A PERFORMANCE-DRIVEN DESIGN MODEL OF TERRITORIAL ADAPTIVE BUILDING SKIN (TABS) FOR DAYLIGHTING PERFORMANCE OPTIMISATION IN OFFICE BUILDINGS IN EGYPT

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Declaration

I certify that this thesis constitutes my own work/investigation, except where otherwise stated; other sources are acknowledged by explicit references.

I declare that this thesis describes original work that has not previously been presented for the award of any other degree of any institution.

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Abstract

Building skins have become an expression of the unique forces that are defining their context, either tangible such as weather conditions or intangible, such as social and cultural heritage. Egypt is currently experiencing excessive importation of Western technology and design concepts in architecture due to the desire of rapid development accompanied by social and political changes, threatening its culture and causing an identity crisis. Nowadays, office building design in Egypt adopts the design principles of fully glazed western buildings that were built for different environmental conditions and cultures. The negligence towards local climates and heritage, especially in a country with a hot desert climate and a rich culture like Egypt, resulted in unsatisfactory building performance. The satisfaction of occupants with their work environment is important, both regarding well-being and productivity. Therefore, ensuring acceptable environmental conditions must be achieved along with the need to include sustainability–performance related features within any design. For office buildings, two of the primary energy demands are associated with artificial lighting and thermal comfort. Therefore, any approach that attempts to reduce excessive solar gains while enhancing daylight availability can be considered as a sustainable design strategy. Building skin is the key moderator between the internal and external environments. Historically, the environmental control through façade was static. However, recent technological advances enabled building skins to dynamically react to the external environment with the aim of enhancing internal conditions. Territorial adaptive building skin (TABS) is one example of this new types of building skins. The methodology proposed in this research employed a parametric modelling, building performance simulation and Genetic Algorithm tools for optimising the performance of TABS for a south facing office space in Cairo, Egypt, based on predefined criteria, at twelve different times during the year. The TABS integrated two subsystems: (1) Shading: a dynamic geometric pattern inspired by the Egyptian solar screen 'Mashrabia'; (2) Daylight redirecting: active horizontal louver system, to harness the advantages of both strategies. The results showed that TABS achieved the required performance at all the twelve examined times using it's predefined capabilities regarding six performance indicators (task points illuminance levels, illuminance contrast ratio, daylight distribution, daylight penetration depth, solar gain and glare). Moreover, the TABS performance surpassed the performance of the fully glazed base case and two other optimised traditional façade solutions at all examined times. Furthermore, in this study, each physical appearance of the optimised TABS solutions was an authentic representation of the Mashrabiya form, which continually achieved to represent the Egyptian cultural identity. An empirical validation process was conducted using 3D printed physical models of optimised TABS in an artificial sky facility. Acceptable agreement between the validation and simulation models regarding illuminance values was achieved. Finally, the findings proved that TABS could be a complex geometry that satisfies the ornamental desires of the contemporary architecture and address the concerns over building performance and user comfort.

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Chapter One

1. Introduction

Architectural practice is in a continuous state of evolution and has become an increasingly more complex task (Dewidar, Mohamed et al. 2013), due to growing demands to satisfy the current dynamic environmental, societal, cultural and economic performance requirements (Loonen, Trčka et al. 2013). In the light of this, the building's form becomes an expression of the unique forces that are defining the surrounding context of the building. These forces can be either tangible, such as the weather conditions (i.e. wind, solar radiation) or intangible, such as the forces arising from cultural and regional heritage (Pellitteri, Concialdi et al. 2008). Therefore, the building's contextual performance can be seen as the adequate consideration of both tangible and intangible forces that are representing the building's local context, with the aim of achieving particular objectives, such as energy efficiency or expressing its cultural influence.

Historically, architecture has not always considered the ambient environment as an adversarial constraint in the design process. Many cases of ancient vernacular architecture show good examples of how building design can deliberately take advantage of available conditions in the exterior environment (Zhai and Previtali 2010), in addition to reflecting their times, cultural identity (LeDoux 1991). Building skins, in the form of the exterior walls, were the subject of ornamentation as a means to express cultural, social and religious identity and the wealth and power of nations, for example in the frescoed Greek and Chinese temples and Islamic palaces and mosques. Thus, building skins have been a central focus throughout history and became a crucial element in architecture (Schittich, Lang et al. 2006). However, the building skin's primary function was as part of the load-bearing structure of the building, in addition, to sheltering the building occupants from external climate conditions and providing security and privacy. Before the advent of air conditioning, architects needed to give considerable attention to site conditions and passive design strategies to create comfortable built environments. For example, orienting buildings to capture prevailing winds, and offsetting windows deep into exterior walls that resulted in overhangs to block out the sun during the summer while allowing the low winter sun to enter. These strategies allowed the building to be naturally heated and cooled. (Murray 2009).

During the 20th century developments in HVAC systems and artificial lighting were able to meet indoor comfort needs (Heiselberg 2007), and were coupled with advances in construction technologies and materials to create a new trend of architectural forms and aesthetics, ‘the International Style’, which characterised by fully glazed geometric forms and unornamented facades. (McMullin 2016). This approach resulted in one united style, whereby a modern office building in London, New York, or in Cairo could look similar regardless of variations in local climatic conditions or cultural backgrounds (see Figure 1.1).

a) Egypt b) UK c) USA d) Hong Kong

Figure 1.1 Modern office buildings

This approach raises many concerns, such as the building skin losing its role as a climatic moderator for energy and comfort. Energy consumption in buildings sector exceeded the energy use in other sectors such as the industrial and transportation sectors (Pérez-Lombard, Ortiz et al. 2008). Moreover, neither variations in climatic conditions nor the cultural identity of a region are considered. Building envelope system performance of non-residential buildings have a significant impact on the energy demand required for building operation. Efficient sun protection and daylight design strategies can contribute to reducing the cooling and artificial lighting demands respectively (Fuchs, Hegger et al. 2008).

In response, the international community has given more attention to building energy efficiency and occupant comfort, accompanied by an emerging demand to integrate sustainability–related performance approaches, such as daylighting and energy, within the early design stages (Lagios, Niemasz et al. 2010). However, the utilisation of the naturally available daylight in the office buildings is viewed as an underexploited resource (Mardaljevic, Waskett et al. 2015). Daylight brings many benefits to buildings and their occupants - replacing an artificial light with natural light can save energy and reduce a building’s environmental impact (Alshoubaki, Rawashdeh et al. 2016), while giving people access to daylight can bring positive benefits regarding their psychological and physical well-being (El Sheikh 2011). Natural lighting is utilised to improve the perceived productivity of office workers while enhancing the indoor environmental (Ander 2003). For office buildings, the primary energy consumed by electric lighting is significant, in the total building energy usage, and much of the general and task lighting needed in offices could be met by natural light. Consequently, daylight design strategies for offices can provide energy savings and a healthy, productive environment, but a balance must be achieved to avoid excessive solar gain and visual glare discomfort (Hee, Alghoul et al. 2015, Mardaljevic, Waskett et al. 2015). This balance is particularly difficult to achieve for offices in hot, dry climates, such as that experienced in Egypt (Sabry, Sherif et al. 2014). Such climates are characterised by clear, bright sky and high levels of direct solar radiation (Peel, Finlayson et al. 2007). The available outdoor daylight resource is great, but its transmission into buildings must be carefully controlled by the building envelope to prevent extreme heat gain or glare (Sherif, El-Zafarany et al. 2012). Despite this, most contemporary office building designs in Egypt are following the International Style with large glass curtain walls and only a few solar/daylight control options, which is clearly not a sustainable solution. Also, such façades do not represent the traditional architecture and cultural identity of Egypt. In the light of that, reduce energy demands using solar/daylight control, is a good starting point to look back at the historical ways of solving these problems through traditional design approaches.

Traditional building envelopes in Egypt developed many shading strategies, such as the famous solar screen “mashrabia”, which is inspired by Islamic patterns, and other shading devices such as louver systems and overhangs, which achieved a reasonable success based on the technology and materials available at that time (Mohamed 2010). However, all these systems were designed as static systems to act as external passive shelters with fixed thermophysical and optical properties and mainly for protecting occupants from an external environment which was changing over time, and this also applies to occupancy and comfort preferences, (Konstantoglou and Tsangrassoulis 2016) (Loonen 2010).

Building façades can play a crucial role as a responsive element, and climate adaptive building shells, which are active controllers of the interchanges occurring between the external and internal environment, can be an important method to save energy (Loonen 2010). The concept of adaptive architecture is meant on the relationship between the changing needs and the capability of a building to satisfy them in a varying environment. (Turrin, Von Buelow et al. 2011). Thus, making an efficient building envelope that interacts with its surrounding environment is one of the most important objectives for architects today (Etman, Tolba et al. 2013).

The current high-performance envelopes have led to the emergence of advanced assemblies coupling real-time environmental response, innovative materials, and powerful automation with embedded microprocessors, wireless sensors, and actuators. This application has fundamentally transformed the way in which architects address building design with a change in importance from form to performance, from structure to envelope (Hensel and Menges 2006), leading to the opportunity to achieve comfortable, energy efficient and well-daylit office interiors by integrating a shading system into the façade that dynamically controls the building envelope configurations (El Sheikh and Kensek 2011), and has the ability to actively moderate the exchange of energy across a building's skin in response to the prevailing meteorological conditions and occupants' preferences (Loonen, Trčka et al. 2013). Adaptivity in architecture as a concept has been given several names, such as interactive (Fox and Yeh 1999), dynamic (Lollini, Danza et al. 2010), kinetic (Fox 2003), and Climate Adaptive Building Shells (CABS) (Loonen 2010), and responsive (Kirkegaard and Foged 2011).

To this extent, the term used to describe building envelopes that are able to change their configuration or properties due to the surrounding climate and different demands are many.

However, most of these approaches are more concerned with the tangible forces (i.e. wind, solar radiation) or the capability of the building envelopes to respond to the meteorological conditions and occupants' preferences. There is less focus on addressing intangible forces that arise from cultural and regional heritage and addressing cultural identities.

For this thesis, the following definition have been chosen as a general basis for defining a (TABS). "A system that can improve overall building performance by adequately addressing the unique tangible and intangible forces that are defining the surrounding context of the building, by utilising the traditional pattern and local adaptation strategies as a source of inspiration for designing a TABS that is capable of changing its functions, or behaviour over time in reply to changing performance requirements and variable boundary conditions. By doing this, the building skin effectively seeks to improve overall building performance along with reflecting its local identity in an innovative way". Thus, the idea of performance is discussed here based on the context of the specific project and can be understood in a very broad sense, reaching fields like economy, spatial planning, society, culture or technology (Kolarevic 2004).

The new computational tools available to architects and engineers can be used as more than optimisation tools for already established architectural forms. Combining these tools with parametric modelling can lead to an active integration of the analysis in the development of architectural form in the early stages of design (Oxman 2008).

With the emergence of the digital age, the concept of façade ornament has made a comeback in design (Gleiter 2012). Nowadays, the world of patterns is one of the growing fields of architecture; many designers are creating a combination of patterns with software, sensors, and robotics, whether their focus is visual appearance or sustainable performance. However, the justification for this approach was established to achieve many objectives, such as economy of means, responsive towards the natural environment, and the satisfaction of human needs and desires (Sanchez-del-Valle 2005). However, the current utilisation of advanced computational tools is more focused on the aesthetical qualities of the building forms rather than addressing real architectural issues regarding building performance, consequently resulting in a final product that falls short out their initial objectives.

Therefore, one of the contemporary challenges facing architects is to examine how to apply façade patterns in meaningful and functional ways and how these advanced computational tools can be used to address real architectural issues beyond the flashy image of the final product as a way to improve building performance and maintain cultural identity.

1.1. Problem Definition and Typology

According to Garry Martin, Oil wealth, social and political alterations along with the ambition of fast development in the Middle East has led to the importation of Western technology, and building design, that were developed for different culture, resulted in identity crises which can be seen in architectural design (Martin 2008 referenced by Referenced by Ghiasvand, J., et al. 2008).

During the last decade, this identity crises reached the Egyptian context. The new office buildings in Egypt started mimicking the fully glazed Western buildings that were designed for different environmental conditions and cultural identities. Resulted, in both cultural and economic crises in a country already suffering from energy shortages accompanied by a significant increase in energy demands over the next decade as it aims to develop economically. Therefore, energy savings is the urgent target of the Egyptian government (Sakr and Sena 2017).

Building skins are playing a crucial role in protecting the building from external environmental elements, such as heat, cold, noise and air contamination. Moreover, they play a significant role in delivering natural daylight to indoor spaces (Brotas and Rusovan 2013). Furthermore, building skins are considered as the architect's statement that represents the connection between culture and architecture.

Figure 1.2 A modern office building in Egypt

Daylight is capable of replacing a significant part of the artificial lighting used in office buildings. The expansion of office buildings that utilised large-scale glazing in the 19th century highlighted the importance of the essential need to restore the efficient use of daylighting in office buildings which nearly became a lost art with the emergence of electric lighting to support sustainable buildings. Many cases of ancient vernacular architecture show good examples of how building design can deliberately take advantage of available conditions in the exterior environment (Zhai and Previtali 2010).

Daylight strategies are a fundamental factor in office building design aiming at improving user productivity and indoor environmental quality while cutting the building's energy consumption (artificial lighting, chilling and heating loads, etc.) (Ander 2003).

Considering the rich heritage of Egyptian architecture when developing new office buildings in Egypt is essential. In traditional architecture, much attention was given to passive climate design to achieve the most of the environment. However, with the introduction of modern architecture a major shortcoming of such a style is the negligence towards local climates and heritage, especially in a country like Egypt. The office building envelope solution in most contemporary office buildings in Egypt do little to bring down energy requirement as they tend to use the International Style with large glass curtain walls - see Figure 1.2. While fully glazed facades offer excellent views and offer great quantities of natural illumination, fully glazed office buildings in Egypt are experiencing inadequate daylighting levels during the working hours in the daytime. In terms of illumination levels on task planes (quantity) the values are out of the recommended range, give an uneven distribution of daylighting and a high risk of glare (quality). Moreover, there are high demands for electric lighting to compensate for the insufficient daylighting depth into space and cooling loads due to the solar radiation accessing space (Etman, Tolba et al. 2013) (El Sheikh 2011).

Tracing the development in adaptation practice in architecture bioclimatic and ancient vernacular architecture reveals valuable lessons in term of taking the advantage of the available conditions in the surrounding environment in building design (Zhai and Previtali 2010). Nowadays, many Middle Eastern architects are reacting to this crisis by reasserting their Islamic heritage through the use of local geometry, local materials, and local architectural strategies to express the Islamic architecture. Moreover, examining the monuments of Islamic architecture shows complex geometrical relationships, a studied hierarchy of form and ornaments, and great depths of symbolic meanings (Martin 2008).

Vernacular architecture has examples of static adaptation in which ornamentation is used to solve multi-task problems and qualify space with attributes. An example can be found in Islamic Architecture with the use of Mashrabiya screen walls (Mahmoud and Elbelkasy 2016). Mashrabiya is a traditional Islamic and Arabic motif of the wooden lattice screen that was considered as a vernacular architecture, it was made for creating an interesting façade, an efficient shading system, reducing solar gain, reducing glare, and providing privacy. Also, it represents the identity of the Egyptian culture. However, by being static, their effectiveness is variable throughout the year due to daily and seasonal climatic changes, resulting in such envelope designs providing less than optimal building performance during some periods of the year (Wang, Beltrán et al. 2012).

Recently, with the speedy growth in material sciences and fabrication technology, coupled with the availability of economic options for hardware, sensors, processors and actuators (Fox and Kemp 2009), (Schaeffer and Vogt 2010), adaptive building envelopes have become a viable and interesting field of study (Addington and Schodek 2005), (Drozdowski 2011). Such systems now mean that a building envelope can be a dynamic element which acts as a negotiator with the external environment and an enhancer of the internal environment to maintain the desired performance throughout the entire year. Moreover, the birth of the digital era has brought about tools that allow for the parametric design of both organic and geometrically derived building skins. However, these skins, largely tend to be an aesthetic expression of the form (or ornament).

The impact of fundamental design strategies such as building orientation, climate, the window-to-wall ratio (WWR), glazing type and fixed exterior shading on daylight performance has been thoroughly analysed in a number of studies conducted over the past several decades.

However, few studies have concentrated on the effect of dynamic ornamental building skin on the natural light utilisation and daylighting quality. (Omidfar 2011).

Furthermore, daylighting devices are currently not well incorporated within the parametric façade system design processes, making the architectural integration of semi-standardized daylight devices, such as louvers or overhangs, in envelopes with complex geometry patterns a challenge, not only regarding their design but also concerning their performance evaluation (Omidfar 2011).

All these aforementioned reasons raise the question about the possibility of recalling traditional patterns and daylight strategies in an innovative way as a source of inspiration for designing a (TABS) that consists of complex geometric patterns integrated with a louver system to harness both the advantages of shading and the daylight redirecting system respectively. This system, by being dynamic, can be applied to adapt to different environmental conditions throughout the year and maintain the required daylighting performance, such as task-plane illuminance, daylight distribution, illuminance a contrast ratio of, daylight depth, glare and solar irradiation, required for office buildings in Egypt, as well as to consider the country's identity in a modernized way.

1.2. Aims and Objectives

The research aims:

The aim of this research is to close the gap in existing work, exploring the feasibility and potential of designing a (TABS) that expresses and addresses the unique forces that are defining the surrounding context of the office building in Egypt (either tangible, such as the weather conditions, or intangible, such as the forces arising from cultural and regional heritage), and fulfilling a predefined multi-dimensional criterion developed according to the local environmental, economic, cultural and social requirements as a mean to satisfy and reflect its contextual needs and cultural identity, respectively.

Moreover, harnessing the advantage of parametric, genetic algorithms (GAs), and building performance simulation (BPS) tools to explore the Islamic geometric patterns that can be evolved from this approach that would have a local identity, a stylistic evolution and significance of the eternal principles of Islamic architecture. Further, it would be a real test of designers' ability to combine the beauty and spirit of the traditional architectural patterns, interpreted in a modern expression harmonious with the current technological advances.

Therefore, a parametrically designed office building skin could be developed, modelled with external intricate ornamental geometries (as a shading system), which is culturally and naturally inspired by the local context's pattern and adaptation strategies and integrated with an internal active louver system (as a daylight redirecting system) as a mean to integrate both advantages of both shading and daylight redirecting strategies in one integrated system. The aim of this study was to investigate and evaluate the effect of the suggested dynamic system's configuration on the office daylight performance, with the objective of finding adequate solutions that could enhance daylighting performance while reducing issues with solar radiation and glare in interior space to enhance environmental performance through daylighting active design in comparison with the traditional static strategies such as fully glazed facades, window-to-wall ratio (WWR), fixed exterior shading, by implementing computational and building performance simulation tools, for making changes in the spatial quality response of the building, in order to enhance environmental performance through daylighting active design. Through this approach, the final form of the architectural artefact is determined by parameters based on performance.

In summary, this work tries to demonstrate that providing adequate daylight, making a visually stimulating and healthy interior environment, as well as directing the cultural identity can be attained by incorporating a well-designed (TABS) that is efficiently capable of responding to its surrounding environment while addressing its own context identity.

The research objectives:

For achieving the research aim, the following objectives are required to be done:

Main objectives:

- Define guidelines for designing (TABS) that integrates both advantages of the shading and redirecting daylighting systems and the impact of these systems on daylighting performance.
- Explore the effectiveness of integrating parametric design, genetic algorithms (GA) and building performance simulation (BPS) tools in designing (TABS) and reaching optimised solutions to inform the design and provide a fluid workflow between architecture and daylighting.

Secondary objectives:

- Explore the evolution of building facades and Daylight strategies.
- Inspect the effect of shading systems and redirecting systems on daylighting performance.
- Extracted relevant adaptation strategies from both Islamic architecture and local adaptation solutions as sources of inspiration.
- Explore the evolution of Adaptive building facades.

• Defining daylighting performance parameters and evaluation metrics for setting suitable criteria and methodologies to be used in the assessment of the (TABS) daylighting performance.

• Set guidelines for activating and integrating the traditional louver systems with the contemporary highly articulated complex forms.

• Set guidelines for validating the performance of (TABS) models.

• Investigate the effect of (TABS) sub-systems (shading and daylight redirecting) on daylighting performance.

• Investigate the possibilities and limitations of (TABS).

• Exploring recent researches that relate to the research aim.

1.3. Research Question

The primary research question of the research is:

Is it possible to design a (TABS) that is capable of negotiating with its surrounding environment to optimise daylighting performance, while addressing its own cultural identity, as a means to integrate and evaluate the ornamental desires of contemporary architecture with the urgent necessity to produce designs that optimise energy and daylight performance?

To answer this question the following research sub-questions have to be answered:

Q1. Is the Adaptive Building Skin capable of providing 'satisfactory performance' all year long, in comparison to other traditional static solutions?

Q2. Is the integration of dynamic, complex geometric patterns with a louver system in one (TABS) system effective, regarding their design and performance evaluation, and what are the impacts of this integration on daylighting performance in buildings, and which subsystem (complex geometric pattern or louver system) of the Territorial Adaptive Building Skin contributes more in fulfilling performance indicators?

Q3. What advantages can parametric, generative design, genetic algorithm (GA) and building performance simulation (BPS) offer in designing (TABS) in early design stages?

Q4. Can a (TABS) be efficiently capable of negotiating with its surrounding environment to optimise daylighting performance, while addressing its cultural identity?

Q5. Do the geometrical characteristics of TABS with complex geometries affect daylighting performance in buildings and do these adaptive response change due to climate, season, hour or orientation?

Q6. Does the (TABS) achieve the proper equilibrium that needs to be made between performance merits of people, planet and profit, according to the Triple Bottom Line principle?

1.4. Methodology overview

This work tries to demonstrate that providing adequate daylight, making a visually stimulating and healthful interior environment of buildings as well as directing the cultural identity, can be achieved by incorporating a well-designed (TABS) that efficiently capable of negotiating with its surrounding environment and addressing its cultural identity as an official representatives negotiator.

To understand the possibilities and limitations of creating a (TABS) and its performance advantages over traditional building skin approaches such as untreated fully glazed facades, window to wall ratio and traditional static shading solutions, comparisons are of essential importance for assessing feasibility of the entire concept and to investigate the true potential of the technology. Therefore, a comprehensive methodology is required to consider the performance behaviour of the (TABS) and its aesthetic qualities.

This thesis introduces a methodology for designing, simulating and validating this application study, aiming for addressing this integrated performance.

The adopted methods to achieve this purpose and answering the research questions include a literature review, project study design, parametric analysis using numerical simulation (modelling, simulation and optimisation) as well as experiments.

Concept Map

The methodology has been summarised in Figure 1.1 and serves to provide a (TABS) that is capable of optimising daylight performance in buildings along with reflecting its context cultural identity. This research has five parts: the definition of the problem, literature review, project study design and exploration, evaluation of the optimise design process concerning daylight performance and experiments.

