License or the ability of the recipient of the Work to exercise the rights granted to that recipient under the terms of the License. You may not sublicense the Work. You must keep intact all notices that refer to this License and to the disclaimer of warranties with every copy of the Work You Distribute or Publicly Perform. When You Distribute or Publicly Perform the Work, You may not impose any effective technological measures on the Work that restrict the ability of a recipient of the Work from You to exercise the rights granted to that recipient under the terms of the License. This Section 4(a) applies to the Work as incorporated in a Collection, but this does not require the Collection apart from the Work itself to be made subject to the terms of this License. If You create a Collection, upon notice from any Licensor You must, to the extent practicable, remove from the Collection any credit as required by Section 4(c), as requested.

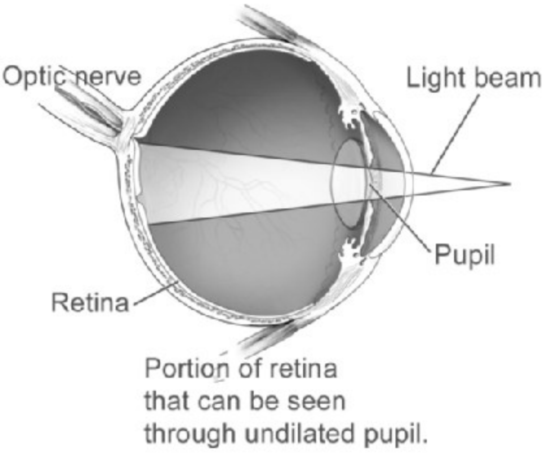
- You may not exercise any of the rights granted to You in Section 3 above in any manner that is primarily intended for or directed toward commercial advantage or private monetary compensation. The exchange of the Work for other copyrighted works by means of digital file-sharing or otherwise shall not be considered to be intended for or directed toward commercial advantage or private monetary compensation, provided there is no payment of any monetary compensation in connection with the exchange of copyrighted works.
- If You Distribute, or Publicly Perform the Work or Collections, You must, unless a request has been made pursuant to Section 4(a), keep intact all copyright notices for the Work and provide, reasonable to the medium or means You are utilizing: (i) the name of the Original Author (or pseudonym, if applicable) if supplied, and/or if the Original Author and/or Licensor designate another party or parties (e.g., a sponsor institute, publishing entity, journal) for attribution ("Attribution Parties") in Licensor's copyright notice, terms of service or by other reasonable means, the name of such party or parties; (ii) the title of the Work if supplied; (iii) to the extent reasonably practicable, the URI, if any, that Licensor specifies to be associated with the Work, unless such URI does not refer to the copyright notice or licensing information for the Work. The credit required by this Section 4(c) may be implemented in any reasonable manner; provided, however, that in the case of a Collection, at a minimum such credit will appear, if a credit for all contributing authors of Collection appears, then as part of these credits and in a manner at least as prominent as the credits for the other contributing authors. For the avoidance of doubt, You may only use the credit required by this Section for the purpose of attribution in the manner set out above and, by exercising Your rights under this License, You may not implicitly or explicitly assert or imply any connection with, sponsorship or endorsement by the Original Author, Licensor and/or Attribution Parties, as appropriate, of You or Your use of the Work, without the separate, express prior written permission of the Original Author, Licensor and/or Attribution Parties.
- For the avoidance of doubt:
  i. Non-waivable Compulsory License Schemes. In those jurisdictions in which the right to collect royalties through any statutory or compulsory licensing scheme cannot be waived, the Licensor reserves the exclusive right to collect such royalties for any exercise by You of the rights granted under this License;
  ii. Waivable Compulsory License Schemes. In those jurisdictions in which the right to collect royalties through any statutory or compulsory licensing scheme can be waived, the Licensor reserves the exclusive right to collect such royalties for any exercise by You of the rights granted under this License if Your exercise of such rights is for a purpose or use which is otherwise than noncommercial as permitted under Section 4(b) and otherwise waives the right to collect royalties through any statutory or compulsory licensing scheme; and,
  iii. Voluntary License Schemes. The Licensor reserves the right to collect royalties, whether individually or, in the event that the Licensor is a member of a collecting society that administers voluntary licensing schemes, via that society, from any exercise by You of the rights granted under this License that is for a purpose or use which is otherwise than noncommercial as permitted under Section 4(b).
- Except as otherwise agreed in writing by the Licensor or as may be otherwise permitted by applicable law, if You Reproduce, Distribute or Publicly Perform the Work either by itself or as part of any Collections, You must not distort, mutilate, modify or take other derogatory action in relation to the Work which would be prejudicial to the Original Author's honor or reputation.