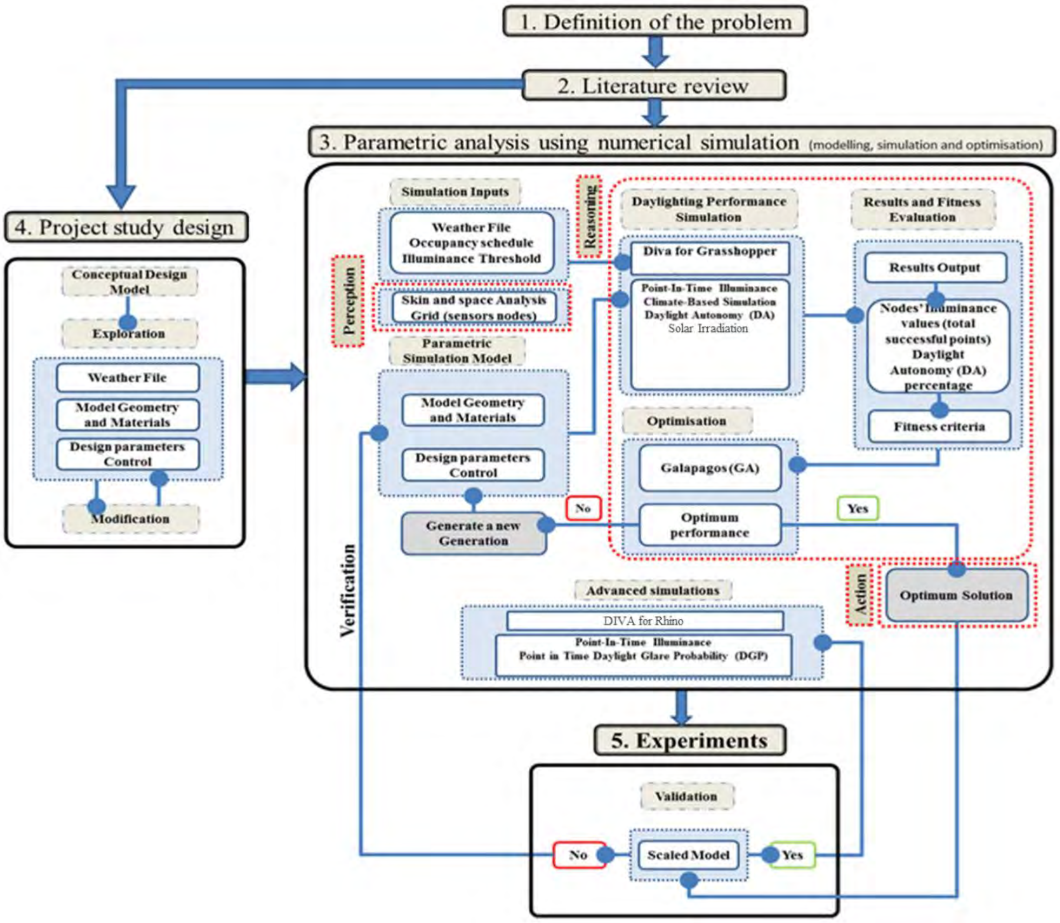


Figure 1.3 The workflow of performance driven conceptual design.

The aim of the literature survey is to study and evaluate existing examples and ideas regarding:

- The historical development of the building skin from a simple enclosure to the International Style as a means to identify, the basic primary functions that building skin played throughout the history, the impacts of technology advancements in the architectural design practice and the associated new roles of the building's skin. (Chapter Two)
- Exploring different daylight strategies and their formal and functional integration with building skin as a mean to identify the suitable shading and daylight redirecting systems that can be utilised as a base for the development of (TABS), with specific focus on the local traditional strategies as a mean to take lessons from local vernacular architecture practice and adaptation strategies, furthermore, analytical studies for the different daylighting performance indicators and standards were carried out to define the most suitable criteria for this research. (Chapter Two)

- The historical development of adaptive building skin concept, different theories that relate to the research aim. Subsequently, recognising the important elements for the successful design of the suggested (TABS). (Chapter Three)
- Moreover, advancement in computational and building performance simulation (BPS) tools (BPS), to find out the suitable tools to be used in designing and performance prediction of TABS. (Chapter Four)

Project study design

This step involves the design of an innovative TABS inspired by traditional patterns, vernacular architectural solution, and Biomimicry, and integrates daylighting strategies (shading and daylight redirecting systems) in the building skin based on the output of the literature review. Moreover, exploring and understanding the interaction of daylight with the designed system at all the examined times using interactive visualisation for sun rays tracing to help in creating an environmentally-conscious architectural design. This stage is performed by the parametric modelling software called “Grasshopper”. This software has a good graphical algorithm editor that enables designers to generate parametric forms and utilised Rhinoceros as an interface, and both are widely used and popular among researchers and professionals, in both traditional and parametric design (Lagios, Niemasz et al. 2010).

In addition to an open source environmental plugin for Grasshopper, Ladybug is used to help in providing a variety of 3D interactive graphics to support the decision-making process during the initial stages of design. (Roudsari, Pak et al. 2013), (Chapter Five).

Parametric analysis using numerical simulation (modelling, simulation and optimisation) for Case Studies.

The methodology proposed in this thesis considers the formal and functional properties of a building’s skin and associating them with a building skin variable; defining functional objectives that will guide a decision-making process which in turn will provide instructions to control variables, and directing them how and when to change, based on findings gathered from the exploration stage. Moreover, defining limits for these variables based on fitness criteria that reflects the environmental, economic, cultural and social quality standard literature; and evaluating the results against baseline data also retrieved from the literature and daylighting simulation.

With the aim of studying the theoretical abilities of the adaptive envelope, the building element was abstracted into primary elements identified as the independent dynamic variables within the study and referred to as the adaptive response variables. Each of the variables was identified as influencing daylight admission and performance in a certain manner inside the office space.

Using this conceptual abstraction of the TABS, the dependent variables is evaluated against traditional static systems models to identify the performance advantages and disadvantages of adaptable envelopes against these traditional static systems.

Focusing on performance criteria, the analysis of available geometric instances based on simulation software and other performance evaluation processes allows exploring and comparing the instances contained in the solution space of the parametric model on a given set of more sharply defined and measurable design criteria. (Chapter Six).

Experimental work

The assumptions of this model were tested in a reduced-scale experimental set-up and exposed to artificial sky conditions. Two physical models of optimised TABS façades were created using a Z-Corp 3D powder printer. The optimised TABS façades were for 12.00 on the 21st June and 12.00 on the 21st December. A model of the virtual Cairo office with each of the façades was placed in the artificial sky facility at University College London (UCL). An array of five photocells was arranged inside the reduced-scale model, and illuminance measurements were made to be compared with the illuminance values predicted in the simulation model. (Chapter Seven)

Simulation methodology overview

The methodology proposed in this research employed computational and building simulation tools (BPS) for modelling, generating and simulating a broad range of solutions, in addition to, utilising Genetic Algorithm (GA) as a design aid was applied within research sets for evaluating and optimising the daylighting performance.

A pool of solutions was designed, and fitness criteria were defined using daylight performance criteria, while limits for the adaptive response variables were set based on standards derived from literature. Daylight performance criteria and parameters were identified through existing literature, providing a quantifiable visual comfort objective function used to define appropriate office space's indoor visual comfort standards. The software was selected based on existing literature and research requirements. The programs assembled in the final algorithm represent a flexible combination of software which allows detailed analysis and accuracy of a parametrically modelled Territorial Adaptive Building

Skin for a south facing single zone office building office space (80 m² floor area) in Cairo, Egypt, during four seasons. This system consists of two subsystems:

1) TABS shading subsystem: a renovated dynamic transformable pattern inspired by the famous Egyptian traditional solar screen 'Mashrabia' and the local planet adaptation strategies in the hot climate as an active shading system; integrated with a subsystem described as follows.

2) TABS daylight redirecting subsystem: active horizontal louver systems as a daylight redirecting system. The geometry of the (TABS) is created by a parametric model managed by the performance preferences correlated with daylight, radiation control, and glare, and analysed using simulation tools, then evaluated and sorted by a genetic algorithm to show best solutions according to the predefined design criteria.

The aim was to achieve a design strategy that can reach building performance further than the level of trial-and-error designs, and also enhance the indoor daylight quality during the four seasons. Therefore, the system optimised and evaluated at twelve times representing the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st of March (vernal equinox); 21st of June (summer solstice); 21st of September (autumnal equinox)) and 21st of December (winter solstice)) to guarantee a pleasant, productive environment for space's users during the entire year.

The demonstrated system is capable of changing its configurations in response to the surrounding environment to maintain adequate daylight performance based on a desired predefined design criteria. The flexibility of the parametric model provided a wide variety of design alternatives. With the assistance of the evolutionary solver, an optimum was found among these variables that provide adequate daylight for the occupants. The active shading subsystem could be fully closed when daylight is not the favourable or an opening ratio between 0.1 and 0.9 or fully opened when daylight is desirable.

The seasonal adaptation of the TABS system will be investigated using twelve separate optimisation analyses (four season sets, consists of three sub-optimisation analyses at 9 am, 12 am, and 3 pm, on the 21st of each month where each season of the year was addressed by a different set of simulations and optimisation).

Aiming for an in-depth understanding of the advantages and disadvantages of the demonstrated (TABS), the study was applied in three main phases that are explained in the following paragraphs.

The first phase, was concerned with optimising the illuminance level at nine task-plan locations inside space to be between 500 lux and 2000 lux, and optimising the daylight depth to be 2x (by optimising the illuminance level of eight points in the central axes of space to be between (300 lux and 3000 lux), while reducing the total solar radiation of 40 points distributed across the façade (1 node per 1 m^2) to a minimum. Numerous solutions were explored, and many successful alternatives were achieved. Finally, 12 solutions were selected, one solution for each time (9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice).

It's important to note that, the main set of light level utilized in this research was to achieve daylight illuminances in the range 300 lux to 3,000 lux, where additional artificial lighting will most likely not be needed. Furthermore, daylight illuminances in the range 300 to around 3,000 lux are often perceived either as desirable or at least tolerable (Mardaljevic, Andersen et al. 2012).

The secondary set of light level utilized in this research was utilized based on group of other researches. One study carried out by (Minseok Kim, 2015) argued that an illuminance range of 500–2,000 lux does not cause discomfort, and in this case, daylighting alone is sufficient for maintaining indoor daylight illuminance. Moreover, an illuminance greater than 2,000 lux causes occupants to experience visual and thermal discomfort. Likewise, (John Alstan Jakubiec, 2014), stated that the definition of uncomfortable daylighting ranged between 2000 lx (Nabil & Mardaljevic 2006) and 5382 lx (USGBC 2009). Furthermore, (Mohamed, 2013) argued that times that represent excessive daylight that can lead to thermal and visual discomfort is the upper thresholds (UDI>2000lux). Also, according to (L. Bellia et al., 2015), the UDI was proposed by Mardaljevic and Nabil in 2005 (A. Nabil and J. Mardaljevic, 2005). It is the result of a series of researches carried out at the Lawrence Berkeley National Laboratory on offices' users. These studies demonstrated that not all the users define as comfortable the same lighting conditions, but generally a range for which all the subjects judged daylight levels as insufficient (below 100 lx) or too intense, and therefore uncomfortable (over 2000 lx) can be identified. The illuminance included in the range of 100-2000 lx was therefore defined as "useful" i.e. helpful to perform the visual task. Moreover the same study pointed out that 500 lx is the minimum illuminance value on the workplane established by the standards for offices. Furthermore, there is a notable discussion regarding the choice of 2,000 lux as an 'upper threshold' above which daylight is not desired due to potential glare or overheating (Reinhart and Wienold 2011). Based on the aforementioned studies the research decision was taken to consider the 300 to 3000 lux (UDI autonomous (or UDI-a)) as the main set of light level utilized in this research as it rested on a more convinced approach as the daylight illuminances in the range 300 to around 3,000 lux were often perceived either as desirable or at least tolerable in largely office buildings based on survey. In addition, it is importantly noted that many of these surveys were carried out before LCD display panels (which are much less prone to glare than CRT screens) became commonplace. Therefore, the range of 500 to 2000 lux was considered as the secondary set of light level for the 9 task-plans only during the optimization stage as a sub-set of the main range. In addition, it was a good opportunity to test the capability of the demonstrated methodology in fulfilling a combination of different sets inside the same space by optimizing the illumination level at certain points (Task-plans).

In the second phase, all the selected alternatives underwent a point in illuminance analysis with a spacing 0.42 m to ensure that the adequate daylight distribution (daylit area) occupies at least 80% of the total office space area at all the required times to guarantee continuous visual comfort inside the space.

Also, all the selected alternatives underwent point in time glare analysis to ensure visual comfort inside the space.

In the third phase, the performances of all optimised Territorial Adaptive Building Skin solutions in term of illuminance level of nine Task-plans points, daylight distribution, daylight depth, illuminance contrast ratio, solar radiation and daylight glare probability DGP are compared (at twelve times) to:

1. The base case of a fully glazed south facing façade.
2. Annually optimised WWR (AOWWR).
3. Annually optimised static building envelope (AOSBE).

Resulting in identifying the performance advantages and disadvantages of (TABS) against traditional static systems.

In the fourth phase, the individual performance of each subsystem was evaluated at all the twelve examined times regarding all performance indicators and compared to each other as well as to the whole system performance to investigate their impact and contribution in achieving the successful performance of the whole systems.

To sum up, a methodology to achieve these objectives proposed in this thesis to respond to dynamic daylighting conditions to reach a better light quality in indoor spaces, and comply with different light level recommend by the international organisation (Figure 1.1)

It is important to state that this research does not present improved optimisation or daylighting simulation methods, but rather a methodology and resulting data that contribute to the understanding of how “Ornamental” (TABS) influence daylighting performance, by integrating both advantages of shading and daylight redirecting strategies in one integrated dynamic system as well as addressing its own context cultural identity by recalling traditional patterns in a renovated performative way.

1.5. Significance of the Study

This thesis acts as an exploration into the effectiveness of future (TABS) for office buildings in Egypt and their possible limitations in satisfying the multi-dimensional criteria derived from the unique forces either tangible or intangible, that are defining the surrounding context of the building.

Also, a contemporary building envelope can consider playing a dual role of a filter between the indoor building and the ambient environment to maintain a visual performance and to reduce energy consumption inside spaces. Therefore, it is important to design facade systems that control daylight appropriately, maximising the benefits and avoiding the potential adverse outcomes (Vine, Lee et al. 1998). Second, the building envelope is considered to be a fragment of the city's image. Therefore, with the advancement of the digital age, the ornament made a comeback in design (Gleiter 2012), as a surprisingly fresh and direct expression of contemporary culture and spirit. However, incorporating shading and daylighting redirecting devices within the contemporary complex pattern's geometries within design processes becomes a challenge, not only regarding their design but also regarding their performance evaluation.

Thus, a methodology for aesthetically and functionally satisfying the ornamental desire of contemporary architecture in a performative way is presented in this thesis, by activating and integrating the local traditional patterns and ornamental solar screens as an active performative patterns (external shading device) with active horizontal louvers system (as an internal daylight redirecting system) in one adaptive system in order to aesthetically and functionally satisfying the "Territorial" requirements of office buildings in Egypt.

Moreover, provide theoretical limits to daylighting performance for office building designers' use of dynamic façade systems and information, to further improvement efforts in developing a genuinely adaptive building envelope. Finding an optimum behaviour for a building will provide a starting point for a learning process through which building would be able to learn from past weather, events in the surrounding physical environment, and occupant behaviour to refine the system's response to reducing energy use and maximising visual comfort.

Using the methodology presented here for the optimisation of daylighting performance within the building design process in a given climate, designers could evaluate proposed buildings against theoretical optimum performance criteria.

Furthermore, investigating the integration of performance simulation techniques and computational methods, especially in the early design stages, will open up a considerable understanding and improvement in the architectural practice in Egypt. The algorithm and resulting data provide quantitative knowledge on theoretical building performance and will help guide future design decisions relating to the applicability of adaptive building envelopes in Egypt. By exemplifying how to acquire data and use it to inform design decisions, to shift the complexity of contemporary forms from product to process. As a result, the representation of this data in and on buildings may become the architecture's new method of ornamentation that stands for something beyond the mere image of the final product of parametric design.

1.6. Thesis Structure

This thesis consists of ten chapters, structured as shown in the graphical representation in Figure 1.2. The first chapter introduces the particular field of research to be explored, identifies the research problem, aims and objectives, research questions, the significance of the study, describes methodology overview and outlined thesis structure.

The body of the text is divided into two main parts. The literature review included in Chapters Two, Three and Four, deal with the general background associated with the main topic, such as the historical development of building envelope and daylighting systems, Adaptive Architecture and the digital age of Architecture respectively. Chapters Five, Six and Seven demonstrate the case study of the (TABS), (modelling, simulation methodology, and validation) in comparison to three conventional facades design approaches.

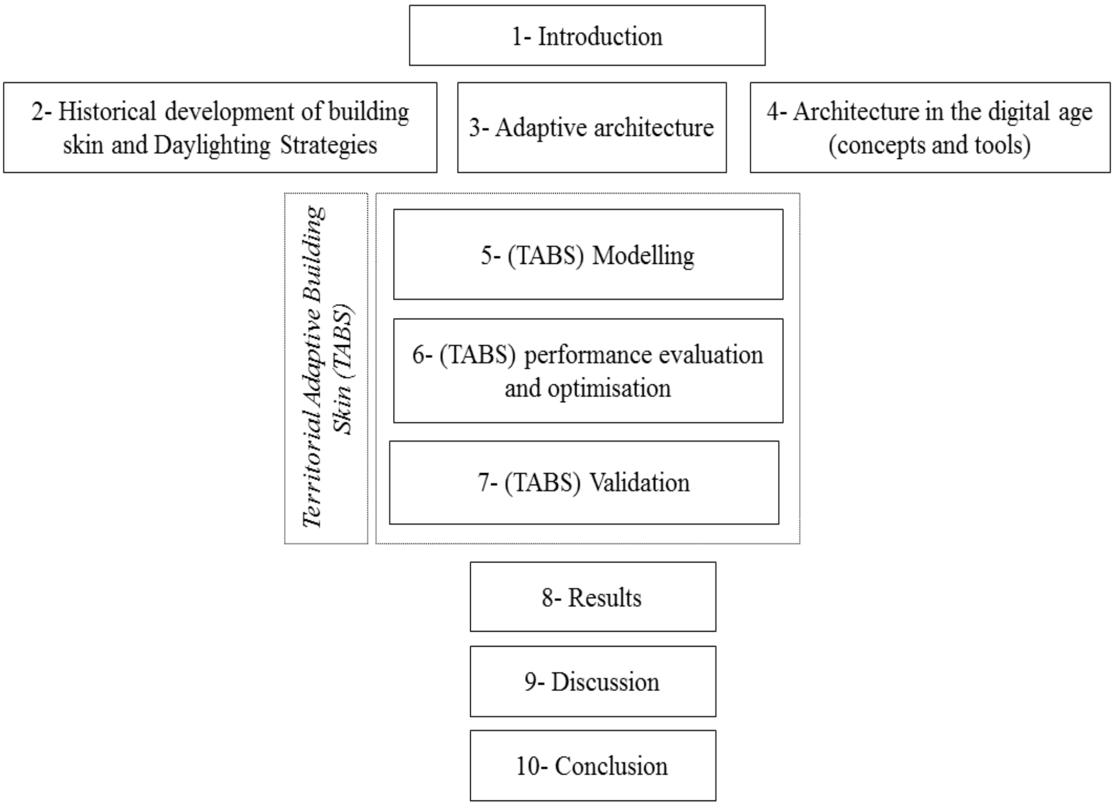


Figure 1.2 Structure of the thesis.

The structure of the chapters is as follows:

Chapter Two: is divided into two parts, with the first part exploring the historical development of the building envelope, highlighting the impact of technology advancement through history on the architectural practice. The second part discusses the importance of daylight in office buildings, including an overview of different daylighting strategies, performance indicators and evaluation metrics utilised in the designing process of building skin to improve the daylighting performance in office space.

Chapter Three: carries on with a discourse of the adaptation in architecture, how the concept that is identified by a legion of different terms was introduced and defined along with a summary and an overview of categories of adaptive architecture is supplied. Furthermore, the general criteria for assessing building performance, characteristics of the adaptable building envelope, advantages, design demands and sources of inspiration were introduced. Moreover, the advantages of the adaptive building envelopes over the traditional static solutions in achieving better daylighting performance were discussed.

Chapter Four: investigates the roles and capabilities of the computational design tools regarding building skin design; moreover, the performance-based design model and the utilisation of the current advancements of integrating computational tools (Parametric

Design, Generative Design, Optimisation, and Form Finding tools) with building performance simulation tools (BPS) as well as utilising Genetic algorithm (GA) as a design aid are discussed. In addition, an overview of the capabilities of the building performance simulation tools with respect to Adaptive Building Envelopes is introduced as a primary stage to implement computation tools effectively in developing Territorial Adaptive Building Skins (TABS) in the next chapter. Moreover, the means of gathering and utilising data to support design decision as a way to shift complexity from the final complex forms to a simplified process is considered.

Chapter Five: is concerned with the Territorial Adaptive Building Skins (TABS), including general concept, objectives, sources of inspiration, and the (TABS) model design process in addition to describing the modelling and simulation toolbox including an explanation of fitness criteria and a designing pool of solutions that are suitable to be used within the design process of (TABS).

Chapter Six: presents a general methodology to be used for performance prediction in Territorial Adaptive Building Skins (TABS). In this chapter, the design method, tools, specifications and assumptions of the suggested (TABS) were explained. Also, the chosen daylighting metrics and the analysing criteria were studied and discussed.

In **Chapter Seven:** the validity of the (TABS) model is tested by using a reduced-scale model, of two 3D printed screens of optimised (TABS) for the 21st June at 12 pm, and 21st December at 12 pm, as a representation of summer and winter seasons, were installed and tested under an artificial sky to assure the credibility of this model's assumptions.

C**hapter Eight:** describes the evaluation of the case studies. The performance of three conventional facades' design strategies (fully glazed façade, Annually optimised WWR (AOWWR), and annually optimised static building envelope (AOSBE)) are presented and used as a benchmark for evaluating the performance of the (TABS), and the chapter also presents the (TABS) subsystems' performance in comparison to the full system performance as a means to examine the impact and contribution of each subsystem on the overall (TABS) performance.

Chapter Nine: presents an extended discussion regarding the interpretation of the results' chapter and research findings.

Finally, **Chapter Ten:** summarises the findings made during the execution of this research, with respect to the research questions asked as well as the methodology employed to resolve them. Also, provides recommendations for future work.

1.7. Conclusion

This thesis argues for integrating more designed adaptive capabilities into a building envelope, harnessing the advancements of computational and building performance simulation (BPS) and "recalling" and "activating" the traditional pattern 'ornaments' and local traditional daylighting strategies (as a source of inspiration) in designing (TABS). Such an envelope would be capable of changing its features, or behaviour in response to varying performance requirements and boundary conditions, so that the performance of the whole building, regarding the environment, economic, cultural and social aspects can be potentially maximised.

This permits the building to be more representative of its cultural identity, affording a pleasant and productive office space environment with less dependence on artificial lighting, which results in reduced energy consumption.

Chapter Two

2. Historical Development of Building Skin and Daylighting Strategies.

2.1. Introduction

To reach the current phase of building skins, the evolution of building skins has crossed through many steps. Thus, tracking the historical evolution of building skins and different daylight strategies utilised by architects to improve the built environment is needed, to create a clear understanding of the initial forms of architecture as it is the root of the current progress and any expected developments.

In this chapter, the development of the building skin from a primary element as an enclosure, to the International Style of fully glazed facades, is discussed, highlighting the impacts of different advancement in building technology and materials on the architectural practice. Moreover, the importance of daylight in buildings, including an overview of using different daylight strategies in the design process to improve and control daylight inside the interior spaces is presented as a means of achieving the aims of this thesis.

2.2. Development of Building Skin (*from shelter to skin*)

People spend around 90% of their time indoors (Bougdah and Sharples 2009), which explains the aim for buildings that are safe, healthy and pleasant. Therefore, nowadays, the building skin in architecture receives central interests which, coupled with a rapid increase in the facades' systems and technology explorations, leads to extending the function of the building facades to play many roles, broader than its traditional functions. These traditional functions were limited to primary purposes such as sheltering the building occupants from external climate condition, providing privacy, reflecting in an aesthetic way their times and cultural identity, and characterising the face of the city (Schittich, Lang et al. 2006). Modern building skins are able to do the same functions as well, but can now adapt to their context and maintain pleasant interior conditions by actively responding to the changes in the external environmental conditions.

The outer surface of the building that connects the inner building spaces with the ambient environment has been named and defined in different ways, such as façade, envelope, and skin. Thus, it is important to identify the precise term that will be used within the context of this study. In the light of that, the word façade refers directly to the exterior of building sides or faces (Schittich, Lang et al. 2006), excluding the roof. On the other hand, the building envelope is defined as a physical separator between the conditioned interior and the unconditioned external environment (Omidfar 2011). When it comes to building skin, it refers to the outside layer or covering of a building. What differentiates the building skin from the building façade and building envelope is that the building skin is not limited to the external side facades of the building as it refers to multiple faces, which could potentially encompass an entire building including the building roof. Also, the building skin could function as a building envelope by physically performing as weather, air, and thermal barrier; the term skin does not necessarily prescribe itself to this particular role. Rather, it reflects the live nature of the skin and the capability to lively regulate and interact with the surrounding environment for the sake of the building interior comfort and preventing discomfort on a continuous basis.

Building Skin as a Shelter

Historically, buildings have various shapes and appearances in different places of the world. The function of the building envelope to protect the occupants from the surrounding environment is the same way regardless of which place across the world they live.

Figure 2.1 Traditional building in cold climate (Norway)

However, as the climate varies so do the materials utilised and design solutions. The people built shelters suitable for their climate and learned how to use design and materials to improve the performance of simple shelters. When looking into vernacular architecture, often referred to as architecture without architects, shelters built by the users and inhabitants, differences can clearly be seen.

The wooden houses in the northern parts of Europe (Figure 2.1) are fast to heat up while the stone buildings in southern Europe, because of their thermal mass, remain cool during warm summer days. The tent structures with animal skins as a protective layer were also common, especially in cultures that move around a lot like the Bedouins in the African deserts as seen in Figure 2.2.

The primary forms of enclosures usually had a lack of the opening as a means of protection from dangerous animals and harsh environment conditions. Later, an opening in the ceiling starts to appear as a way of ventilation, and daylight supply.

Figure 2.2 The traditional Bedouin's home

The basic form of windows starts, to appear in the shape of small openings in the sides of the spaces with the purpose of providing a visual connection with the exterior environment and permitting the light in space when it is favorable and opaque cover was introduced to these openings for closure possibility for protection or when daylight is unfavorable. After that, transparent materials for openings were adjusted to let the light penetrate into space (Carmody 2007).

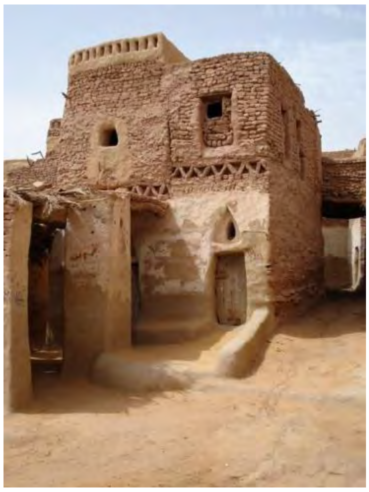


Figure 2.3 Traditional House Siwa Oasis, Egypt

Examples of vernacular architecture have very elaborate features, such as heat storage, shading, and ventilation (Figure 2.3). It can be noticed that there was knowledge about the surrounding climate that always influenced the design of the envelope. Architects used many different passive design concepts to achieve a real comfort in the buildings, ranging from surface finishes to light shelves, atriums to natural ventilation. (Van der Aa A. 2011)

Skin as a Part of the Load-Bearing Structure of the Buildings

Gottfried Semper divided the building into two main elements: load-bearing structure and cladding (Semper, Mallgrave et al. 2004). This division formed the root of the current concepts that relate to building skins nowadays.

Building skin in the form of the exterior walls was acting as the role of protection. However, its primary function was as a part of the load-bearing structure of the buildings, in addition to being a subject of ornamentation as mean to express the cultural, social and religious identity (Figure 2.4). This ornamentation desire has spread all over the world as a means for constructing a fantastic image about these earlier eras. Thus, building skin received a central focus throughout the history and became a crucial element of the architecture (Schittich, Lang et al. 2006).

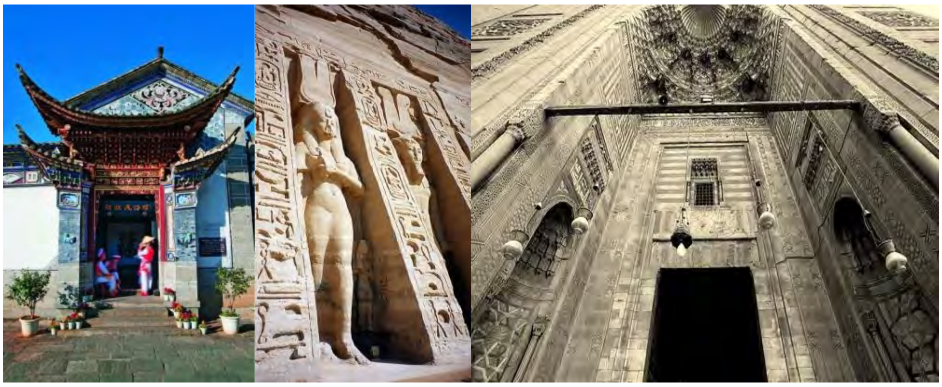


Figure 2.4 a) Bai minority in Yunnan, China; b) The Nubian monuments, constructed by Pharaoh Ramesses II (1300 BCE). Abu Simbel, Nubia, Egypt; c) Mosque Sultan Hassan gate In Cairo

The Manufacturing of Glass and Iron

Thus, due to this central focus on the building skin, it became a field of advancement and innovations regarding materials and techniques. The manufacturing of glass leads to a crucial turning point in the architectural practice by introducing light into the interior spaces through the large windows that were not previously possible. The light weight of glass in comparison to the traditional construction materials helped in minimising the loads acting on load-bearing walls, and as a result, thinner walls with larger openings and new building techniques such as stone skeletons composed of ribbed vaulting and the pillars were introduced as a central theme of the Gothic architecture (Schittich, Lang et al. 2006).

The utilisation of glass in the building skin is considered to be a significant step in liberating the skins from the constraints of the load-bearing wall (Fletcher 1931). However, like any new technology, the use of these techniques and material at the beginning were still not broadly used due to the high cost.

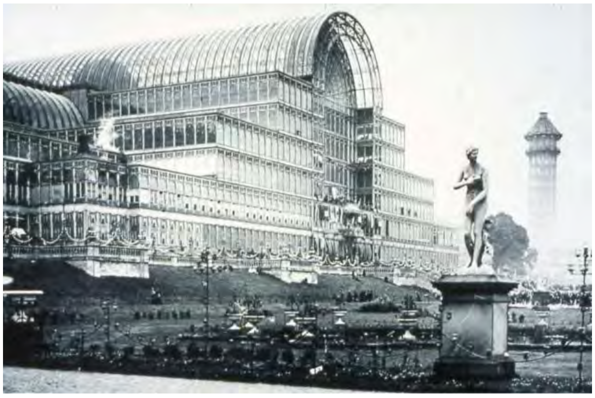


Figure 2.5 The Crystal Palace, Hyde Park, London in 1851

The 19th century Industrial Revolution has introduced innovative materials and production methods that completely changed the built environment. According to Schittich: “iron and glass conquered architecture.” (Schittich, Lang et al. 2006). The Crystal Palace in London (see Figure 2.5) is one of the iconic examples, where the combination of iron with glass resulted in a beautifully light and transparent building. This building inspired architects all over the Europe and as a result, Exhibition and public buildings began to arise with this style (Schittich, Lang et al. 2006). Eventually, designers gave up on their decorated facades and began to partake in this revolution.

Figure 2.6 Carson, Pirie, Scott Building (1899) by Louis Sullivan offers a clear distinction between structural and non-structural elements of the facade.

Mass produced iron was widely used to produce a skeleton structure for a building, and these metal frames provided open and flexible interior spaces, characterised by less load-bearing responsibility to external walls, allowing for more openings. For example, the Carson, Pirie, Scott Building (1899) by Louis Sullivan (Figure 2.6) offers a clear distinction between structural and non-structural elements on the building façade. At this stage, building skins achieved a considerable amount of independence from the load-bearing structure, however, are not completely free.

The Desire of Liberating the Building Skin

The desire of liberating the building skin from the building structure was due to the functional objective of allowing as much light in as possible, for workers in industrial buildings, through maximising the amount of glazing in building skin. The Fagus factory in Germany by Walter Gropius and Adolf Meyer was an example of freeing the building façade as they hung a three-story curtain wall in front of a brick facade (Figure 2.7). The glass facade even turns the corner without support, resulting in a beautiful aesthetic that highlights the principle of the curtain wall (Blundell-Jones 2002).

Figure 2.7 Fagus Factory (1911-13) by Walter Gropius and Adolf Meyer demonstrates the idea of the curtain wall and its freedom from load-bearing functions.

The International Style

Figure 2.8 The Seagram Building in New York City.

To that extent, the architects finally reached their goal of liberating the building skin from its primary structural tasks, and they started exploring the high rise buildings with the fully glazed curtain walls as a theme of the International Style. By freeing the exterior walls from their structural function, the steel frame made it possible for architects to design floor to ceiling glass curtains walls that offered ample natural light and unobstructed views. Unfortunately, this new building type did not provide sufficient thermal insulation and required a substantial amount of mechanical heating and air-conditioning to maintain a comfortable work environment (Murray 2009).

The Seagram Building in New York City (Figure 2.8) built in 1958 by Mies van der Rohe was the most famous example of this style (Perez 2010). The designer, despite all the efforts spent in liberating the building skin from the structure, he attached non-structural, bronze-toned I-beams onto the building, running them vertically across the glass curtain wall, to make sure the external building skins was yet articulated externally and they are capable of being ornamentally decorated and conceptually stylish.

Drawbacks of the International Style

Before the advent of air conditioning, architects needed to give considerable attention to site conditions and passive design strategies to create comfortable built environments. For example, orienting buildings to capture prevailing wind, and offsetting windows deep into exterior walls that resulting in overhangs to block out the sun during the summer while allowing the low winter sun to enter (Figure 2.9). These strategies allowed the building to be naturally heated and cooled (Murray 2009).

Figure 2.9 Monadnock Building

Conversely, the International Style received criticism from clients, owners and architects regarding:

- The validity of a style that is not responding either to the surrounding context nor the occupant preferences of the internal spaces.
- The full dependence on the artificial air-conditioning for occupant comfort, which leads to an energy nightmare during the oil crisis of the 1970s.
- The building skin lost its role as moderator for energy and comfort, which is now admitted that buildings sit a major load on our environment. Energy consumption in buildings has increased in such a way that it now dominates over the industrial and transportation sectors (Pérez-Lombard, Ortiz et al. 2008).
- Enabled one united style all over the globe no matter where in the world building was situated the building could follow the same aesthetics. A tower in New York, Singapore or in Beijing could look the same despite the very different climatic conditions. And the problems concerning heating, cooling, and air quality was solved by mechanical heat and ventilation systems, which gave more people the possibilities to control their comfort, but at the cost of large energy consumption. The use of HVAC systems not only consumes energy but is also known to create discomforts, like problems with dry air (Boer, Ruijg et al. 2011).
- The architectural design no longer is as firmly connected to the climate nor the environmental factors; the building design became more about designing a beautiful shape rather than anything beneficial for the comfort. It was instead left to the HVAC engineers to solve the comfort problem (Van der Aa A. 2011).

The United Nations Secretariat Building by Harrison, Le Corbusier, and Niemeyer in the United States (Figure 2.10) represents the modernist vision of steel and glass construction. At the time, many referred to this building's curtain wall as "The World's Largest Window" (Murray 2009). The main facades were made up of 'tinted heat-absorbing' glass panels that were orientated in the direction that gave the best views. Unfortunately, this choice took precedence over the best orientation of the main facade that would control excessive solar gain (Banham 1984). Le Corbusier warned his co-designers to provide "brise-soleil" (sun shading devices) for these exposed glass facades. However, Harrison decided to address the increased cooling demand, due to the building's orientation, by commissioning Carrier to design one of the most sophisticated air- conditioning systems of the time (Banham 1984).

Figure 2.10 United Nations Secretariat Building

Still, during the building's first summer in use, office workers found that it was necessary to keep the blinds lowered for the entire day, reducing the natural light and views that the initial design intended (Banham 1984). Moreover, increased the building's dependence on artificial lighting, which increased the building's demand for energy.

Though clearly flawed in its design, the United Nations Secretariat Building nevertheless marked a significant step forward in the development of the glass curtain wall system (Murray 2009). Unfortunately, it also represents the beginning of a design era that disregarded passive design strategies and marked a large step towards the trend to design energy dependent office buildings. But in an endeavour to reduce energy demands looking back on the traditional ways of solving, protection and comfort through design is a good starting point.

Closing Remarks

The overall building design and the design of the building envelope passes through several stages, starting from utilising the available local materials with the aim of providing a shelter; however, early examples show that people in different regions built simple shelters suitable for their climate and learned how to use design and materials to improve the performance of simple shelters. Advances in building technology and materials have had a great impact on fulfilling the architect's desire of liberating the building skin from its structural role and on architectural practice in general, resulting in the widespread emergence of the high rise buildings with the fully glazed curtain walls as a theme of the International Style. In the years that followed, the demand for office buildings steadily increased. Moreover, one united style all over the globe, no matter where in the world the building was situated, followed the same aesthetics, without considering the climate differences from region to another.

Therefore, it can be concluded that the more buildings are adapted to their particular situation and the specific environmental loads that will affect it, the less time the mechanical system need to step in to maintain the comfort.

The principal function of the building's envelope can be expanded from solely providing a shelter and an image of the building, to improve the building's performance by providing comfort to its users and aids in reducing energy consumption. Rather than a form with aesthetic elements, facades can be used for the aim of integrating natural daylight, manage solar heat and provide a visual connection to the outside.

The aforementioned discussion highlighted the importance of looking back at the daylight systems as a means to achieve these goals. The following sections would discuss the importance of integrating natural daylight within the space, and the most common facade strategies used for enhancing daylighting performance.

2.3. Architecture and Daylighting

Introduction

"*The history of architecture is the history of struggle for light*" (Le Corbusier) (Baker and Steemers 2014).

"*No space, architecturally, is a space unless it has natural light*" – Louis Kahn (Zawidzki 2015).

Daylight is an abundant natural resource that can provide useful light to the interiors of buildings and is associated with other benefits such as view and a lowered use of electric light. (Olbina and Beliveau 2009). Improving energy efficiency by the use of daylighting can be troublesome due to the many and often contrasting performance parameters a designer faces. Managing daylighting quality successfully with less incoming daylight would open up opportunities for energy saving. In the light of that, affording daylight to building spaces is a principal aspect of the building design. However, natural daylight is usually accompanied with a potential of overheating, glare and increased cooling loads for a building (Ruck, Aschehoug et al. 2000). Therefore, since the performance of daylighting depends on delivering daylight efficiently, designers have the challenge of meeting quantitative and qualitative requirements, and solving them spatially (Castorina 2012). Therefore, it is important to design a facade system to control daylight appropriately, maximise the benefits of avoiding the potential adverse outcomes (Vine, Lee et al. 1998).

Daylighting Definition

Introducing the definition of daylighting from different perspectives is essential for understanding the importance of daylight and the role it plays in building performance. The following section presents five different definitions for daylighting.

- From the Architectural perspective: the interplay of natural light and building form to provide a visually pleasing, healthy, and productive interior environment.
- From the lighting energy saving perspective: the replacement of indoor electric luminous environment needs by daylight, resulting in the reduced annual energy consumption for lighting.
- From the building energy consumption perspective: the use of fenestration systems and responsive electric lighting controls to reduce overall building energy demands (heating, cooling, lighting).
- From the cost perspective: the minimisation of operating costs and maximising output via daylighting strategies (Galasiu and Reinhart 2008).

Daylight in Architecture

Daylight 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). Traditional building design indicated that the earliest architects throughout history gave great importance to daylighting in their practice. For instance, Vitruvius, in the first century BC, argued that the function of interior rooms should be determined based on their orientations towards the sun, in both daily and annual cycles (Vitruvius and Morgan 1960). Moreover, the Renaissance architect Alberti reiterated that approach, while adding that considering the contextual climate and building site is essential (Alberti and Rykwert 1991). Furthermore, the 20th-century's designers confirmed the same interests in light as a key element in Architecture. Wright believed that all spaces within a house should receive daylight at some point during the day (Wright 1955). Similarly, Le Corbusier defined architecture as "*the masterly, correct and magnificent play of masses brought together in light*" (Corbusier 1986). Thus, from the architectural perspective, daylight is a fabulous inspiration in architectural design throughout history, even before the release of many types of research that confirmed the advantages of daylight over artificial lighting regarding users' health, well-being and mood. For example, one study showed that decreased exposure to daylight was associated with a higher potential for health problems. (Webb 2006), while another study indicated that workers who are exposed to daylight have lower stress levels than those working under artificial lighting (Van Bommel 2006).

Daylighting in Office Buildings

Building facades are designed for different purposes, such as function, environment, occupant comfort, energy consumption, sustainability, economy, technology and aesthetics (Poirazis 2008). Façades account for between 15% and 40% of the total building budget and can be an important contributor to building cost (Wigginton and Harris). A central attention was given to the daylighting of building at the end of the 1990s, due to two main significant “drivers”: the belief of potential to save energy through effective daylighting strategies, and the studies suggesting the positive outcomes of daylight exposure on the building occupants' productivity, health and well-being (Mardaljevic 2013).

As the primary purpose of office spaces is to afford a pleasant and productive space (Dinapradipta 2015), an efficiently designed daylighting strategy in office buildings requires the optimal effective utilisation of the natural solar energy via managing and harvesting the available natural daylight. Today, a growing need to create sustainable buildings has led to a greater emphasis on daylit spaces in buildings that use lighting controls to reduce electrical energy needs. According to (Wen and Agogino 2011), lighting consumes about 19% of the total electricity generated. The efficient utilisation of daylighting offers many advantages such as reducing the building's energy consumption, make a positive contribution to the lighting quality of space (Boubekri 1995). Also, occupants' preferences for natural daylight over artificial light has been shown by research (Boyce, Hunter et al. 2003, Reinhart and Wienold 2011) and provided a definition of a daylit space as space which is fundamentally lit by natural light, and results in both high occupant satisfaction with the visual and thermal environment and lower overall energy use for lighting, heating, and cooling.

Parameters Influencing Daylighting Performance

According to (Velux 2010), parameters influencing the daylighting performance can be identified as follows:

2.3.1.1.Climatic Conditions

The general climatic conditions of a building site are a dominant parameter as it defines the preconditions for the daylighting design affecting visual comfort, thermal comfort, and energy performance.

2.3.1.2.Solar Altitude

The solar altitude properties of a particular location for a given time of day and year are significant inputs for the design, particularly regarding control of direct solar radiation.

2.3.1.3.Site Properties

Surrounding buildings' reflections, trees, ground surface, etc., have an impact on the amount of daylight approaching the space. In addition to the building's self-reflections and obstructions from (masses, shadings, etc.) that affect daylighting performance.

2.3.1.4.Orientation

Building's orientation has a significant impact on the quantity and quality of daylight inside the space. Northern light is a sky diffused light, which provides a functional and comfortable light. Also, no direct sunlight will enter the space. In the cases of the light approaching space from the south, east and west orientations, in many cases will supply the interior with unfavourable direct sunlight and light levels that change significantly throughout the day.

2.3.1.5.Building Geometry

The building's geometry and space's dimensions included has a significant influence on the daylight levels in the interior spaces. For spaces with increased depth, the daylighting is dependent on the facade windows. However, it will only be possible to achieve an adequate daylight distribution (DF > 2%) a few metres from the facade, regardless of the window size (See Figure 2.11). The utilisation of light shelves and daylight redirecting systems can improve the light distribution and depth. However, the capabilities of these solutions are often associated with visual discomfort.

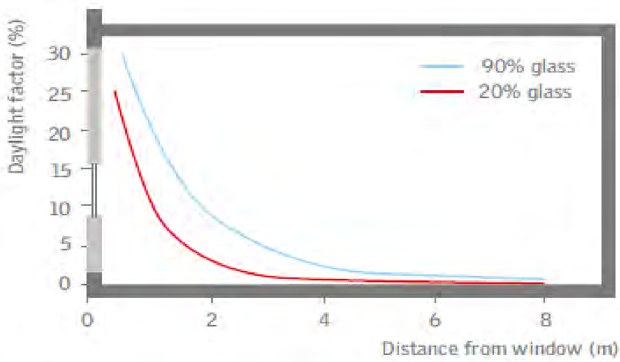


Figure 2.11 Daylight factor levels for two facade window configurations (Velux 2010).

2.3.1.6.Material Properties

The reflectance and colour of surfaces used in a space influence the daylight performance of that space. For example, a bright diffuse surface reflects more light than a dark surface (see Figure 2.12). Consequently, bright surfaces are more likely provide an efficient luminous environment as there is more indirect or reflected light. However, too bright a surface may create the risk of glare.

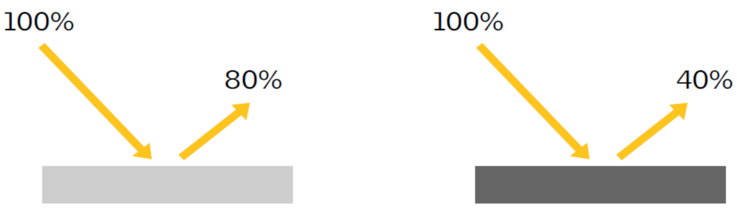


Figure 2.12 The influence of surface reflection on light distribution (Velux 2010)

2.3.1.7. Windows

a. Glazing area

Glazing area of windows affects the quantity of daylight penetrating the space.

b. Glazing pane

The glazing pane affecting the daylight transmitted in space through the window as it is reduced by the number of glass layers it has to pass through. For example, double glazing (without any coating) lets in approximately 80% of the light, while triple glazing (without any coating) allows in approximately 10 % less. In the case of coloured or coated glass, the visible transmittance of a window pane can reduce to values as low as 20% and significantly adjust the spectral quality of the transmitted light, as well as the perception of surface colours in the space.

c. Position

The positioning of windows will influence the distribution of daylight in the room and determine the amount of "useful" daylight. Window position also needs to consider the relationship between the view to the outside and the eye level of the occupants.

d. Reveal

The window reveals' geometry and dimensions influence the amount of daylight penetrating the room. Also, it can be utilised to soften the luminance transition between the high luminance values of the window and the surfaces of the space.

e. Shading

Shading and sun screening has significant impacts on the quantity of daylighting performance. The louvers can be employed for regulating the amount of daylight entering space, preventing direct solar radiation and reducing glare. Also, it can be used as a shading device and a daylight redirecting system to adequately control the luminance levels, as a means to avoid the risk of glare.