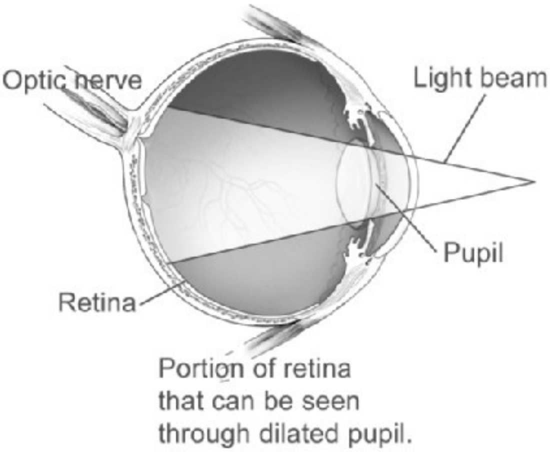
5. Representations, Warranties and Disclaimer
   UNLESS OTHERWISE MUTUALLY AGREED BY THE PARTIES IN WRITING, LICENSOR OFFERS THE WORK AS-IS AND MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND CONCERNING THE WORK, EXPRESS, IMPLIED, STATUTORY OR OTHERWISE, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF TITLE, MERCHANTIBILITY, FITNESS FOR A PARTICULAR PURPOSE, NONINFRINGEMENT, OR THE ABSENCE OF LATENT OR OTHER DEFECTS, ACCURACY, OR THE PRESENCE OF ABSENCE OF ERRORS, WHETHER OR NOT DISCOVERABLE. SOME JURISDICTIONS DO NOT ALLOW THE EXCLUSION OF IMPLIED WARRANTIES, SO SUCH EXCLUSION MAY NOT APPLY TO YOU.
6. Limitation on Liability. EXCEPT TO THE EXTENT REQUIRED BY APPLICABLE LAW, IN NO EVENT WILL LICENSOR BE LIABLE TO YOU ON ANY LEGAL THEORY FOR ANY SPECIAL, INCIDENTAL, CONSEQUENTIAL, PUNITIVE OR EXEMPLARY DAMAGES ARISING OUT OF THIS LICENSE OR THE USE OF THE WORK, EVEN IF LICENSOR HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

7. Termination
    - This License and the rights granted hereunder will terminate automatically upon any breach by You of the terms of this License. Individuals or entities who have received Collections from You under this License, however, will not have their licenses terminated provided such individuals or entities remain in full compliance with those licenses. Sections 1, 2, 5, 6, 7, and 8 will survive any termination of this License.
    - Subject to the above terms and conditions, the license granted here is perpetual (for the duration of the applicable copyright in the Work). Notwithstanding the above, Licensor reserves the right to release the Work under different license terms or to stop distributing the Work at any time; provided, however that any such election will not serve to withdraw this License (or any other license that has been, or is required to be, granted under the terms of this License), and this License will continue in full force and effect unless terminated as stated above.
8. Miscellaneous
    - Each time You Distribute or Publicly Perform the Work or a Collection, the Licensor offers to the recipient a license to the Work on the same terms and conditions as the license granted to You under this License.
    - If any provision of this License is invalid or unenforceable under applicable law, it shall not affect the validity or enforceability of the remainder of the terms of this License, and without further action by the parties to this agreement, such provision shall be reformed to the minimum extent necessary to make such provision valid and enforceable.
    - No term or provision of this License shall be deemed waived and no breach consented to unless such waiver or consent shall be in writing and signed by the party to be charged with such waiver or consent.
    - This License constitutes the entire agreement between the parties with respect to the Work licensed here. There are no understandings, agreements or representations with respect to the Work not specified here. Licensor shall not be bound by any additional provisions that may appear in any communication from You. This License may not be modified without the mutual written agreement of the Licensor and You.
    - The rights granted under, and the subject matter referenced, in this License were drafted utilizing the terminology of the Berne Convention for the Protection of Literary and Artistic Works (as amended on September 28, 1979), the Rome Convention of 1961, the WIPO Copyright Treaty of 1996, the WIPO Performances and Phonograms Treaty of 1996 and the Universal Copyright Convention (as revised on July 24, 1971). These rights and subject matter take effect in the relevant jurisdiction in which the License terms are sought to be enforced according to the corresponding provisions of the implementation of those treaty provisions in the applicable national law. If the standard suite of rights granted under applicable copyright law includes additional rights not granted under this License, such additional rights are deemed to be included in the License; this License is not intended to restrict the license of any rights under applicable law.









Use of Images

The NEI Photos and Images Catalog is provided as a source of free visuals. Permission is granted to use these items for educational, news media or research purposes, provided the source for each image is credited. The NEI Photos and Images catalog may not be used to promote or endorse commercial products or services. Use by non-profit organizations in connection with fundraising or product sales is considered commercial use.

Permission to use NEI website graphics found any place other than the NEI Photos and Images catalog is granted on a case-by-case basis. Some are public domain, some are created by NEI contractors, some are copyrighted and some are used by NEI with specific permission granted by the owner. Therefore, the logos, photos and illustrations found on the NEI website should not be reused without permission.