Benefits of Daylight in Buildings

The main benefits of daylighting as a design strategy in office buildings can be discussed from three aspects - environmental, social and economic, and all are related to sustainability. The following sections discuss the advantages of good daylight in office spaces from these perspectives.

2.3.1.8.Environmental Aspect

Daylight substantially reduces the energy consumption and greenhouse gas emissions (Bodart and De Herde 2002). The International Energy Agency (IEA) states that artificial lighting is almost 20% of the electricity consumed globally (Agency). Moreover, the heat caused by artificial lighting systems raises the cooling loads. Consequently, the reduction of artificial lighting consumption can potentially reduce building cooling loads by 10–20% (Ander 2008). Thus, decreasing the energy consumption of a building by utilising daylighting strategy affords a potential for reducing carbon dioxide emissions, which ultimately reduces greenhouse effects. Thus, the reduction of artificial light in a building by introducing daylight into space is a crucial aspect of an environmentally conscious design.

2.3.1.9.Social Aspect

One advantage of offering daylight in deep plan office space is providing a connection with the external environment and, consequently, increase the sense of orientation, time, and weather (Phillips 2004). Creating luminous conditions that satisfy the occupants' needs can produce a pleasant emotional state within the working space that leads to greater performance, higher effort, less conflict, and greater willingness help others" (Veitch 2000). Over the years, research has identified daylight and sunlight in buildings as essential to good health and people's well-being (Webb 2006).

2.3.1.10. Economic Aspect

Another advantage of offering daylight in deep plan office spaces is energy savings, as lower electricity demands are needed to sustain a comfortable zone, for both artificial lighting and cooling loads on the mechanical cooling system due to the excessive heat gains caused by artificial lighting. All of this results in a lower energy consumption. The US National Institute of Building Sciences stated that one-third of the building total consumption can be decreased through a good integration of daylighting strategies (Ander 2008). Another study carried by the British Council for Offices (BCO), argued that efficient lighting design and adequately daylit environments can increase the productivity of office employees by 20%. Thus, a well-daylit environment has a crucial financial impact on office building design (Morrell and Duffy 2004). Incorporating daylight strategies into commercial buildings' design during the daytime when sunlight is available, and the use of artificial light is optional can contribute to a significant reduction of energy consumption of light as it accounts 30-50% of the total energy use of these types of buildings. Also, a well-designed daylight strategy can indirectly contribute to energy savings due to reducing thermal loads in office spaces (Phillips 2004).

Daylight Strategies in the Building Design

A broad range of studies has discussed the impacts of building form and facade design strategies regarding daylight, such as building mass and orientation, window-to-wall ratio (WWR), glazing type, and static exterior shading (Carmody, Selkowitz et al. 2004), (Lee, Selkowitz et al. 2009). These studies highlight the importance of the fenestration design on the performance in terms daylighting, energy use and occupant comfort. Moreover, they showed that windows play a central role in providing daylight and views to occupants, especially in office spaces, where adequate daylight is important for paper- based and computer-based tasks, careful design of windows is of particular importance. However, proper solar control is critical to minimising building energy demand and maintaining occupant comfort. Thus, different daylight strategies were discussed in the following sections.

2.3.1.11. Massing and Orientation

Massing and orientation of buildings have a significant impact on building performance regarding heat gain and daylighting. Orienting the building towards the north is favourable (Twinn 2003), as it decreases the heat gain of the building and, as a result, minimises the energy consumption. The building orientation is influencing the amount of the sunlight that enters the space, for example, during the summer season the East and West orientations are exposed small amounts of sunlight, however, a larger cooling load is required for the West orientation due to the afternoon sunlight. For east and west façades where the sun angle is low-angle, vertical louvers are useful blockers. On the other hand, horizontal shading is efficient in blocking the solar radiation on south façades (Kim, Kim et al. 2014).

2.3.1.12. Window to Wall Ratio

One positive impact of windows is providing daylight and visual connection between occupants and the outside environment; on the other hand, windows can introduce significant complexity regarding daylight control and managing thermal transfer. Historically, architects utilised small size windows in vernacular buildings in the desert environments as a mean to minimise glazing area to reduce solar radiation penetration and as a result, reduce overheating (Figure 2.13).

Figure 2.13 Ancient homes of Egypt with small openings

Nevertheless, it leads to a lack of daylight availability and external view. On the other hand, contemporary office buildings followed the International Style of using fully glazed facades; this strategy came with a higher expectation of affording ample daylight, views, and connection to the outside. However, the fully glazed façade, with the exception of those with advanced systems for controlling heat gains, is not usually environmentally sustainable, as they bring new challenges such as inadequate daylight performance, heat gains, risk of glare, increased cost, an additional operation, and maintenance requirements. Thus, rethinking about integrating the traditional shading systems in a renovated way with the advanced, automated and highly articulated building envelope design could be worthwhile to consider as a successful strategy to meet the efficient building energy use and occupant comfort requirements in contemporary office buildings

2.3.1.13. Daylight and Solar Control Systems

a. Introduction

Shading and light redirecting devices are the key design aspects influenced by a daylighting analysis based on a survey on the utilisation of daylight simulations during the design process of building (Reinhart and Fitz 2006). The impact of daylighting strategy on office buildings and its occupants is a critical part of the sustainable design as the natural daylight has a significant impact on occupants' physiology and psychology, productivity and the overall mental state and health. Moreover, poorly lit space requires artificial lighting to sustain the light efficiency, in addition to excessive heat gains, increases energy demand for lighting and cooling loads (Ruck, Aschehoug et al. 2000). However, the adequate implementation of daylight strategies is crucial as poorly integrated daylight strategies into the building, can result in the opposite of its intended purpose: as excessive levels of daylight can reduce productivity and, excessive glare, and temperatures (Edwards and Torcellini

2002). To sum up, building skin performance of non-residential buildings have a significant impact on energy demands required for building operation. Efficient sun protection and daylight design strategies contribute to reducing the cooling, and artificial lighting demands respectively (Fuchs, Hegger et al. 2008). Architects used a number of different passive design concepts to achieve a good comfort in the buildings, such as surface finishes, solar screens, light shelves, atriums to natural ventilation via thermal stacks (Van der Aa A. 2011).

Therefore, different daylight strategies are discussed in the next sections as a crucial step to achieve the objectives of this study.

b. Classification of Solar Control Systems

The classification of solar control systems can be sorted into two main groups: solar shading systems and daylight redirecting systems. Regarding solar shading systems, they are more efficient in facades that are exposed to direct sunlight as they are capable of preventing direct sun under clear sky conditions. On the other hand, light redirecting systems do not fundamentally provide shade; they control the diffused and direct sunlight to improve the daylight depth into space. Nevertheless, several systems can perform as both shading and light-redirecting at the same time. Hence, categorising these systems in particular groups without intersecting is a challenging task (Ruck, Aschehoug et al. 2000). Regarding the system positioning both groups can be applied either internally or externally. However, external applications of these systems are more convenient regarding protecting from the external weather condition and better maintenance. A broad range of daylight controlling strategies has been used throughout the history of architecture with a variety of efficiency, regarding controlling heat gain and glare produced by the sun and a high sky illuminance. In addition to softening harsh daylight contrasts and enhance the daylight distribution inside spaces.

The following sections are representing several possibilities for classification the widely used daylighting systems.

Table 2.1 Classification of different daylighting systems

	Daylight control system	Shading / Harvesting		Location		
		Shading	Redirecting	External	Internal	Glazing
		Shading systems				
1	Vertical shading	×		×		
2	Horizontal shading	×		×		
3	Solar screen	×		×	×	
		Daylight harvesting systems				
1	Laser cut panels		×			×
2	Prismatic system		×			×
		Shading / Redirecting systems				
1	Light shelf system	×	×	×	×	
2	Louvers and blends	×	×	×	×	

Shading systems

Introduction

Overcoming problems such as overheating and glare problems, while maintaining an adequate daylight performance requires preventing direct sunlight from transmitting into space. (Vartiainen 2001). Consequently, utilising well-designed shading systems as a mean to prevent thermal and visual discomfort and therefore reducing energy consumption considered being a widely used effective strategy in perimeter office spaces.

Regarding the shading device operation, they can be integrated with the envelope systems and managed automatically and manually to control the daylight performance in interior space (Barkkume 2007). The shading devices usually applied to the exterior façade to control natural light. However, integrating the shading systems with the contemporary, highly articulated facades require considering the aesthetics and environment aspects during the early design stages.

Horizontal shading

Horizontal shading devices are one of the commonest used shading devices to decrease direct solar gain for a high altitude sun (Figure 2.14). Moreover, horizontal shading devices are capable of affording fully shading based on the sun position. However, obstructed visual contact with the exterior for the occupants is considered a disadvantage of these types of shading systems.

Figure 2.14 The use of horizontal shading devices in the Head Office building of Telecommunications Market Commision (CMT), Barcelona, Spain.

Vertical Shading

Vertical Shadings are efficient in blocking direct sunlight at a low angle sun position, such as at the early morning, and the evening, in addition to east and west façades as they block low solar radiation coming from the side (Figure 2.15). The disadvantage of these types is limiting the outside view (Ruck, Aschehoug et al. 2000).

Figure 2.15 Vertical fins attached to the curved building face, Langley Academy, England.

Special types of shading systems: solar screens

The Islamic architecture in the Middle East afforded a different shading strategy via a special external wooden solar screen, called "mashrabiya" (Figure 2.16)). Islamic architects utilised these shading screens in both a functional and aesthetic way as shading as well a design element. When integrated within the building envelope, these screens provide a high visual contact from the interior to the exterior while providing privacy to the interior. Moreover, these traditional screens nowadays inspire architects by harnessing the current advanced technologies in designing modern versions of these types of screens as a mean to reflect the local cultural identity in the form of static and active systems. (Radwan 2013)

Figure 2.16 Traditional Islamic Mashrabia, Beit Alsehiemy. Cairo, Egypt

Daylight harvesting systems

Introduction

Daylight harvesting is the use of natural sunlight to reduce the need for artificial lighting in buildings, by sending direct sunlight to the interior of the room without the secondary effects of glare and overheating (Ruck, Aschehoug et al. 2000). Thus, with the aim to increase the benefits of daylighting in buildings, the designers have utilised many strategies to redirect light into space while minimising the negative effects of direct sunlight into space. Such strategies include reflective architectural elements (McGuire 2005). Many systems can be categorised under harvesting systems such as Louvers, light shelf, light tube, laser-cut panel, and others, however, as mentioned before that Louvers and light shelf can act as both shading and redirecting systems they will be discussed in shading / redirecting systems. The following sections discuss examples of harvesting systems such as prisms, laser cut panels (LCP) and, sun directing glass.

Prismatic System

The design of the prismatic panel system is based on the principle of refraction to redirect incident sunlight. The panels are arranged on one side, creating prisms across the face of the panel (Linhart, Wittkopf et al. 2010). Based on their inclination, the system can improve daylight collection or rejection according to the required design objective (Garcia-Hansen 2006). As a result, the panels should be adjusted seasonally to compensate for the solar altitude differences (Lee, Selkowitz et al. 2002). Moreover, a high-reflectance aluminium film is used in certain types as a coating material on one or both surfaces of the prism.

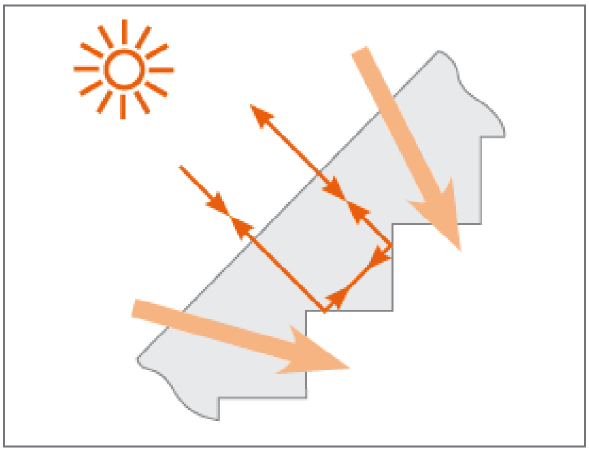


Figure 2.17 The prismatic panel system.

Laser cut panels

Laser-cut panels use straight horizontal cuts in an acrylic panel to refract light. The angle of refraction depends on the material characteristic. Consequently, its efficiency depends on the number and spacing of the grooves and the thickness of the panel. The disadvantages of this type are slightly distorted external viewing and uncontrolled glare (Lee, Selkowitz et al. 2002).

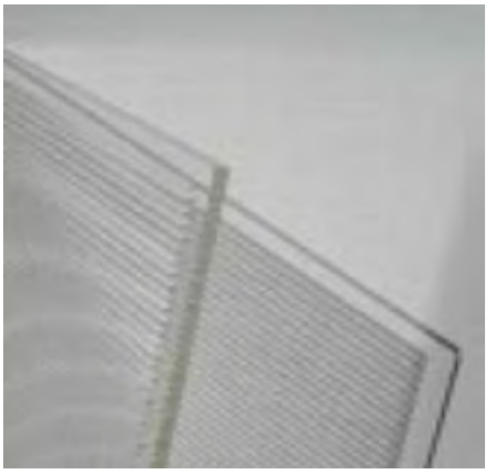


Figure 2.18 Laser cut panel, (Lee, Selkowitz et al. 2002)

Shading / redirecting system

Introduction

The functionality of traditional louvers and light shelves was essentially aiming to block direct light and bounce light back into the outdoor environment. Thus, they were not introduced as light deflectors. They allow the blocking direct sunlight and re-directing natural daylight towards the ceiling outside of the occupants' line of vision. As a result, they ensure even illumination into space, increasing daylight depth in space and protecting occupants from glare and direct sunlight.

Light Shelf System

A light shelf association's solar shading and sunlight redirection, improving the distribution of daylight and permitting a view through the lower part of the window. Light shelves are applicable in sunny climates in mid-latitudes for south orientations (in the northern hemisphere). Light shelves are a classical device in the daylighting toolbox (Ruck, Aschehoug et al. 2000).

A light shelf is a horizontal or nearly horizontal device designed to capture sunlight, particularly in the interior space and the shield building from direct glare (Huang 2010). A light shelf divides the window into two parts. The lower part helps to provide the exterior view, and an upper window helps redirect the daylight towards the back of the room away from the window pane (Boubekri 2008). Such a system should be located high enough to avoid reflected glare and can be used both in exterior and interior spaces. Interior light shelves are more effective in sunlight capture into the back of the space.

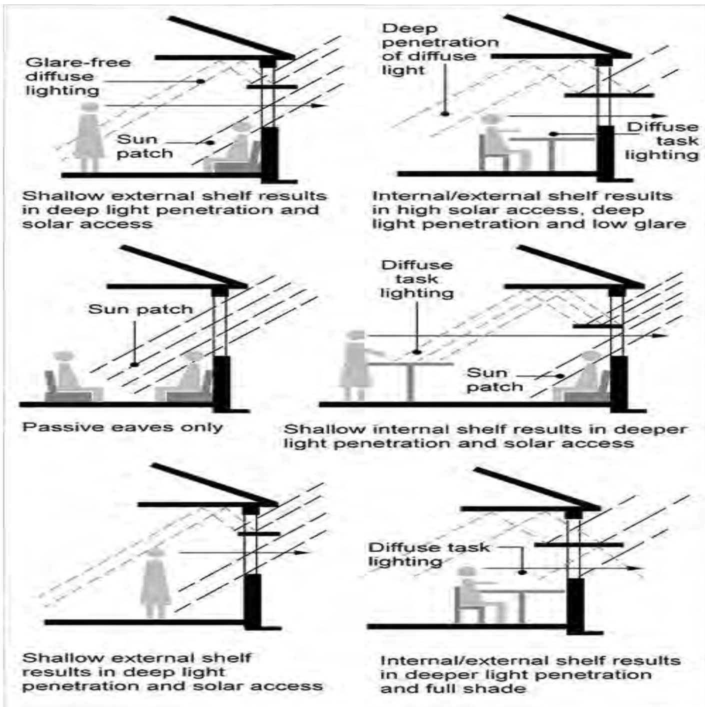


Figure 2.19 A diagram shows sunlight capture with exterior and interior light shelf systems to create a glare-free area, but still allow natural light.

Physical Principles and Characteristics

The orientation, position in the facade (internal, external, or combined), and depth of a light shelf will always be a compromise between daylight and shading requirements. An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior. For south-facing rooms (in the northern hemisphere), it is recommended that the depth of an internal light shelf is roughly equal to the height of the clerestory window head above the shelf. Moving the light shelf to the exterior creates a parallel movement of the shaded area towards the window facade, which reduces daylight levels near the window and improves daylight uniformity (Ruck, Aschehoug et al. 2000). The suggested depth of an external light shelf is approximately equal to its own height above the work plane (Littlefair 1995).

At low latitudes, the depth of internal light shelves can be extended to block direct sunlight coming through the clerestory window at all times. At higher latitudes and with east or west facing rooms, a light shelf may let some direct sunlight (low solar elevation) penetrate the interior, through space between the light shelf and the ceiling, resulting in the need for additional shading devices. Increasing the depth of the shelf will reduce the problem but will also obstruct desired daylight penetration and the outside view. Shading the window perimeter by tilting the shelf downward will reduce the amount of light reflected to the ceiling. Upward tilting will improve penetration of reflected daylight and reduce shading effects. A horizontal light shelf usually provides the best compromise between shading requirements and daylight distribution (Ruck, Aschehoug et al. 2000) (See Figure 2.20).

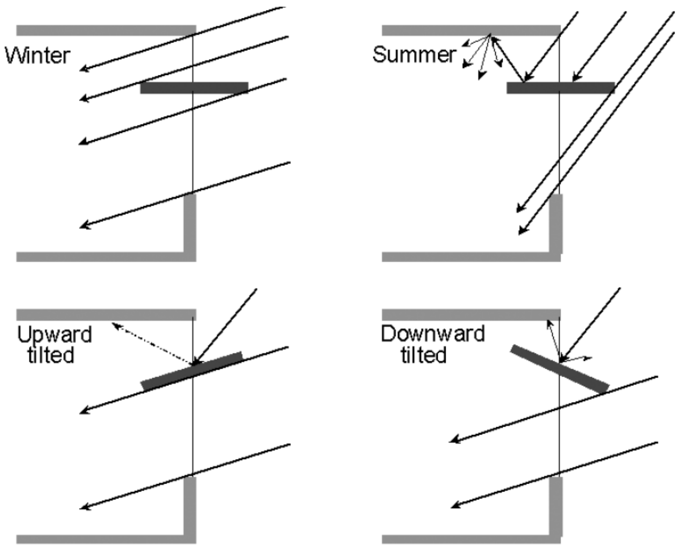


Figure 2.20 Top section of an interior and exterior light shelf with the specular surface, showing the path of sunlight rays in the winter and the summer. The bottom section shows how an upward or downward tilted reflective light shelf influences shading and daylight reflection. Note that, in winter; the light shelf alone does not adequately control glare (Ruck, Aschehoug et al. 2000)

The ceiling is an important secondary part of the light shelf system because light is reflected by the light shelf towards the ceiling and then reflected from the ceiling into the room. The characteristics of the ceiling that affect this process are surface finish, smoothness, and slope. Although a ceiling with a specular surface will reflect more light into the room, care should be taken to avoid glare from the ceiling reflections near the light shelf. To avoid glare, the ceiling finish is usually white diffusing or low-gloss paint. The penetration of light from a light shelf system depends on the ceiling slope. The ceiling that slopes upwards from the window towards the centre of the building will dramatically increase the depth to which light from the light shelf penetrates into the building. For a flat ceiling, light from the light shelf is mostly reflected in space near the window, so penetration of light into the room is more modest (Ruck, Aschehoug et al. 2000).

Many studies have examined the impact of utilising light shelf systems as a mean to improve the daylight performance in different building types. Regarding educational spaces, a study was carried out by (Moazzeni and Ghiabaklou 2016), to investigate the impact of light shelf parameters, such as its dimensions, rotation angle and orientation on daylight performance and visual comfort in educational spaces. The results showed that light shelf dimensions, especially in southern orientation, are significant in the distribution of natural light, as well as decreasing the disturbing and intolerable glare hours.

Another study evaluated the daylight performance of a light shelf (for shading and light redirection) combined with semi-transparent movable external blinds (for more shading, adjusted to the occupants' needs), which were mounted on the glazing of a south-facing classroom. The results indicated that the investigated system upgraded the daylight performance in the examined space under study (Meresi 2016).

Regarding office spaces, a study carried out by (Lim and Heng 2016), proved that high-rise office without any shading had poor daylighting quality with average illuminance as high as 11,193 lux and uniformity ratio below 0.1. However, the optimum cases showed a significant increase in distribution uniformity which was up to 178.6%. The authors proposed a dynamic internal light shelf which could provide optimum daylighting performance for different sky conditions, times, months and orientations under a tropical sky. Nevertheless, the proposed light shelf failed in giving significant improvement in the CIE Glare Index.

Louvers and blinds

Traditionally, louvers have been used as a shading device through managing the sunlight, to improve light penetration depth within the space. However, blocking the direct view of the outside and creating a problem for cleaning and maintenance are considered as being disadvantages of applying exterior louvers (Boubekri 2008).

Reflective louvers redirect sunlight to the back of space and forms a large diffuse light source on the ceiling instead of falling on the occupants (Littlefair 1990).

Horizontal louvres are best suited to south facing windows. For east and west facing windows using louvres which slope diagonally across the window is efficient (Hashemi 2014).

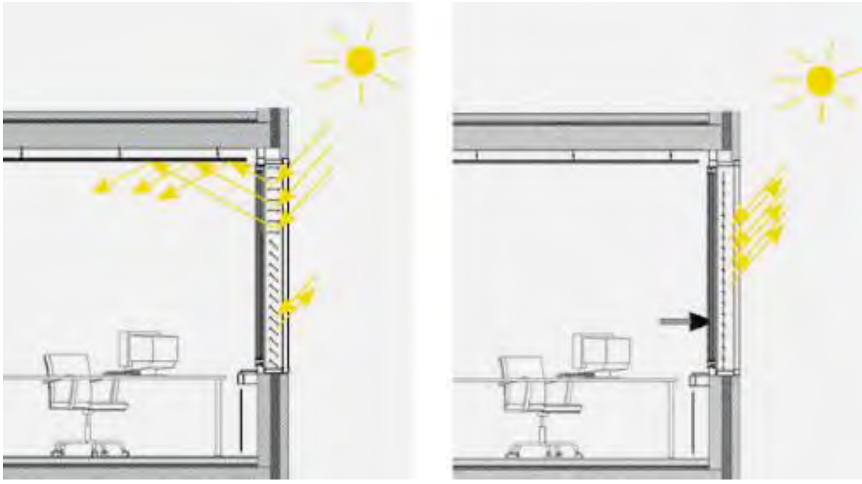


Figure 2.21 Shown an example application where louver can act as both daylight Light-redirecting ad shading system based on different inclination angles (Boubekri 2014).

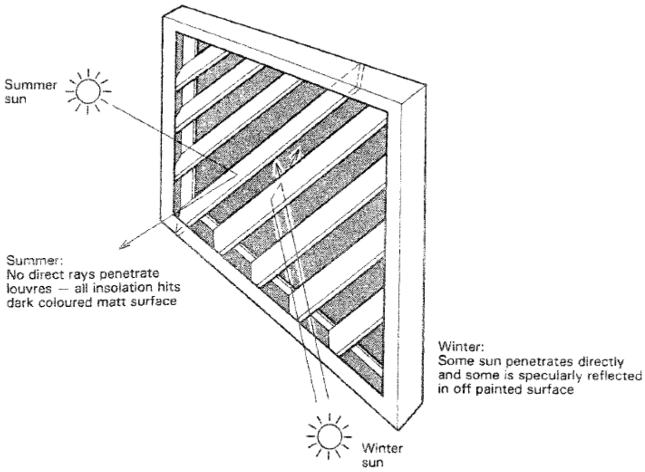


Figure 2.22 Inclined louvre for west-facing window Littlefair (Littlefair 1990).

Louvers systems can consist of multiple horizontal, vertical, or sloping slats and can be applied internally or externally. Well-designed louver systems are capable of blocking the sun ray's either partially or entirely. Moreover, they can improve the daylight penetration depth and uniform daylight distributions, in sunny and overcast conditions respectively (Ruck, Aschehoug et al. 2000). However, in sunny conditions, a well-designed system is essential if they required playing a role of shading devices.

Many studies have examined the impact of utilising reflective louver systems as a mean to improve the daylight performance in different building types. One study proved that reflective louvers and blinds are capable of playing the role of both shading and light redirecting systems. Parameters such as dimensions, geometry, and rotation are significant addressing the system's functions. For instance, downward inclination angles can perform as a shading device, while upward inclination angles can act as a daylight redirecting system and improve the daylight penetration depth into space. A combination of two groups of louvers, one act as a shading system while another serve as a redirecting system or by rotating each louver with an independent angle can integrate both advantageous shading and redirecting systems (McGuire 2005). (See Figure 2.23).

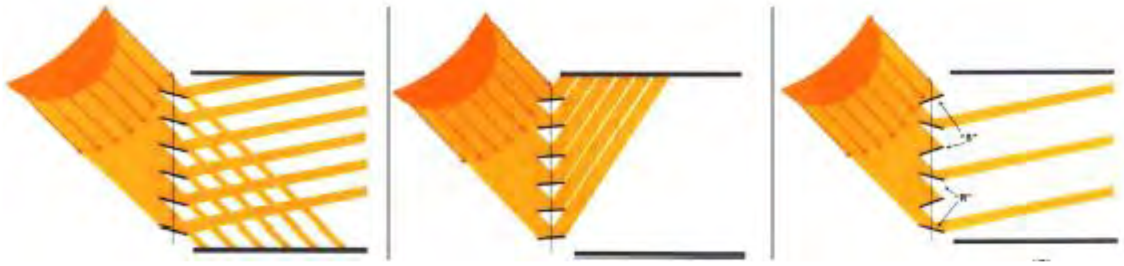


Figure 2.23 Louvers optimised for sunlight redirection, shading and combined system (McGuire 2005).

Another study by (Hashemi 2014) showed that reflective louvres could delay the air temperature rise by blocking/reflecting the sunlight, thereby reducing the cooling loads. The system allows each louvre to be controlled and placed separately from other louvres. The results showed that the system significantly improved daylight distribution and reduced the need for artificial lighting by 60%.

Physical Principles and Characteristics

Louvers and blinds could obstruct, absorb, reflect and/or transmit solar radiation (diffuse and direct) to a building's interior. Their influence depends on the position of the sun and their location (exterior or interior), slat angle, and slat surface reflectance characteristics. Thus, the optical and thermal properties of a window with louvers or blinds are highly variable. Horizontal blinds in a horizontal position can receive light from the sun, sky, and ground. Upward-tilted slats transmit light primarily from the sun and sky, and downward-tilted slats transmit light primarily from the ground surface. Both louver and blinds can increase penetration of daylight from direct sunlight Ruck (Ruck, Aschehoug et al. 2000). The Building Research Establishment, United Kingdom (UK), tested conventional 38-mm Venetian blinds with a light grey finish. The blind system was monitored at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office, under overcast sky and clear sky with the sun, the results are presented as follows:

Overcast Sky

The daylight factor on the work plane for Venetian blinds was measured at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements were made for 3 days in the reference room and then averaged. The conventional Venetian blinds with a light grey finish in a horizontal slat angle position produced moderate, uniform variation in light between the window area and at the back of the room. The excessive light was reduced in all cases, even when the slats were in horizontal position (Ruck, Aschehoug et al. 2000). (See Figure 2.24).

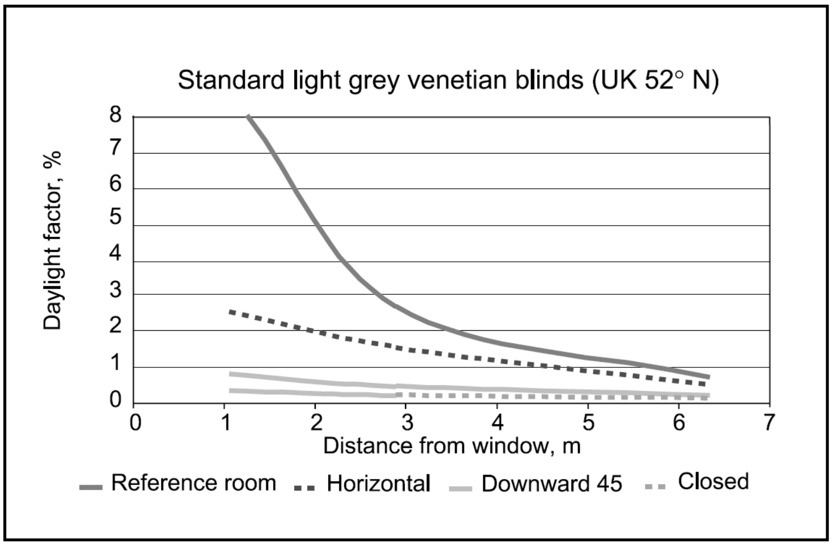
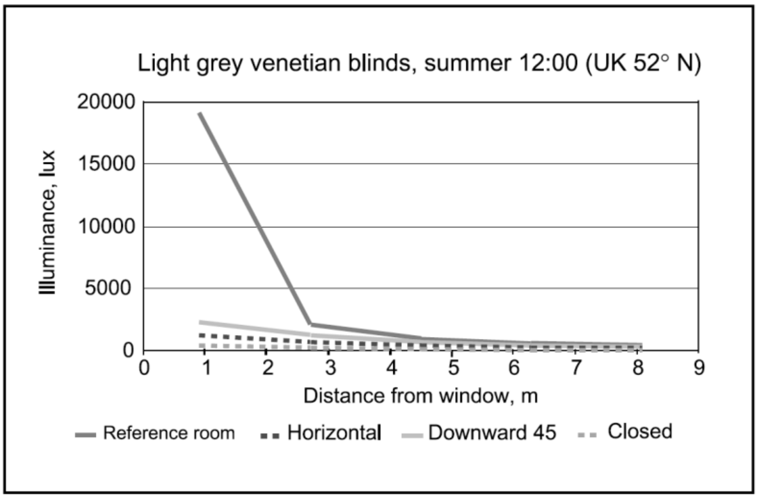
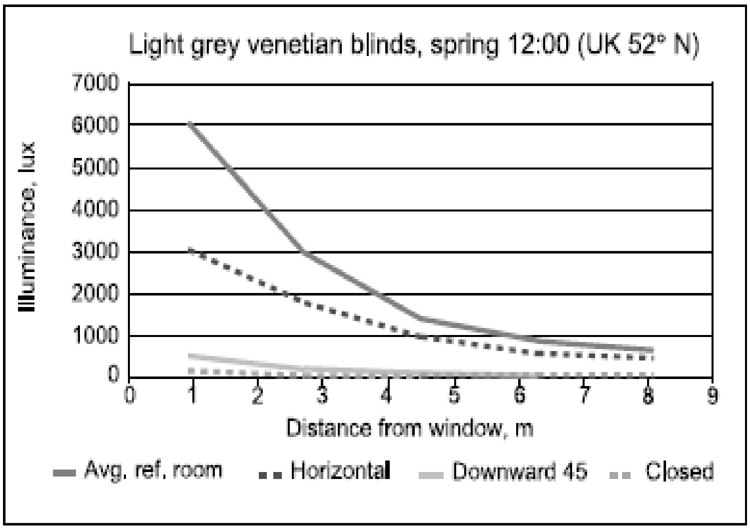


Figure 2.24 The daylight factor on the work plan for standard grey Venetian blinds was measured at three slat angle positions (horizontal, 45° downward tilted, and fully closed) under the Overcast sky.

Clear Sky

The illuminance level was measured on the work plan for standard grey Venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). At high sun positions, the blind inhibited sunlight from entering the room and reduced the difference in illuminance levels between the window area and the rest of the room. At low sun position, the slats in horizontal position reflected the sunlight into the interior, increasing the illuminance considerably compared to the effect of the downward-tilted position (Ruck, Aschehoug et al. 2000) (see Figure 2.25).





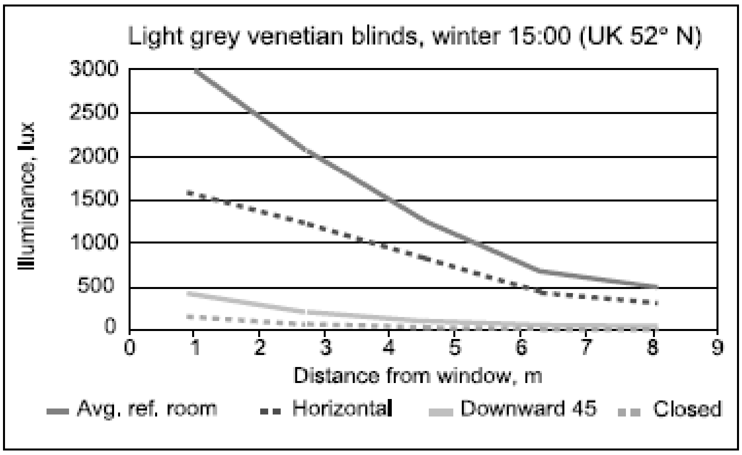


Figure 2.25 The illuminance level on the work plan for standard grey Venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed), measurements were taken over three days under a clear sky.

The results of this study concluded that there is no advantage for glare control in closing the slats beyond 45°, and there are significant disadvantages regarding room illuminance levels.

Daylight performance indicators in office spaces

Performance parameters can be utilised to justify whether a lighting or daylighting solution is suitable for particular design objectives. The parameters can also be used to quantify the effectiveness of an innovative daylighting strategy or system. The evaluation of daylight system requires performance parameters to benchmark its effects and performance. These parameters can be used to evaluate whether a given lighting condition permits sight or visibility (Ruck, Aschehoug et al. 2000).

Several studies regarding daylight quality and performance have been carried and showed different assessment criteria for the quality of daylight inside a space. In 1994, the committee of quality of the visual environment of the Illuminating Engineering Society of North

America (IESNA) identified ten aspects that impact upon lighting quality, and which can also be used to evaluate daylighting quality:

- Brightness (comparative luminance) of room surfaces;
- Task contrast; Task illuminance;
- Source luminance (glare);
- Colour spectrum and colour rendering;
- Daylight (view);
- Spatial and visual clarity;
- Visual interest;
- Psychological orientation;
- Occupant control;
- System flexibility.

In the IESNA assessment criteria, factors like visual interest, psychological orientation, and occupant control, are hard to evaluate, due to the various personal variables involved in each factor. The remaining factors can be evaluated through calculations and computer simulations (Dubois 2001).

In office spaces, considering Task plan illuminance, daylight distribution, illuminance contrast ratio, and glare can produce good visibility and enhance the visual experience. Based on the objective of this research, the four mentioned factors are considered for evaluation parameters, in addition to two associated parameters, which are light penetration depth, and solar radiation as they considered being effective regarding improving occupant comfort, energy conservation, and preventing glare. Thus, the following section briefly introduced these parameters.

Performance Indicators

2.3.1.14. Task Illuminance

Illuminance is the whole, illuminating light flux falling on surfaces per unit area; it is a measurement mode for the amount of the lighting that illuminates the surfaces. Many international organisations recommend illuminance levels for office spaces. IESNA, for example, recommends illuminance levels in a typical office space of 200-500 lux (America 2000), while the NRC suggests a level of 400 to 500 Lux (Newsham, Veitch et al. 2004) and the European Standard for Light, Lighting for Indoor Work Spaces recommends a minimum for office work of 500 lux (CEN 2002), and LEED (Leadership in Energy and Environmental

Design) (USGB 2014), suggests a level of 300 to 3000 Lux, and likewise, (Mardaljevic, Andersen et al. 2012).

2.3.1.15. Luminous Distribution

Luminance distribution is a measure of how lighting varies from point-to-point across a plane or surface. A certain degree of uniformity across the task plan is desirable for good visibility (Ruck, Aschehoug et al. 2000), while a luminance distribution with a large range will produce bad visibility, forcing the eye to adjust itself very rapidly and uncomfortably.

(Mardaljevic, Andersen et al. 2012), states that the daylight illuminances in the range 300 to around 3,000 Lux, are often regarded as desirable or at least tolerable. Moreover, additional artificial lighting will most probably not be necessitated. Furthermore, the UDI scheme is applied by defining at each calculation point the incidence of daylight levels where:

• UDI 'fell-short' (or UDI-f) when the illuminance is less than 100 lux.

• UDI supplementary (or UDI-s) when the illuminance is greater than 100 lux and less than 300 lux, i.e.

• UDI autonomous (or UDI-a) when the illuminance is greater than 300 lux and less than 3,000 lux.

• UDI combined (or UDI-c) when the illuminance is greater than 100 lux and less than 3,000 lux.

• UDI exceeded (or UDI-e) when illuminance is exceeding 3,000 lux.

2.3.1.16. Illuminance Contrast Ratio

For a healthier visual environment within the occupant's field of view, IESNA recommends that the ratio between the maximum and minimum illuminance value should not exceed 1:10 (America 2000). However, the NRC recommends 1:20 (Newsham, Veitch et al. 2004).

2.3.1.17. Glare

Glare is a visual condition which results in discomfort with visual efficiency, or eye fatigue because of the brightness of a portion of the field of view (lamps, luminaires, or other surfaces or windows that are significantly brighter than the rest of the field) (Ruck, Aschehoug et al. 2000).

There is the potential for a high level of glare and a risk of overheating when illuminance levels are more than 2000 Lux (Reinhart and Wienold 2011), (Wienold 2009). The Daylight Glare Probability [DGP] metric is used in the comfort evaluation and considers the brightness of the view, the position of 'glare' sources and visual contrast. Glare is deemed to be intolerable if DGP is larger than or equal to 45%, disturbing when it is between 40% and 45%, perceptible when it is between 40% and 35%, and imperceptible when it is less than 35% (Wienold 2009). A DGP of less than 35% was the criterion set for TABS performance in this study.

2.3.1.18. Light Penetration Depth

According to (O'Connor, Lee et al. 1997), daylight penetration with typical depth and ceiling height is 1.5 times window head height for standard windows. Utilising light shelf allows deeper daylight penetration into the building of up to 2 times, leading to improved daylight performance inside space and consequently less dependence on artificial light (Figure 2.26).

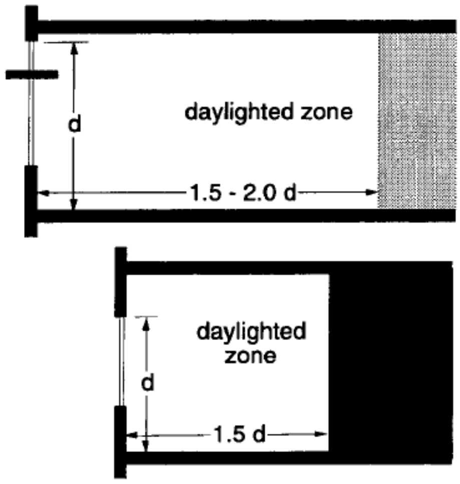


Figure 2.26 A rule of thumb for daylight penetration with typical depth and ceiling height is 1.5 times head's height for standard windows and up to 2.0 times head height with light shelf, for south facing windows.

Daylight Metrics

Introduction

Many daylight metrics have been developed over the years for the purpose of setting a scale for designers to use when comparing the aspects of daylighting design. Each metric differs and has a variety of strengths and weaknesses. Some metrics are limited in use to a particular type of sky, while others are restricted to measure a single date and time. The aim of the different metrics is to help designers to distinguish well daylit, and comfortable spaces.

2.3.1.19. Daylight Factor (DF)

Daylight factor can be calculated by dividing the internal horizontal illuminance value of a point inside the space on the horizontal illuminance value of the unshaded external point under a CIE overcast sky (Reinhart and Fitz 2006). One advantage of Daylight Factor is well-defined and simple to calculate. However, it does not account for orientation, shading and glare control, or changes in sky conditions. As defined, the Daylight Factor was mainly proposed for overcast sky condition and cannot be used under another sky condition. Moreover, the daylight factor was meant to be a measure of a minimum legal lighting requirement, rather than good daylighting design (Reinhart, Mardaljevic et al. 2006). Daylight Factor can give a general report of the average daylight conditions in space, but in cases of greatly high illuminance cannot be addressed. Hence, locations with sunny skies or direct sunlight are not well represented. Therefore, locations with direct sunlight or sunny skies are not well represented.

2.3.1.20. Single Point in Time (SPT)

In this metric, illuminance calculation at a certain point can be measured for a specific time of the year. The SPT method accounts for variation in designs such as orientation and shading mechanisms. However, with changes in the functions of buildings, it is urged to account for different measuring times that represent the various conditions throughout the whole year. Therefore, Annual Dynamic Metrics were developed.

2.3.1.21. Dynamic Daylight Performance Metrics (DDPM)

Dynamic daylight performance metrics are based on time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. DDPM offer an outstanding opportunity to study the annual performance of daylighting. This method quantifies the daylight availability's measurements inside space based on annual illuminance. These measurements were generated from a weather file and utilised through hours of occupancy. The key point in utilising these metrics is its ability to consider the pattern and quantity of daily and seasonal differences of daylight for a given building site throughout the irregular meteorological events during the entire year (Reinhart, Mardaljevic et al. 2006).

These metrics include:

a. Daylight Autonomy (DA)

Daylight Autonomy (DA) is a performance indicator based on record climatic data. It can be defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is achieved by daylight alone (Reinhart and Walkenhorst 2001). For example, it is utilised for calculating the percentage of time during the entire year for which daylight can provide a specific illuminance value (e.g. 500 Lux) in the interior space (on a work plan). Thresholds for work plane illuminance values are given in certification documents such as LEED, where the minimum value is 300 lux (Hu, Place et al. 2014). In this thesis the daylight autonomy threshold was chosen as 500 lux, taking into account the effects of direct solar radiation on the indoor illumination levels and considering any given hour, geographic location, and sky condition on an annual basis. Furthermore, daylight autonomy uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that occupants can work by daylight alone (Reinhart, Mardaljevic et al. 2006).

Recently, modified methods of daylight autonomy have been introduced, such as continuous daylight autonomy, useful daylight illuminance, and spatial daylight autonomy.

b. Continuous Daylight Autonomy (DAcon)

Proposed by (Rogers 2006), DAcon is a modified version of the daylight autonomy metric. Continuous Daylight Autonomy gives a partial count to, times when the daylight illuminance at a given point lies below the task/ambient lighting threshold. For example, when a point receives 400 lux but the required illuminance is 500 lux, the point is credited 400/500 or 80% for that time step. This method gives credit to spaces that are not fully saturated with daylight but do receive some daylight contribution (Reinhart, Mardaljevic et al. 2006).

c. Useful Daylight Illuminance (UDI).

Useful daylight illuminance (UDI), proposed by (Nabil and Mardaljevic 2006), calculates the complete occupied hours that "useful" daylight enters a space at a selected point. Useful daylight is defined as providing ambient light at the work plane at illuminance levels between 100 lux to 2,000 lux, where the upper limit might lead to discomforts such as glare or thermal. However, there is a notable discussion regarding the choice of 2,000 lux as an 'upper threshold' above which daylight is not desired due to potential glare or overheating (Reinhart and Wienold 2011), (Wienold 2009). However, the selection of 2,000 lux as an absolute upper threshold is supported by some researches (Reinhart, Mardaljevic et al. 2006). In a more recent study, the daylight illuminances in the range 300 to around 3,000 lux were often perceived either as desirable or at least tolerable in largely office buildings based on survey. In addition, it is importantly noted that many of these surveys were carried out before LCD display panels (which are much less prone to glare than CRT screens) became commonplace. The UDI range is further subdivided into two ranges called UDI-supplementary and UDI-autonomous. UDI autonomous represents the daylight illuminances in the range 300 to 3000 Lux where additional artificial lighting will most probably not be necessary (Mardaljevic, Andersen et al. 2012). Moreover, long-term beneficial health effects had found In the case of regular exposure to high illuminances during daytime (Webb 2006). Furthermore, US Green Building Council. LEED recommends daylight illuminances in the range 300 to 3000 Lux (USGB 2014).

d. Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy is the percentage of area that receives at least 300 lux for 50% of the annual occupancy hours. Additionally, evaluating the occurrence of direct daylight (> 1000 lux) on an annual basis using a metric called annual sunlight exposure (ASE). The metric sets a threshold of 10% of the evaluated area that is receiving direct daylight for more than 250 hours per year this metric is used for fulfilling the requirements of LEED (USGB 2014).

e. Daylight Availability

This metric was developed to combine DA and UDI. The metric presents three evaluation criteria: "Daylit" areas, similar to DA, for spaces that receive at least half the time sufficient daylight, "Partially Daylit" areas, which are below useful illuminance and "Over lit" areas that provide warning when an oversupply of daylight (10 times target illuminance) is reached for at least 5% of the working year (Reinhart and Wienold 2011).

F. Daylight Glare Probability (DGP)

DGP estimates the probability that a person is affected by glare and is derived from a subjective user evaluation (Wienold and Christoffersen 2006).

This metric is used in the comfort evaluation and considers the brightness of the view, the position of 'glare' sources and visual contrast. Glare is deemed to be intolerable if DGP is larger than or equal to 45%, disturbing when it is between 40% and 45%, perceptible when it is between 40% and 35%, and imperceptible when it is less than 35% (Wienold 2009).