For information about the copyright holders of a given photo or illustration on the NEI website; how the owners can be contacted; and what, if any, use those owners allow of their material; please contact the NEI Website Manager (link sends e-mail) and provide the URL, file name, and intended use.

Granting the right to use a graphic from the website does not explicitly or implicitly convey NEI's endorsement of the site where it is used.

Appendix H: Method of presenting results of light simulation.

Presenting results of daylight simulation

The results of experiments related to daylight simulation are represented in charts and tables. The results of average illuminance experiments for each studied parameter are represented in tables, one table for each orientation. Each table is listing a matrix of average illuminance values covering the following:

- Average illuminance values for each zone of the three zones: (Near, Mid and Far), named according to the distance from the wall with openings.
- Average illuminance values for each specific time (7:00, 10:00 and 13:00) of summer and winter solstices and the autumn and spring equinoxes.
- Average illuminance values for each case of the studies cases of that parameter (e.g. perforation percentage has 9 cases: 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10%)

The cells of the average illuminance values table are highlighted to show the results easily. Black cells represent results that have illuminance levels more than $1000lx$, grey cells represents results that have illuminance between $500lx$ and $999lx$, finally, light grey cells represents results that have illuminance between $300lx$ and $499lx$. These ranges aimed to ease comparisons between different timings and zones. Results parameters that showed significant different between each variation, have helped also to produce tables to indicate recommended values for the tested parameter.

The results of Daylight Availability "DAv" experiments for each studied parameter are represented in charts and tables. The simulation results give each sensor point on the grid (of the 345 sensor points) a value of DAv from 0–100%, this percentage is calculated using this equation:

$$DAv = \frac{Occupied\ time\ achieving\ the\ target\ illuminance\ (300lx)}{Total\ occupied\ time} \times 100$$

Each sensor point then would have a value of DAv, then it is represented on the plan of the classroom as a grid of squares, one square for each sensor points in order to show the distribution of DAv on the plan. Each square is coloured according to its DAv value using a coloured scale that ranges from Blue (0%) to Red (100%). Squares with magenta colour indicate the 'Overlit' areas, which have received received at least $3000lx$ (10 times the target illuminance threshold) for at least 5% of the occupancy time. Figure: 1 is an example of a grid of DAv to explain how the grid is resulted out of the values of each sensor point and the colour scale. When studying each parameter, a table for each orientation illustrates a DAv grid for each studied case. In order to simplify comparisons between results of each orientation, all grids in all tables are superimposed on the classroom plans where windows are always on the upper side of the grid regardless of the studied façade orientation in that table.

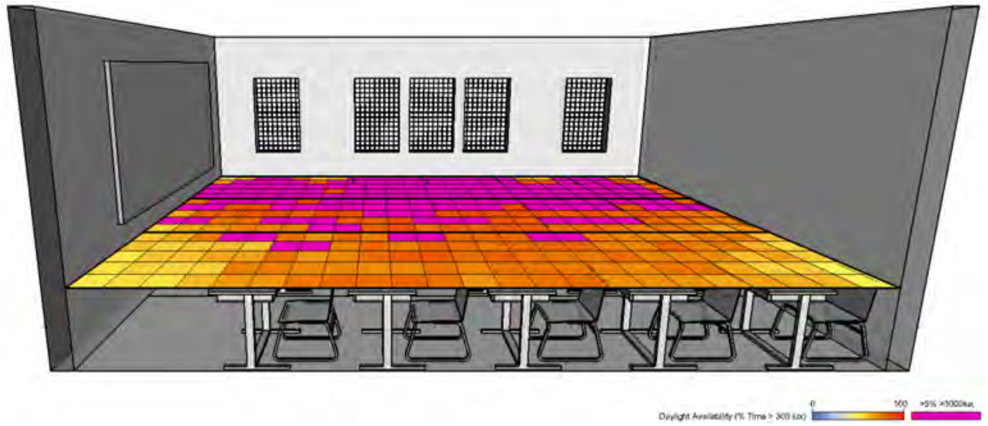


Figure 1: An example of the analysis grid resulted from the simulation for Daylight Availability.

After that, the total area of Overlit squares is calculated, and total area of squares that failed to achieve at least 50% DAv is calculated and considered as 'Partly lit area', and total area of squares that achieve 50% or more DAv without being categorized as 'Overlit area' is calculated and considered as 'Daylit area', in other words Daylit area is all the remain areas that were not categorized as neither Overlit or Partlylit areas because the total has to be 100% (Table: 1).

Table 1: Representing DAv resulted areas in a graph.

Area	**Description**
Overlit	Receiving $3000lx$ or more for at least 5% of occupied time
Partly lit	Receiving $300lx$ or less for less than 50% of occupied time
Daylit	All remain areas

These data is then illustrated in bar charts. Four charts for every parameter, one for each one of the four main orientations. In every chart, the studied cases of that parameter on that orientation is compared, the case providing the biggest 'Daylit area' would give the best value for that parameter. All of daylight simulation experiments in this research were presented using the same methods discussed above.