Several studies have been conducted on architectural lighting design to maximise daylight performance in the building (Oh, Chun et al. 2013). The role of computerised building design tools provides such information efficiently. A survey conducted by (Reinhart and Fitz 2006) regarding the current use of daylight simulations in building design and confirmed that 69% of professional designers used software to analyse natural light in the building. However, dynamic daylight simulations (DDS) require a three-dimensional computer generated model of a building which includes data on the building geometry and its context as well as reflection and transmission characteristics of material surfaces (Reinhart 2006).

The different daylighting metrics are summarised in Table 2.2:

Table 2.2 Daylighting metrics for office buildings.

Daylighting metric	Sky Type	Minimum Threshold		Maximum Threshold		Calculations
Daylight Factor (DF)	CIE Overcast	2-5%		NA		Annual
Single Point in Time Illuminance (SPT)	All	500 Lux		NA		In time
Daylight Autonomy (DA)	All	500 Lux		NA		Annual
Continuous Daylight Autonomy (cDA)	All	500 Lux (partial count for points below)		NA		Annual
Useful daylight illuminance (UDI)	All	100 Lux 300 Lux		2000Lux 3000Lux		Annual
Spatial daylight autonomy (sDA) and (ASE)	All	300 Lux 50% of the annual occupancy hours.		10% of area receiving direct daylight for more than 250 hours per year		Annual
Daylight Availability	All	500 Lux		provide warning when an oversupply of daylight (10 times target illuminance) is reached for at least 5% of the working year		Annual
Daylight Glare Probability (DGP)	All	Categories				Annual In time
		Imperceptible (DGP < 35%)	Perceptible (40% > DGP ≥ 35%)	Disturbing (45% > DGP ≥ 40%)	Intolerable (DGP ≥ 45%)	

Static vs Adaptive Building's Skin Systems Regarding Daylighting Performance.

One of the primary functions of buildings is to protect the residents from the extremes of climate conditions, in a way that building skins act as mediators between internal and external conditions (Velikov and Thun 2013). Building envelopes' thermophysical and optical properties play an important role in building energy consumption and indoor environmental conditions. Climatic conditions which provide an environmental context in any geographical location vary between different times during the entire year. Consequently, traditional static building envelopes, by being static, may find their effectiveness varies throughout the year due to daily and seasonal climatic changes, resulting in envelope designs that provide unsatisfactory building performance during some periods of the year (Wang, Beltrán et al. 2012).

According to (Lee, Selkowitz et al. 2009) the coupling of an automated shading system with moderate to large window areas provides comparable savings in thermal loads as those attained by simply downsizing the window, but with the added benefit of more daylight.

Adaptive opportunities incorporated into the building's skin can offer a range of responses to environmental stimuli, to mitigate undesirable elements and provide the ability to significantly modify indoor comfort without the need of mechanical climate control systems. (Konstantoglou and Tsangrassoulis 2016).

Thus, adaptive facade technologies that actively adjust in response to ambient conditions, occupant preferences and building energy management control system, can overcome some of the limitations of fixed exterior shading. Technologies such as automated shading systems, switchable Electrochromic and Thermochromics glazing can more effectively manage daylight while minimising solar gain (Lee, Selkowitz et al. 2002).

Nowadays, innovative building envelopes are more adaptive by actively responding to prevailing climatic conditions for enhancing energy performance and indoor comfort levels. Therefore, a further discussion regarding the state of the art of the Adaptive building envelope is the main objective of the next Chapter.

Conclusion

Natural lighting is a vital factor in building design to improve the quality of indoor environment and user well-being and productivity, while decreasing the energy used by artificial lighting, cooling and heating loads (Ander 2003). This is especially true for office buildings, which are considered to be high-energy consumers compared to other building types (Westphalen and Koszalinski 1999). However, an excessive amount of light may cause excessive heat gains and the possibility of uncomfortable glare (Etman, Tolba et al. 2013). The expansion of office buildings that utilises large-scale glazing in the 19th century highlighted the importance of the essential need to restore the efficient use of daylighting in office buildings which nearly became a lost art with the emergence of electric lighting to support sustainable buildings.

Daylight is capable of replacing a significant part of the artificial lighting used in office buildings through the efficient utilisation of daylighting strategies such as the building massing and orientation, envelope transparency concepts, shading and daylighting systems.

Many cases of ancient vernacular architecture show good examples of how building design can deliberately take advantage of available conditions in the exterior environment (Zhai and Previtali 2010). The designers utilised solar shading and light-redirecting systems efficiently throughout the history to control sun penetration in buildings with the aim of improving daylighting performance indicators, such as daylight distribution and penetration depth, as well as preventing excessive heat gains and preventing glare.

The impacts of shading devices on energy use have been widely studied, focusing on the impact of shading devices on the cooling loads, and other studies indicated that shading could efficiently reduce the cooling load of buildings (Dubois 1997). Furthermore, during the last decades the impact of shading devices on daylighting took a central interest as a means of artificial lighting reduction.

A light shelf can combine solar shading and sunlight redirection, improving the distribution of daylight and allowing a view through the lower part of the window. However, in winter, the light shelf alone does not adequately control glare.

Some systems, such as exterior louver, are designed to satisfy all functions of a standard window as a stand-alone system. However, such a “one size fits all” system, which usually covers the whole window area, in most cases, will have a poor performance. Regarding glare control shading devices are designed to block the direct sunlight and as a result, keep the heat outside. However, in the case of applying shading devices internally, they cause overheating in between the shading device and the window also, it results in heating up space's interior surfaces and air by radiation and convection.

Therefore, applying louvers internally can be considered to be a glare control devices and daylight redirecting system rather than a shading device.

The Islamic architecture in middle east afforded a different shading strategy via a special external wooden solar screen, called "mashrabiya" Islamic architects utilised these shading screens in both functional and the aesthetic way as shading as well a design element. These solar screens are efficient strategy regarding shading provision and privacy concerns by blocking direct sunlight to reduce heat gains and glare while allowing the indirect light to diffuse into space through shading elements. However, these solar screens usually fail in improving daylight penetration depth.

To sum up, a good selection of systems means a good mixture of systems (Ruck, Aschehoug et al. 2000).

All these systems require much less expensive and maintenance; However, they are not capable of responding to the changing environmental conditions to maintain satisfying the occupants demands throughout the year due to its static nature.

On the other hand, well-designed automated adaptive systems can continuously provide a pleasant and productive environment in office spaces in a proper way due to the embedded adaptive capacity.

Therefore, exploring the advancement of modern technologies in designing dynamic systems should be the starting point for any successful design and play a dominant part in the early design stages, to achieve the primary objectives for effective daylighting such as providing adequate daylight to the spaces, controlling glare, and solar radiation to minimise energy consumption.

Thus, an extended discussion regarding the adaptivity in architecture and the current advancements in computational tools is essential to understand the characteristics of such systems and the available parametric, Genetic Algorithm (GA), and Building performance simulation (BPS) tools that assist the design and performance evaluation process of these adaptive systems. These are the objectives of the next chapters.

Chapter Three

3. Adaptive Architecture

3.1. Introduction

A central attention to energy efficiency and occupant comfort were given internationally, accompanied by an emerging demand to integrate sustainability–related performance approaches within design stages as daylighting and energy (Lagios, Niemasz et al. 2010). Adaptivity in architecture is based on the relationship between the variable needs and the capability of a building to satisfy them in a varying environment (Turrin, von Buelow et al. 2011).

Thus, making an efficient building skin that interacts with its surrounding environment is one of the most important objectives for architects today (Etman, Tolba et al. 2013). Building skin plays a crucial role as a responsive and active controller of the interchanges occurring between the external and internal environment, and is one of the most important methods to save energy inside a building.

This chapter carries on with a discourse of adaptation in architecture. The concept is identified and defined along with a summary and an overview of categories of adaptive architecture. Furthermore, the criteria for assessing building performance, characteristics of adaptable building skin, advantages, design demands and sources of inspiration are introduced. Moreover, the advantages of the adaptive building envelopes over the traditional static solutions are discussed. Finally, conclusions are provided.

3.2. Adaptation in Architecture

In an ideal case, the building skin would be designed in such a way that the operation of the whole building, regarding environmental, economic and social attributes, is maximised (Loonen 2010). All buildings (except masterpieces) adapt anyhow, however poorly, because the usages in and around them are always changing.

All these factors remark the need of updating the traditional approaches of the building skin from acting as a passive barrier towards a building skin which acts as an active negotiator with the surrounding environment. Recent advances in materials, controls and system modelling now mean that building envelope can be a dynamic element which acts as a negotiator with the external environment and an enhancer of the internal environment (El Sheikh 2011).

Recently, with the speedy growth in material sciences and fabrication technology, coupled with the availability of economic options for hardware, sensors, processors and actuators (Fox and Kemp 2009), (Schaeffer and Vogt 2010), adaptive building envelopes become a viable and interesting field of study (Addington and Schodek 2005), (Drozdowski 2011).

Adaptivity in architecture as a concept has been given several alternative names, such as interactive (Fox and Kemp 2009), dynamic (Lollini, Danza et al. 2010), kinetic (Fox and Yeh 2000), and Climate Adaptive Building Shells (CABS) (Loonen, Trčka et al. 2013), and responsive (Kirkegaard and Foged 2010), are examples of these systems, that when applied to a building skin, can actively adapt their behaviour over time in reply to varying environmental conditions and performance requirements. Therefore, they have the ability to harness the natural energy available in our environment much more effectively. These adaptive building skins can contribute to reducing the energy demand for lighting and space conditioning, positive enrichment to indoor air quality and thermal and visual comfort levels (Loonen, Trčka et al. 2013).

3.3. Building Performance

Discussing the business concept of successful technology and the operation features of building envelopes is a significant step to be undertaken first to increase awareness about the requirements and accepted level of successful techniques and buildings' functioning, before discussing adaptive building skin in specific. In that context, the adequate performance of the contemporary building skin can be explained by the Triple Bottom Line principle. This business concept argues that, for any successful technology a proper equilibrium needs to be achieved between performance merits for people, planet and profit (Elkington 1998). (See Figure 3.1.)

Figure 3.1 Triple Bottom Line principle

For narrowing down the performance aspects of the building skin more precisely, a widely accepted list of eleven principle functional requirements to be conceived in the design process of building envelopes was presented by (Hutcheon 1963).

1. Control heat flow;
2. Control air flow;
3. Control water vapour flow;

4. Control rain penetration;
5. Control light, solar and other radiation;
6. Control noise;
7. Control fire;
8. Provide strength and rigidity;
9. Be durable;
10. Be aesthetically pleasing;
11. Be economical.

In this respect, it is sensible to reconsider the role of the building skin as a mediator with multiple critical functions that dictate the building's energy consumption and perception of indoor environmental quality.

The impact of new advancements in materials and dynamic automation with embedded microprocessors, wireless sensors and actuators have changed the way architects approach building design, from form to performance and from structure to the envelope (Hensel and Menges 2006).

3.4. The Characteristics of Adaptive Building Skins (ABS)

Conceptual Characteristics

Adaptive system design is coupled with various terminologies for describing the different characteristics of the system's flexibility, such as adaptability, multi-ability and evolvability.

The following section summarises these aspects:

3.4.1.1. Adaptability

Adaptability is the capability of providing a planned functionality based on multiple criteria under variable condition via changing the physical values of its design variables over time (Ferguson, Siddiqi et al. 2007). By having these capabilities, building envelopes can be considered as a building negotiator between building demands and the fluctuating environmental conditions (Addington 2009).

3.4.1.2. Multi-ability

The multi-ability system can give the possibility of individually responding building skin's faces to the ambient conditions or to distinct comfort preferences demanded by the users in different zones, resulting in a potential for spatial performance flexibility within the building spaces (Addington 2009).

3.4.1.3.Evolvability

Evolvability is the capability to keep options open to react to changes in the future. In that sense, it is more concerned with changes over a longer time-horizon. Accordingly, having this quality increases the opportunities that the building can continue operating as intended, without suffering from the potential negative impacts of expected future conditions, either coming from the outside (e.g. climate change, changing urban environment, wearing of the façade) or from the inside (e.g. organizational function changes of the building, new space layout) (Fawcett, Hughes et al. 2012).

Functional Characteristics (process)

According to Wyckmans, the skin adaptive to its environment can be described as similar to a human's adaptive to their surrounding environment. Thus, by following the same psychophysical process sequence of perception, reasoning and action that human used to adapt, the building envelope will be able to deal with changing situations that are happening in its environment as well as solving conflicts. Thus, having these three functional characteristics enables the building envelope to be successfully adaptive to the surrounding dynamic environment. The psychophysical process of perception, reasoning and action are described in the following sections (Wyckmans 2005).

3.4.1.4. Perception

According to Albus, it is the conversion of data derived from sensors into meaningful and useful illustrations of the external states of the world as well as the internal states of the system itself (Albus 1999). By doing this, the building skin will be able to supervise the operation of its parts to ensure optimal performance. The final purpose will be modifying and fine-tuning its performance to environmental conditions as they happen, in addition to monitoring the building occupants, such as their existence as a mean to consider the required degree of comfort, or at some times their certain needs, such as task performance in the office building as required in this thesis (Wyckmans 2005). Therefore, spreading over the system to collect real data and being reliable are two important visions that the system should meet to be effectively used in this stage (Moradi, Razini et al. 2016).

3.4.1.5. Reasoning

The reasoning is the capability of processing information from multiple sources into an optimal solution, expecting environmental conditions based on previous situations, learning occupant preferences and predicting the outcome of skin actions (Wyckmans 2005).

The most important capability of any successful adaptive building skin is the ability to learn the appropriate manner in which to react to the environment conditions and occupants' preferences to achieve desired solutions for each case. In doing this large memory capacity and fast ''number crunching'' abilities are required (Kasabov and Kozma 1998). Moreover, in the reasoning stage for online operation an extraordinary speed decision- making the algorithm which can be handled by parallel processing of intelligent negotiators is essential (Moradi, Razini et al. 2016).

3.4.1.6. Action

Action process is the capability of taking an appropriate response in reaction to environmental conditions in suitable timing for the execution of a response based on the type of event that initiated the response (Wyckmans 2005).

For the action stage, an independent physical action of mediators needs to be considered so that the combination of negotiators' actions sustains the stability of the system and fulfil the given overall objectives (Moradi, Razini et al. 2016).

3.5. Adaptive Building Skin (ABS) System Analysis

The development in the area of adaptive building envelopes is spread along many domains and formulated by a variant of developments’ fragments, associated with the contemporary advancement in design teams’ creative capabilities and the afforded material sciences and technologies. With the aim of exploring the fully diversity of this concept, the notion of ABS with special focus on climate has been analyzed and classified based on many themes, by (Loonen, Trčka et al. 2013), (Loonen, Trcka et al. 2011), Accordingly, within the context of this thesis, the analysis and classification of adaptive building envelopes are considered to be discussed based on six main themes: Application area, adaptive behaviour, time scale, control types, relevant physics and sources of inspiration. All these themes are discussed in the following sections.

Adaptive Application Area

Adaptive features can be applied to different parts of the building, individually or the whole exterior skin, In the light of that, Loonen considered five possibilities for applying the adaptive features, described below and shown in Figure 3.2.

- Opaque envelope elements.
- Glazing or the transparent and semi-transparent parts of the envelope.
- Roof.
- Inside the skin surface.
- The whole building skin.

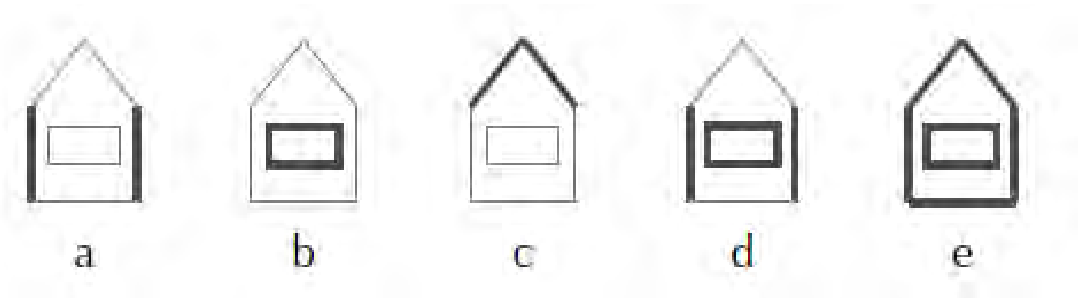


Figure 3.2 Possibilities for applying the adaptive features (Loonen 2010).

Adaptive Behaviour

3.5.1.1.Climate

Passive architecture has been evolving over hundreds of years as a means to control indoor comfort via applying static design structures with the aim of achieving a seasonal and annual suitable control over environment impacts (Butti and Perlin 1980); on the other hand, with fluctuating weather patterns, seasonal differences and the changing comfort demands and energy requirements of indoor occupants, these passive strategies due to hourly and daily changes in the weather cannot afford stability and continuity in term of climate control. Thus, utilising dynamic controls are required (Wigginton and Harris).

The traditional impression is to consider the surrounding environment as an enemy of occupants and to try to mitigate the impact of climate on the occupants by considering the building envelope as shelter. This is usually achieved through artificially conditioned buildings with adequately sealed envelopes; as a result, the building becomes insensitive to surrounding environment and prevent the envelope from playing its real role as a moderator (Addington 2009). Conversely, adaptive building skins take full advantage of the positive influences found in nature, while mitigating the disadvantages via utilising its adaptive capabilities.

Loonen considered six elements are the most important weather elements of interest in architecture and buildings, together with their corresponding implications:

1. Dry bulb air temperature regarding thermal comfort, heating and cooling.
2. Relative humidity regarding thermal comfort, condensation, mould growth.
3. Rain regarding drainage, loading, damage.
4. Speed and direction of Wind regarding Energy, ventilation, comfort.
5. Solar radiation regarding daylight availability and useful solar heat gains.
6. Cloud cover regarding diffuse daylight and radiation to the sky.

In the light of that Loonen argues that these elements are either actively addressed by such adaptive systems, or indirectly as these effects are hidden within the setting algorithm that manages the skin adaptive behaviour, or responding directly as a reaction due to surrounding conditions' changes, such as ambient temperature (Borden 2009), and intensity of solar radiation (Fernández 2007). In these cases, no advanced control algorithm is required as the sun is following a well-known path. Thus, the behaviour of the adaptive envelope is transformed into a 'step sequence' that can be determined in advance.

3.5.1.2.People

As the main objective of the building is to provide a pleasant and protective space for human to live and work, in the realm of low energy architecture, an adaptive envelope is sensitive to the impacts of occupants in term of providing favourable comfort conditions while at the same time conserving energy. People respond to discomfort by regulating their needs to cope with what is provided by the building or adjusting their environment to suit their needs (Nicol and Humphreys 2009). Thus, along with the capability of responding to the climate changes, the adaptive behaviour of adaptive building skin is extended to include the capability of responding to the required performance based on the occupants' preferences.

In the light of that, Lee, argues that maintaining a satisfactory condition to the average person while at the same time keeping options open to meet personal preferences, is essential for any automated system (Chappells† and Shove‡ 2005), in the same way, the most common complaint about adaptive building skin is the inability to over control the system by the occupants (Wyckmans 2005); thus, occupants should be given a chance to manage their preferences through manually controlling the adaptive skin (Lee, Claybaugh et al. 2012). Therefore, taking the occupants' performance requirements into account during the design stage of any adaptive skin is essential, to fulfil their vital essentials such as thermal and visual comfort. In addition, the existence of occupants affecting the building performance in term of internal heat gains by the use of equipment and occupant metabolism activity should be recognised. Furthermore, occupant behaviour is, to a certain extent, the same as the climate conditions, and are subjected to high variability and uncertainty due to variation in occupants existence based on the building type (residential, commercial, etc.), in addition to the unexpected occasional events. In that sense, occupants' preferences are expressed as constraints and set points, as a mean to identify the adequate performance in a quantitative way. However, each building type or even space has its own requirements based on its function. As a result, occupant satisfaction requires adaptive behaviour rather than the static behaviour of the building envelope.

Time Scales

In this section, the response of the adaptive envelope is discussed based on the time scale. As the adaptive building envelope is designed with the aim of continually maintaining adequate performances while, at the same time, it is influenced by a variety of environmental impacts and occupants' preferences. Regarding environmental impacts, theses influences are happening in varied ranges, ranging from sub-seconds to the building's whole life time. In terms of occupant's preferences, adaptive building envelopes should respond in a short time limit. In the light of that, Loonen classifies the time scale of adaptive building envelope into four categories: minutes, hours, diurnal and seasonal (Loonen, Trčka et al. 2013).

- **Minutes**

Some influences such as daylight availability and cloud cover have a characteristic of this time constraint. Therefore, Adaptive building skins that designed to optimise daylight utilisation and solar shading to improve the visual comfort while reducing energy consumption are required to respond through changing their configuration or degree of transparency in the order of minutes.

- **Hours**

An Adaptive building envelope that tracks the path of the sun, and fluctuation in air temperature or directly adapt in response to temperature stimuli (Leung 2008), is an example of this category.

- **Diurnal**

However, the building's occupants usually exist in diurnal patterns 'working hours', and these days' nocturnal hours are considered in meteorological boundary conditions like availability of solar radiation and ambient air temperature. Therefore, some adaptive building envelopes may be designed with the aim of taking advantages of the whole 24 hours of the day, such as the nocturnal release of thermal energy via roof ponds with moveable insulation (Spanaki, Tsoutsos et al. 2011).

- **Seasonal**

One of the smartest application areas of the adaptive building envelope is adapting to variability in conditions across the four seasons (winter, spring, summer and autumn), as these advanced systems are capable of adapting to widely different boundary conditions, and as a result provide substantial performance benefits.

Scale of Adaptation Mechanism

The adaptation mechanism that adaptive building skin utilise can be categorised into two main classes: macro and micro scale, where the adaptation mechanism is based on the adaptive skin's configuration or changes in material properties respectively, although, the combination between both classes is also possible. The following sections describe both scales in more details (Loonen, Trčka et al. 2013).

3.5.1.3.Macro Scale

In conditions of a macro scale, the adaptive behaviour is accomplished via the changes in the envelope configuration associated with the apparent movement of its parts, such as rotating, folding, sliding, etc, where these transformations can be easily seen. Normally these types of adaptive envelopes are referred to as 'kinetic envelopes', which means that a certain form of observer motion is present. For continuing these movements, electromotors that are activated by an input from sensors and driven by outside energy input are usually the driving principle behind this type of mechanism. However, when it comes to the big scale projects that use these mechanisms, they tend to be more mechanical and sometimes problematic from the maintenance perspective due to the work of a large number of parts, especially, when something sounds bad. An instance of a macro-level adaptive concept is mechanically controlled Venetian blinds, but they could come in all different forms and transformation patterns, for example, Al Bahar Towers, where the panels fold or unfold to act as solar shading (Oborn 2013). (See see Figure 3.3)

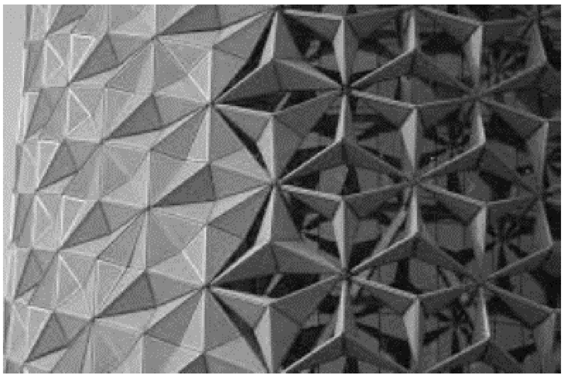


Figure 3.3 Example of a macro- level adaptive system at Al Bahar towers, where the panels fold or unfold to act as solar shading.

3.5.1.4.Micro-scale

Micro scale adaptation happens via changes at a minor scale, inside the material itself. For example, when a material change from one phase to another, such as from liquid to solid or gas, the arrangement or the structure of the material's molecules will change; as a result, the material properties will change and logically will perform in a different way (see Figure 3.4).

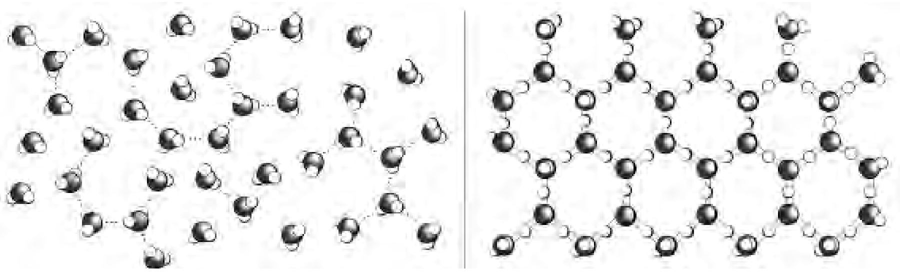


Figure 3.4 Molecule configuration of water as fluid and ice.

In adaptive building skin this change in material characteristics can be used as an invisible change to achieve different adaptation objectives, such as through the exchange of energy from one phase to another or opaque optical properties (Karlessi, Santamouris et al. 2009), (Ma, Zhang et al. 2002), via changes in thermophysical (Kuznik, David et al. 2011), According Loonen, most of the micro scale adaptive envelope area is concerned with the light transmitting properties of materials. This smart glazing can modulate levels of incoming daylight and solar energy by adjusting their optical properties. In addition to new advancements in adaptive windows will have more capabilities such as light redirecting properties (Viereck, Ackermann et al. 2008), and the ability to produce electricity to support its own operation (Debije 2010), (Loonen, Trčka et al. 2010).

Control

As an adaptive envelope has to respond to changing conditions in an effective way, then, the different sub-systems of the adaptive envelope should cooperate with other building systems to handle trade-offs and overcoming conflicts, with the aim of achieving the desired performance requirements in the best possible way. Thus, an effective control system is essential for any successful adaptive building skin. First, two types of basic control approaches are discussed: open loop (Figure 3.5) and closed loop (Figure 3.6). Secondly, a further discussion related to adaptive building skin control systems is conducted. Intrinsic control and extrinsic control are means to understand the components, capabilities and the advantages and disadvantages of each system, where the main difference between both approaches is somehow similar to the micro and macro mechanism' scale in terms of either the controls take place, internally or externally. In the light of that, open loop and closed loop, extrinsic control and intrinsic control, are discussed below:

In terms of closed-loop and open-loop control (Figure 3.5), the subtle semantic difference between the words 'automated' and 'automatic' marks the distinction between these control concepts. As the following sub-sections show, both types of control can work automatically, but only the first type is automated.

3.5.1.5.Open loop system:

Sensors, processors and actuators are the three basic constituents of open loop controlled adaptive building envelopes (Teuffel 2004). The data are measured by the sensor (a technical component that can register specific physical or chemical ambient conditions (e.g. temperature, moisture, pressure, sound, brightness or acceleration). These parameters are recorded by means of physical or chemical effects and are invariably transformed into quantities (e.g. electrical signals or digital data) that can be interpreted by a processor, and passed on the actuator (s); the actuator is the part of the system that converts the processed data into a mechanical, physical or chemical action according to a predefined logic.

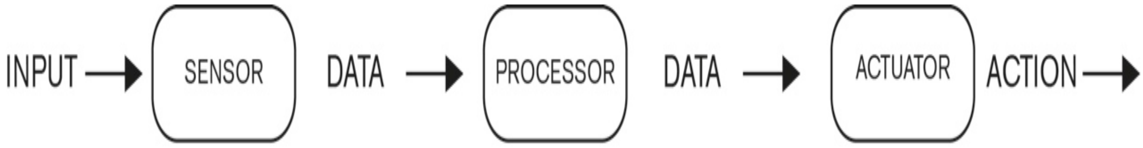


Figure 3.5 Diagrammatic concept of open loop system

3.5.1.6.Closed Loop System:

The utilisation of a control unit that can measure the output action, and as a result, the collected information could then be used as feedback to the processor, is the main difference between the closed loop system and the open loop system (Addington and Schodek 2005).

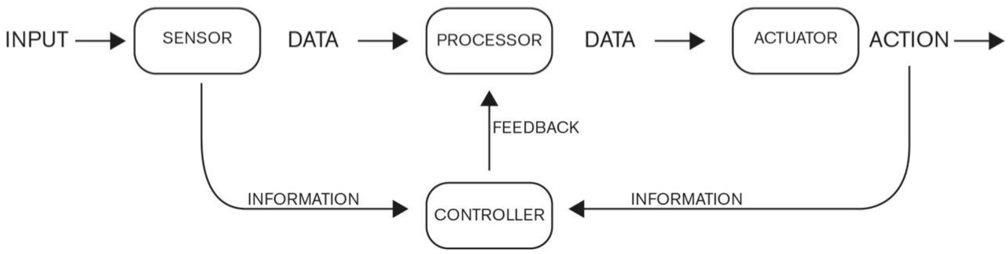


Figure 3.6 Diagrammatic concept of closed loop system loop system

Relevant Physics

There are many physical interactions occurring between the ambient environment and building skin as it is considered to be the building interface with the surrounding environment. From this perspective, in the realm of adaptive building skin systems, each system responds and interacts individually in its own way based on the system's adaptiveness objective. Therefore, the adaptive building envelope's response can be in the form of collecting, redirecting, passing, blocking, converting, filtering, storing, etc.

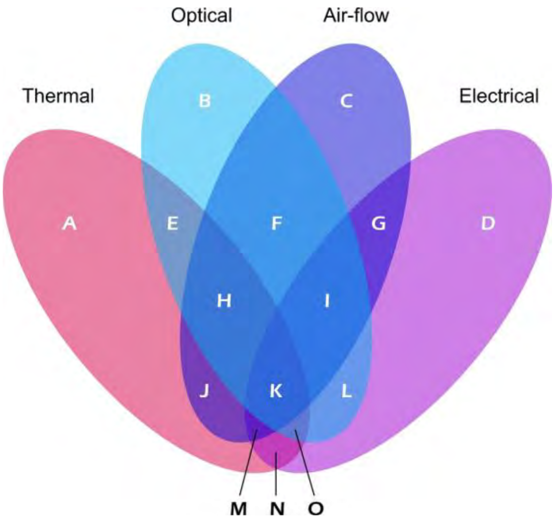


Figure 3.7 Classification of relevant physics: each system can be characterised by one of the fifteen areas in the figure.

In the light of that, four main domains can be identified to differentiate between different adaptive envelopes. Also, the single and multi-ability of some of adaptive systems can be visualised via the four-ellipse Venn diagram shown in Figure 3.7. According to Loonen there are fifteen possible combinations to represent the relevant physical interactions of adaptive systems regarding climate (Loonen, Trčka et al. 2013).

The main four domains of the physical interaction of adaptive building envelope are discussed below:

- **Thermal** Adaptation causes changes in the energy balance of the building via conduction, convection, radiation and storage of thermal energy
- **Optical** The adaptive behaviour influences occupants' visual perception via changes in the transparent surfaces of the building skin.
- **Air-flow** A flow of air across the boundary of the façade is present, and adaptive behaviour is influenced by the direction and speed of the wind
- **Electrical** Building integrated energy generation takes place on the façade level, or electricity consumption is an essential part of the adaptation mechanism.

Source of Inspiration

The concept of adaptive building envelopes was inspired by many approaches from building and architecture disciplines, such as vernacular architecture, intelligent building, biomimicry, smart material, etc. different disciplines that adaptive envelopes draw its inspiration from are discussed in the following sections:

3.5.1.7.Biomimicry

Biomimicry is a design approach that strives for sustainable solutions by following nature's time-tested ideas, and term is introduced from the Greek words *bios* (life) and *mimesis* (imitation) (Benyus 1997). Biomimicry is a field in development that has the potential to be applied in the most of academic sciences; its concept is based on the principles and processes observed in nature, and they can be replicated in any society system referring as economical, technological or cultural (Mathews 2011). Nature affords eternal sources of inspiration for scientists and engineers. Each creature is unique and adapted successfully to its own environment, as creature evolves by responding to environmental demands and finding answers that work (Badarnah and Kadri 2015). The mechanisms in nature have developed over billions of years, and the successful ones have come through. Nature has experimented with many possibilities to deal with properties of materials and structures which gave rise to the most efficient systems found in nature. For architects, it is a source of innovation, particularly in the creation of a more sustainable and potentially regenerative architecture (Reap, Baumeister et al. 2005). In the light of that, a biomimetics is an approach to design by capturing inspiration from the schemes and principles of biological systems. This imitation passed through two approaches, first, designing buildings in a way that looks like natural creatures or organisms in terms of form (Aldersey-Williams 2004); however, the results usually were odd buildings that just aimed to imitate the organism's appearance. The second approach was more concerned with the building's functionality and performance optimisation of the building with respect to its appearance, In addition, it utilizes energy in a more efficient way, moreover it's capable of producing materials and structures that are more complex and advanced than what human achieved in the industry (John, Clements-Croome et al. 2005).

Many researches were inspired by biological organisms' adaptation strategies. For example, a recent conceptual design, combined solar-responsive acclimated kinetic envelope with bio-inspired design. The movements inspired by butterfly wings' honeycombed structure maximises the adoption of solar heat or minimise according to different seasons (Wang, Li et al. 2010). (See Figure 3.8)

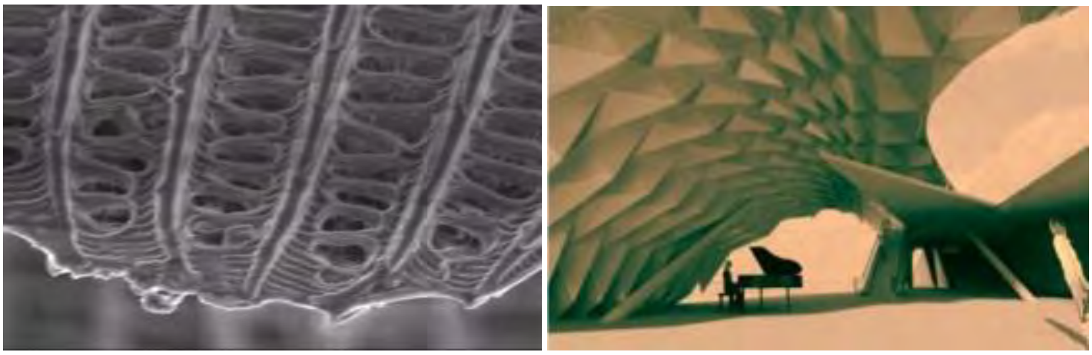


Figure 3.8 Bio-inspired kinetic honeycombed canopy
http://www.architects.org/news/treat-heat-butterfly)

A more recent study investigated the building skin by applying botanical inspirations for thermo regulation of building skins to design a parametric skin for an office building in a hot climatic area to minimise cooling loads while maintaining daylight standards. Various parameters were examined, such as the number of folds in the X axis and Y axis, fold displacement and fold depth. The results show that the optimised folded skin decreases the overlit areas of space from 60% to 14% while providing adequate daylighting performance and decreasing the heat gained by radiation (Elghazi, Wagdy et al. 2014).

A distinct type of biomimicry that related to Adaptivity in architecture is the concept of tropisms. A tropism is defined as a movement found in nature's fostering adaptability to change and occurs over a single lifespan. Both phototropism (i.e. adjusting in response to light) and heliotropism (i.e. adjusting in response to the sun), have been effectively transformed into buildings in CABS-concepts, enabling to collect or reject solar energy (Vermillion 2002).

Likewise, another study investigated and developed skylight system that responds to both external, environmental conditions and adjustable internal functional demands by controlling daylight to assure adequate illuminance and low visual contrast inspired at several levels of features of biological systems. This research was inspired by certain vegetables whose shape and surface texture enabled them to control their inner temperature in hot climates (Fig. 3.9). Some organisms have behavioural mechanisms and respond to changes in local conditions, in real-time like the snow buttercup which follows the sunlight direction to get more sun, in a heliotropic response. Other plants, like the King Protea, open more to get sunlight, reacting to the quantity of light, responding to non-directional stimuli in a photo nasty response. The process of changing the apertures of the skylights is inspired by such responses (Henriques 2012). (See Figure 3.9)

Figure 3.9 Daylight simulations (Henriques 2012).

In brief, enormous examples in biology, where the emergent response of plants and animals to temperature, humidity and other changes in their physical environments, are based on relatively simple physical principles. However, the application of design solutions which exploit these strategies is where the inspiration for man-made structures should be (Godfaurd et al. 2005). Efficient adaptive building envelopes of the future can be planned by bringing inspiration from biological organisms' adaptation strategies. Therefore, to create a truly sustainable construction that minimises the use of energy, materials, and produce less waste, then taking lessons from creatures adaptive strategies as a source of inspiration is an efficient approach. Biomimicry is a field in development that has the potential to be applied in most academic sciences; its concept is based on the principles and processes observed in nature, and they can be replicated in any society system referring as economical, technological or cultural (Mathews 2011).

3.5.1.8. Polyvalent Wall

The British architect Mike Davies established his imaginary concept for ‘a wall for all seasons’ by demonstrating the idea of the ‘Polyvalent wall’, as a mean to integrate multi functions into one layer, he described his concept as follows:

“What is needed is an environmental diode, a progressive thermal and spectral switching device, a dynamic, interactive multi-capability processor acting as a building skin. The diode is logically based on the remarkable physical properties of glass but will have to incorporate a greater range of thermal and visual adaptive performance capabilities in one polyvalent product. This environmental diode, a polyvalent wall as the envelope of a building, will remove the distinction between solid and transparent”. (Davies 1981).

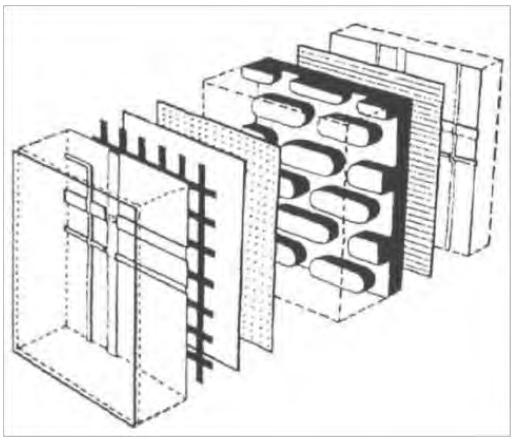


Figure 3.10 Mike Davies, the concept of the polyvalent wall as drawn in 1981.

In that sense he suggested a multi-task wall consisting of several layers, where each layer was responsible for fulfilling a specific function as described below i.e. a multi-functional layer of glass component that was capable of providing sun and heat protection, and to control the envelope’s functions automatically based on the current environmental conditions and, in addition, the ability to generate the required energy. Many adaptive building envelope designers were inspired by Davies’ study regarding the capability of one system to perform multi tasks.

3.5.1.9.Smart Materials

Smart materials’ is a term for materials that have variable properties and able to reversibly change their thermophysical or optical properties in response to certain physical or chemical influence (Ritter 2007). In the light of that, these new materials go further than regular bricks, concrete, steel or glass, regarding performativity.

Regarding characteristics, the material is considered to be smart if it bears the following features:

- Immediacy - thus the reaction is immediate and in real-time.
- Transiency - they respond to several environmental states.
- Self-actuation - the intelligence is in the fabric itself.

- Selectivity - their response is predictable and discrete.
- Directness - the response is local, i.e. it occurs in proximity to the activating event.

Thus, smart materials can be effectively utilised for adaptive building envelope applications due to the adaptive and dynamic nature of these materials; however, it has sometimes been difficult to understand the possibility of utilising these smart materials in the application of adaptive building envelopes through these theoretical definitions, thus; the following sections demonstrate examples of these smart materials.

Thermo-bimetals

This concept utilises the differences in thermal expansion coefficients of two materials that are attached by welding, brazing or intersecting. This difference causes the metal to bend when it exposed to heat.As as a result, these materials can be used to convert the change in temperature to a mechanical movement, as shown in Figure 3.11).

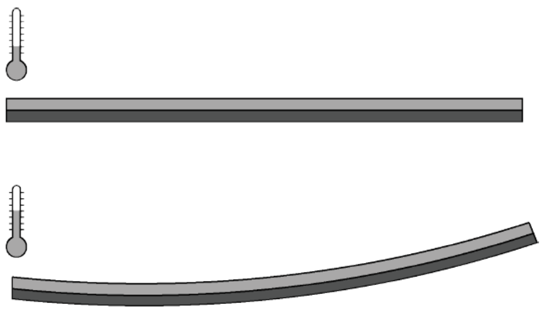


Figure 3.11 Principle illustration of thermo-bimetal

This concept has been used in different disciplines in a simple way, such as circuit breakers, and thermostats. In the light of that, the active material (with the larger coefficient of thermal expansion) is usually an alloy of iron-nickel-manganese or manganese-nickel-copper, while the passive component usually is alloys of iron-nickel or nickel-cobalt-iron, as their coefficient of thermal expansion is very small. In architecture, this concept was utilised by the architect Doris in designing a pavilion called Bloom as a proof of concept, where the bimetallic strips respond as a self-regulating ventilation based on the temperature they exposed, in a way that the bimetallic strips are opened when they exposed to high temperature, and reverse to the initial position when it cools down again (Kim Sung 2013).

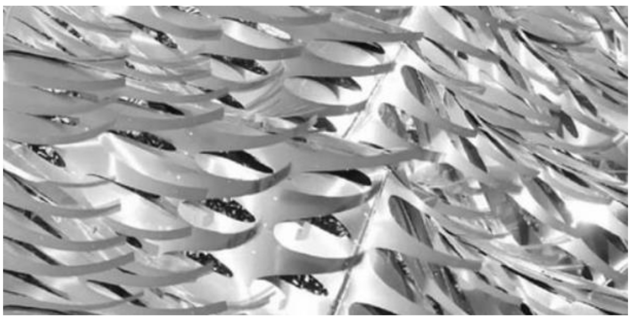


Figure 3.12 Self-regulating ventilation, proof of concept (Kim Sung 2013)

Regarding the practical use of these materials in the building sector, the following conditions should be fulfilled:

- The reliability of the cost/benefit ratio needs to be convincing.
- The technology has to be suitable for the labour's skills and meeting the capabilities of the building industry.
- From the architectural perspective, the concepts need to be accepted aesthetically.

From that perspective, smart materials demonstrate a great promise; however, it is still limited to the high-budget projects because the reliability of cost/benefit ratio is more suitable for this kind of project, in addition, the utilisation and application of these materials require an expert labours.

3.5.1.10. Intelligent Buildings

With more and more innovative degrees of technology integrated into modern buildings, the concept of the "intelligent building" came forth in the 1980s to describe the advanced systems employed to manage building services and indoor climate control systems (Wong, Li et al. 2005). The word 'intelligent' involves some human characteristics that give the building skin the ability to read, adjust and react automatically to its immediate environment (Wigginton and Harris). Thus, the existence of a 'brain' or supervisory control system that control all components and subsystems is essential.

The intelligent building envelope was described in several ways, Lee, described it as the system that's capable of acting the part of traditional building skin in addition to possessing the power to serve as a building filter in terms of collecting, ordering and distributing energy, and dynamically react to changes in climate and user needs (Lee, Selkowitz et al. 2002). Nevertheless, the concept of intelligent buildings is much broader than that of adaptive building envelope as it also sometimes includes surveillance cameras, security and access control, safety systems, etc., it is believed to be a source of inspiration for adaptive building envelope due to the concept of reacting to the surrounding environment with the intention of maintaining a certain performance.

3.5.1.11. Vernacular Architecture (Traditional Pattern and solar screens)

Traditional patterns have been broadly used in the Middle-East and South Asia as a source of inspiration for shading provision and privacy concerns by blocking direct sunlight while allowing the indirect light to diffuse into space through shading elements. The following options are representative for the many dimensions in control of adaptive skin: solar shading vs. artificial lighting, daylight vs. glare and solar gains vs. potential overheating.

The southern wall of the Institute du Monde Arab in Paris is possibly the most well-known example of an adaptive building envelope (Figure 3.13). It was designed by Jean Nouvel and Architecture studio and was completed in 1989. It is made out of 240 photosensitive shutters that work as a sun-shading device for the otherwise glazed wall. This system is a closed-loop system in which the level of radiation on a certain part of the façade is collected and the information interpreted and fed to the actuators cause small motors to open or close the shutters. There is no chance to over rule the system for a user. The shutter is crucial to the interior climate of the building, but this kind of highly mechanical solutions tends to break easily, and the different parts are not easy to replace when that happens (Coelho and Maes 2009). There have been many problems with the façade, especially with fatigue in the moving parts of the system.

Figure 3.13 Institute du Monde Arab in Paris.

The Al Bahar Towers were recently completed in Abu Dhabi and were designed by the architecture office Aedas. Each of the two towers has an adaptive outer skin to reduce the solar gain into the spaces. The sunscreen is a triangulated pattern similar to that of traditional Arabic sunscreen, *Masharabiya*. It is made of metal frames and fibreglass panels.

The shading screens are programmed to open and close according to the movement of the sun. This macro-system is estimated to reduce the solar gain by 50%, which in turn reduces the need for air conditioning. The solar screen also gave other advantages, as the solar gain is reduced the glass in the windows does not have to be highly reflective, and that improves the interior daylight conditions significantly.

Figure 3.14 Al Bahar Towers

Learning from the problems with The Arabic Institute in Paris. All the elements and components in the Towers' sunscreen have been experimented, both in wind tunnels and for fatigue, to ensure that they will have the same lifetime as the building. The system is also constructed in such a way that if a part is damaged it is easily replaceable (Oborn 2013).

Finally, the Claustra is one of the Egyptian architect Hassan Fathy's visual elements that inspired from the wooden solar screen (mashrabiya). Hassan Fathy applied Claustra as shading devices to allow diffuse light, limit direct sunlight, and control glare (Steele and Fathy 1997). (See Figure 3.15)

Figure 3.15 The use of claustra by Fathy

3.6. Conclusion

Building skins are of the utmost importance in the field of architecture today. Whether it is visual, explorative, conceptual, performative, environmental, or economic, building skins are capable of doing more now than ever before. (Van der Aa A. 2011). Therefore, creating an efficient office building skin that interacts with its surrounding environment is one of the most important objectives for architects today (Etman, Tolba et al. 2013). One of the possible ways to achieve adequate daylighting performance while minimising solar gain and glare risk is by integrating a dynamic and responsive shading system into the façade (El Sheikh and Kensek 2011). Recent advances in materials, controls and system modelling now mean that building envelope can be a dynamic element which acts as a negotiator with the external environment and an enhancer of the internal environment (Konstantoglou and Tsangrassoulis 2016).

Performance benefits of Adaptive building skin (ABS)

To sum up, an effectively operated CABS system can offer positive contributions to all the three aspects of the Triple Bottom Line principles: people, planet and profit.

People: benefits for people are typically stated in terms of improved indoor environmental quality, including thermal and visual comfort, and air quality, resulting in comfortable working environments that associated with improved health and productivity levels.

Planet: higher potential energy savings compared to conventional building skin. Resulting in less need for utilising fossil fuel based energy.

Profit: energy savings leads to decrease owners' energy bills. Moreover, increased building lifetimes. Furthermore, providing high comfort levels directly influences the productivity levels and subsequently, economic aspect as well.

Also, they have an impact on more indirect performance aspects such as cultural or socio-economic performance. Therefore, Adaptivity in the building skin offers architects and designers an attractive additional design variable.

To conclude, the existing advanced technologies allow the architect to go further than the conventional passive daylight strategies of integrating large openings or light shelves in the architecture. Instead, architects can move towards systems that are capable of actively responding to the changes in natural daylighting and occupants' preferences throughout the year to maintain the required different illumination schemes regardless changes happen in the surrounding environment.

Controlling sunlight penetration into office spaces is a broad strategy that improves light levels, and reduces solar heat gain, especially in hot climates. Nevertheless, energy savings are dependent on many other parameters such as orientation, season, and envelope design. Many studies show opportunity for reducing lighting, heating, and cooling loads by the design of better performing façades. However, passive daylighting systems can increase energy savings, active strategies can achieve a broader achievement, due to its dynamically adaptable capability of adapting to the sun throughout the entire year. The utilisation of dynamic surfaces as shading and daylight redirecting systems on façades could improve the daylight performance and increase daylight penetration depth inside office space. Nevertheless, these advanced systems require advanced performance-based design models and tools that afford the possibility of generating and evaluating a broad range of design alternatives; therefore, these tools are discussed in the following chapter.

Chapter Four

4. Architecture in the Digital Age

4.1. Introduction

Recent advancements in parametric design tools have influenced the architectural design process by offering the possibility of giving varieties in design while sustaining the dependencies and associations between iterations. Accordingly, architects utilise these tools as a means to control design parameters and consequently to facilitate analysing and optimising design solutions for various kinds of architectural problems in early design stages (Ming, Anderson et al. 2012).

Regarding buildings skin, these design tools afforded unlimited design possibilities by facilitating the patterning and manipulation of buildings skins as a symbol of Parametricism (Schumacher 2009). However, the current utilisation of these tools usually results in superficial complex forms of endless repetition and variation. Consequently, many concerns were raised regarding the method of creating such complex forms, the meaning or purpose behind their shapes, and the impact of the availability of computing power and software would outcome in solving real social, environmental and technical problems as a means to achieve the challenges of performance significance instead of superficial forms (Wild 2015).Therefore, the current interest in building skins that adapt to varying environment situations and user preferences (Wigginton and Harris), made such systems appropriate subjects through which the design and implementation of computational tools may be explored to be utilised in an integrated approach for modelling and analysing the behaviour of such system. In the light of that, the performance-driven parametric model allows designers to integrate parametric modelling, simulation, and genetic algorithms (GAs) tools into one integrated process governed by design objective and supports their design decisions by being in direct association with the context. (Huang and Niu 2016).

Therefore, the aim of this chapter is to investigate the roles and capabilities that the computational design tools can play regarding adaptive building skin design as a primary stage to implement computation tools effectively in developing Territorial Adaptive Building Skins (TABS) that represent a cultural identity and respond to its environmental and contextual demands. Within the context of this chapter parametric modelling, Building Performance Simulation (BPS), and Genetic Algorithm (GAs) were explored.

4.2. Performance in Architecture

The idea of performance in architecture is dependent on the specific context of the project and can be interpreted in a very broad sense, reaching fields like economy, spatial planning, society, culture or technology (Kolarevic 2004).

Today's computational environment allows architects to determine with great precision and to visualise that which remained unseen and a series of analysis tools can inform the design process on several aspects of performance related to a project. This shift and focus on performance in architecture is driven by the need for more resilience in architecture and design, as a central signature tune of contemporary architecture. Traditionally, architects design a building or space and shape it according to their will (Anton and Tănase 2016). After space is designed, the project is delivered to an engineering team that tries to analyse the environmental performance of the project and develops various energy scenarios and selects one of the best scenarios available (Moradi, Razini et al. 2016).

The problem in this workflow is that the analysis rarely changes the form of the architectural artefacts, and the change is implemented with much effort. Although engineers use advanced computational tools for performance analysis, they are employed without affecting the architectural form and without being used directly as morphogenetic agents in the process of form generation. The new computational tools available to architects and engineers can be used as more than optimisation tools for already established architectural forms. Combined with parametric modelling, these tools can lead to an active integration of the analysis means in the development of architectural form in the early stages of design (Oxman 2008), (Kolarevic 2004).

Architects like Brank Kolarevic and Rivka Oxman advocate an approach in which architectural form is tied to a result of a performance analysis that induces a feedback loop into the design of the architectural form. Kolarevic points out that in these cases the result, based on performance criteria, may lead to a performance based optimised solution, but it might not be the best solution in respect to its aesthetic criteria, and architects need to find a way to manage the two. A solution is to include in a parametric model all the relations that lead to the development of a form under the emergent actions of performance driven forces simulated in a digital environment (Kolarevic and Malkawi 2005) (Oxman 2008).

By combining performance with formal generation, performance becomes just another parameter in an algorithm development of architecture, where the shape is negotiated by several criteria. By using a parametric model in which formal generation rules are transformed into an algorithm, analysis tools can be easily implemented and provide precise feedback in the generative process. By doing that, analysis can contribute actively in the generative process of the architectural form. However, performance should not be understood as a mere conditioning of the project based on a generic solution applied as a solution to create a great number of practical problems. This reductive approach based on performance and efficiency can lead to a very functionalist design. The domain of performance criteria must be extended and seen as an opportunity to develop the generative design process based on local information relevant to each project, such as cultural, technical and environmental conditions. Moreover, this approach must find a way to incorporate performance criteria into a project by levelling creativity with efficiency (Kolarevic 2003).

Furthermore, as recent developments in the field of computation can lead to the possibility to use the digital environment to simulate the real behaviour of architectural artefacts and its components. This analysis must be done in all stages of design, construction and usage, from conceptual design to the building decommission (Malkawi 2005). As mentioned above, a traditional design workflow uses simulation after the formal development of the architecture of a building. In this situation, the project would be very rigid and could implement only small changes in the formal arrangement of the project. If the performance criteria analysed were indeed a decisive factor in the project development, the optimisation process would have been a very laborious. Therefore, after each change in the project the analysis model must be rebuilt and a new series of analyses would be made. The new result lead to new changes and the process was reiterated until an optimum was reached. The focus in design now lies with the capacity of the digital environment to integrate, not only to calculate. Today's analysis software, although specialised for different types of analyses, are developed for interoperability. Performance issues are addressed no more in an isolated mode, in a linear progression, but all at the same time. The aim is to get an overall performance analysis of the whole building, linking all criteria, to be able to draw conclusions and develop solutions at a holistic level (Guglielmetti, Macumber et al. 2011).

The integration and control of several levels of information is one of the most attractive promises made by the recent developments of the digital tools. The final architectural artefact is no more an imposition of the architects will but becomes a response based on performance, on analysis and collaboration between a high number of variables and real data. Greg Lynn defines design as an abstract space where active modelling forces, informed by real data act as form generators (Lynn and Kelly 1999).

4.3. Performance-Based Architectural Design

Adopting building performance as a guiding design approach for buildings and cities emerged and received a good deal of focus by the beginning of the current century due to the developments in technology and cultural theory and the rise of sustainability as a defining socioeconomic issue. This type of architecture places performance objectives above or next to form-making. The most powerful aspect of a performance-based design model is providing a comprehensive new approach to the design of the built environment via utilising quantitative and qualitative performance analysis and simulation tools (Kolarevic 2003), that can be used during the early stages of the design process (Kolarevic and Malkawi 2005).

Access to these values during the early phases of design allows the designers to understand the results and consequences of their design decisions better. Moreover, aesthetic decisions can be made simultaneously with performance objectives, leading to a more integrated design. According to Oxman (Oxman 2008), the most compelling aspect of Performance Based Design (PBD) is that it's a design informed by internal evaluation. It is capable of creating a system of parameters that can be verified, validated and evaluated by evidence and data supported by the modelling and simulations as the essential design driver rather than designer's assumption. Thus, the performance simulation is the engine of form generation and no longer just a phase to evaluate the form.

This new approach shifted the creation from the modelling of a designed object to the modelling of the design's logic to progress a particular design task or solve design problems. These specifications can be rules or constraints (Leach 2009).

Regarding defining performance, it can be defined very broadly from different perspectives such as technical, economic, social and cultural. Therefore, the central challenge in this approach is balancing various performative aspects and overcoming conflicting performance aims efficiently. However, it is important to note that the selected solution among the wide range of performative possibilities produced is not a condition to be the optimum optimised solution as it could be an unacceptable proposal from an aesthetic or some other perspectives.

Thus, a sub-optimal alternative could be decided from the in-between performative range, as it meets other non-quantifiable performative demands (Oxman 2009).

This new approach significantly improves the design process in comparison to traditional design approaches.

Architectural performance is the efficiency with which architecture fulfils its intended purpose. The assessment of the expected architectural performances refers to architectural requirements, which confront needs and demands of human actors (users, investors, society, etc.). Behind architectural performance, there is a complex formulation of requirements based on expertise through which phenomena are decomposed, modelled and interrelated. This leads to the first level of complexity of performance oriented design. A second one derives from the fact that the architectural performance does not depend only on the building with the human actors. Also, it is directly related to its natural, built surrounding environment as these conditions have a great impact on the fulfilment of the architectural requirements and must be considered when evaluating building performance. Therefore, both the human demands and the environmental conditions are counted as part of the context. Accordingly, the context of a building is defined as a double data set (specific data describing the context and its components and identifying a design solution which satisfies the expected performances). However, this operation has been a challenging task since; human needs change over time. Likewise, the environmental conditions. Consequently, the building performance is affected by several layers of changing needs in changing conditions, which are essential to be considered through the design process (Turrin, von Buelow et al. 2011).

Conventional Design vs. Performance-Driven Architectural Design

The conventional architectural design methodology is an approach involving some basic design principles, mainly based on functions and forms. The driving force is the combination of the architect's rationality and sensibility. When performance criteria must be met, this design methodology is facing unprecedented challenges. Architects have to deal with the following three problems.

- The prerequisite for performance analysis is a building model that can be analysed. However, the complexity and variance of buildings make an analyzable model quite difficult to obtain. The current practice usually involves setting up a model using design software and then importing the model into performance simulation programs. This process is time-consuming and labor-intensive.
- The model created in most modelling programs only contains geometric information (the latest development and application of building information modelling might change it). Many non-geometric parameters have to be input in the simulation program. This, combined with the previous point, discourages the engineer to use the architect's model for performance simulation purposes. Rather, they prefer to directly set up the model in the simulation program for he can input both geometric and non-geometric information at once.

- However, the modelling capability of most simulation programs is not on the level of commonly used architectural modelling programs, especially when dealing with complex shapes and forms. The engineer does not want to use the architect's model because they have to import it and add many parameters before a simulation can be run; on the other hand, the architect is not satisfied with the engineer's simplified model and believes that it lacks details and is not aesthetically pleasing.

These three problems are difficult to overcome using a conventional design methodology. New approaches and techniques must be developed to assist the architects in carrying out performance-driven design.

An architectural design process can be divided into three steps, namely, conceptual design, detailed design, and construction document design. It is widely agreed that design decisions made in the conceptual stage have the largest impact on the final overall performance of the building. Guillemin and Morel conducted a survey of 67 buildings and found that 57% of technological decisions were made in the conceptual design stage, compared with only 13% in the detailed design stage (Guillemin and Morel 2001). Therefore, the right paradigm is to incorporate performance analysis into the early conceptual design stage so that right technical decisions can be made. Moreover, the performative outcome of different designs should be quantifiable and visible to the client and the architect (Shi and Yang 2013).

To sum up, traditionally the conceptual phase of architectural design addresses only a rather limited selection of requirements (in most cases, functional and aesthetic aspects). In contrast, the concept of performance oriented architecture has recently emerged, as a design approach in which building performance, becomes a guiding criterion (Kolarevic 2003). It aims to broaden the range of performance assessments in the conceptual phase, and to support their assessment based on early numeric evaluations (Becker 1999). By using performance oriented a design the level of interdisciplinary, the level of complexity, and the key impact that geometry has on the realisation of the performance related goals naturally increases.

According to (Aksamija, AP BD et al. 2012) there are many differences between performance-driven and traditional design methods could be summarised in the following points:

- The traditional method has certain shortages because:

(1) It involves reduced assumptions based on rules-of-thumb that can be inaccurate.

(2) May not fulfil with performance measurements of design solution.

Building performance-based design method: has control in predicting a design solution because it:

(1) Uses performance measures with actual quantifiable data.

(2) Uses the model to analyse and predict the behaviour of the system.

(3) Accompanied by a robust evaluation of the design.

As the performance-driven parametric model supports designers design decision by allowing the integration of parametric modelling, simulation tools, and genetic algorithms (GA), into one integrated process governed by design objective, these tools are discussed in the following section.

Parametric Design

The parametric design has become a trend in the current architectural design practice. The term implies profiting from parameters to create a form and refer to a practice of digitally modelling a series of design variants whose relationships to each other are defined through one or many mathematical relationships (parameters) which then form a parametric space which may compress a broad range of related but unique forms (Lagios, Niemasz et al. 2010).

Thus, parametric design is a set of relations and variables parameters to develop a form, in which by changing the parameters, different shapes can be defined. Moreover, the entire building form can be manipulated by modifying certain parameters, which are automatically able to adapt construction data, such as the total number of floors, overall gross area, building aspect ratio and its height (Jin, Zhang et al. 2013). (See Figure 4.1)

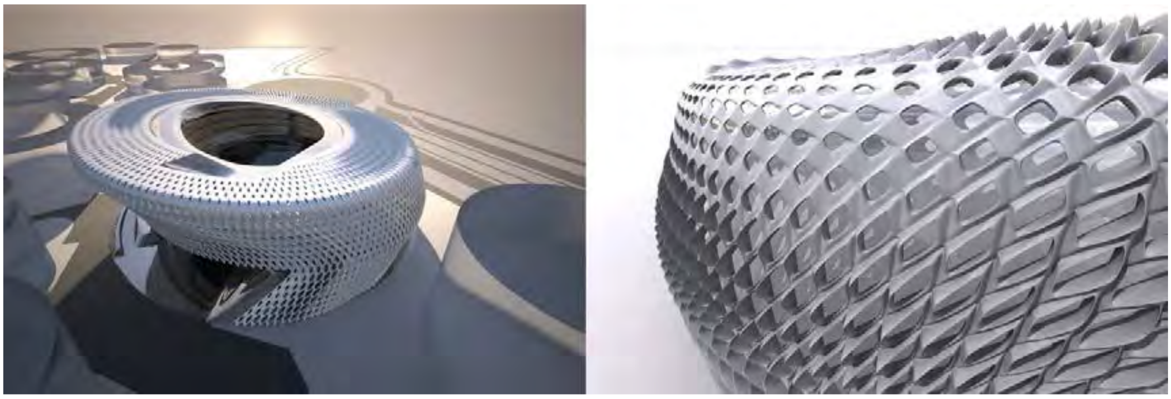


Figure 4.1 Parametric Design by Zaha Hadid

This requires precise thinking to find an efficient geometrical structure based on a complex model, which is flexible enough for doing variations. Thus, the designer must calculate and find the type of variations they want to explore due to defining the kinds of transformations the parametric model should do. So, as the nature of the design process is unpredictable, this process is a very hard and sophisticated one (Hernandez 2006).

Nowadays, the parametric CAD software offers 3D interactive interfaces, being able to perform variations in real time, when a parameter is changed and allows the designer to have more control over the project and to have immediate feedback (Hernandez 2006).

This process helps the architect to analyse a variety of possible solutions in a very fast and quick way (Jin, Zhang et al. 2013).

In the light of that, the digital modelling capability that can define the relationships between a series of design variants through mathematical formulae and different parameters is considered to be the main advantage of parametric tools in architecture as a means to produce diverse of related but various geometries (Schumacher 2009). This advantage is considered to be efficient for environment modelling process; for instance, according to (Hernandez 2006), one essential characteristic of the effective environment modelling process is the dynamic customization to develop design variations and affording multiplicity instead of a singularity in the design process. Moreover, many advantages could be obtained by coupling parametric modelling, dynamic process, and static customization to manage parameters during the building skin design process (Figure 4.2).

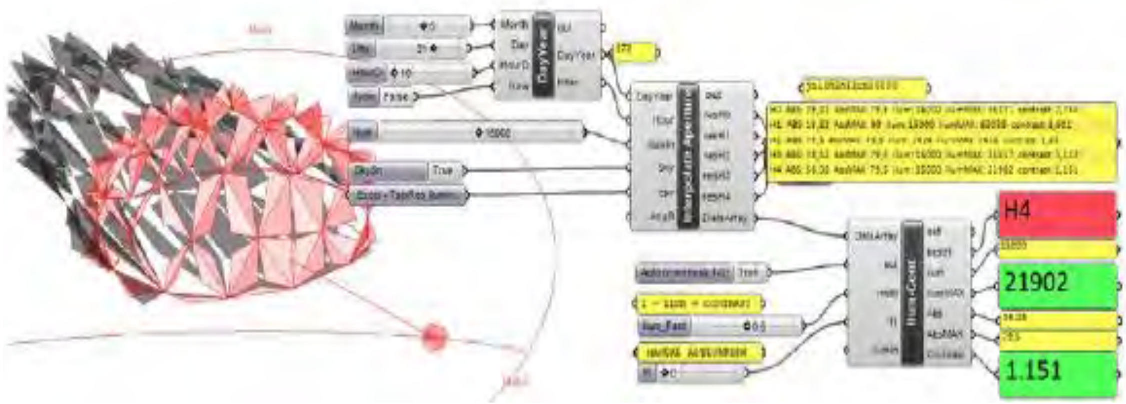


Figure 4.2 Dynamic process and static customisation using parametric software (Henriques, Duarte et al. 2012)

Furthermore, a parametric modelling tool can be utilised to control overall shape as a means of accomplishing a performance oriented process to increase solar gain in winter season while reducing solar gain in the summer season on the complex cladding system in the building (figure 4.3). (Turrin, von Buelow et al. 2011).

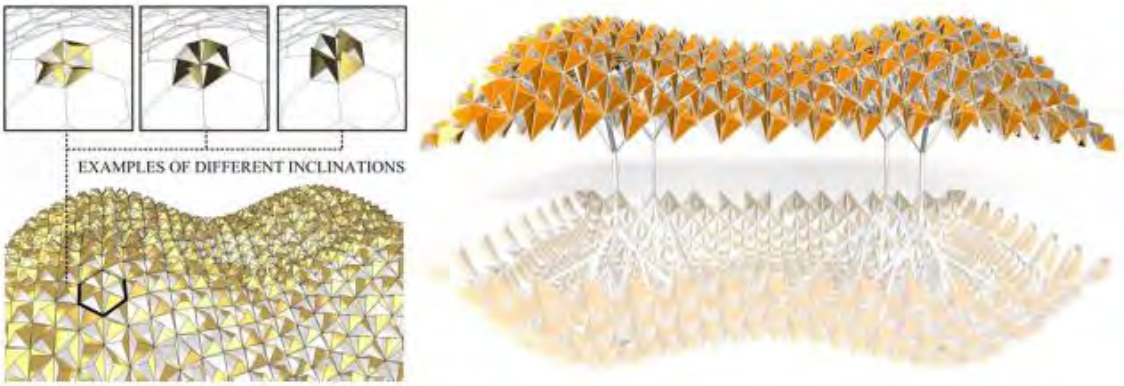


Figure 4.3 Cladding system, showing parametric inclinations of the panel (Turrin, von Buelow et al. 2011).

Building Performance Simulation (BPS):

The architectural design process includes various variables that exist for achieving required objectives. Thus, for achieving successful design solutions, understanding the association between the possible design decisions and the desired performance is essential (Mackenzie and Gero 1987).

Building performance simulations are commonly used by designers to test design options before construction (Hong, Chou et al. 2000), as the interests in energy-efficient buildings are growing and extensively leading to the development of numerous building energy simulation tools. Therefore, the designers became more encouraged for more sustainable, and energy-saving buildings' design. The building simulation applications include building heating and cooling load calculation, daylighting calculation, control system design, building regulations, cost analysis, and many other aspects (Hong, Chou et al. 2000).

Recent developments in computational design tools have bridged a gap between a well-established parametric building modelling (Woodbury 2010) and analysis or simulation software such as EnergyPlus (Crawley, Lawrie et al. 2001), Radiance (Lagios, Niemasz et al. 2010), and Daysim (Jakubiec and Reinhart 2011). This opens up the possibility for architects to use the computational power to model and simulate the real environmental behaviour of the architectural artefact and its components. Therefore, now architects can evaluate the behaviour of a project, whether it is a building, a city, a landscape or infrastructure and a new road towards an architecture based on performance is opened (Oxman 2008). Therefore, the idea of performance can be put as a precedent to shape development, and the architectural form becomes informed by the performative aspects. Various computational tools can be utilised to gather qualitative and quantitative aspects of the architectural artefacts, performance in the early stages of design, and go further from just optimising a form after it has been defined (Anton and Tănase 2016).

Genetic Algorithms (GA)

Adopting biologically-inspired design strategies derived from genetic evolution principles, such as genetic algorithm (GA) (Holland and Reitman 1977), have received more attention in the architectural design practice to visualise and evaluate a broad range of well-performing design alternatives and with a central focus on the production of optimal solutions and the processes used to find these solutions from the pool of possible alternatives (Besserud and Cotten 2008).

This approach was employed in many studies for determining the optimum configurations that fulfil the desired performance aims (Monks, Oh et al. 2000), (Turrin, von Buelow et al. 2011), (Rakha and Nassar 2011), (Zemella, De March et al. 2011), (Etman, Tolba et al. 2013), and (González and Fiorito 2015). The concept of Genetic Algorithms (GA) is based on mimicking the rule of natural evolution. The optimisation process is starting by randomly choosing a set of initial solutions (a generation/population). Then, each solution is evaluated to define its performance "fitness" based on predetermined criteria, resulting in identifying a group of well-performed solutions that used as a "parents" for the next generation. By using a genetic operator called crossover, parent members are combined to generate a new generation of "Childs", which assumed to be genetically improved as they made based on the best performing solutions in the previous generation of their parents. Similarly, all the generations are evaluated, and the poor performers are rejected, while the well performed is accepted to the next stage. The optimal design solution will be the achievable combination of parameters values, which minimises or maximises the objective function. However, the design problem may have a group of solutions based on the available, accepted solutions within the search space “pool of solutions" (Goldberg 1989). Finally, this cycle lasts until a fit solution or group of alternatives is affirmed or until a predetermined number of generations have been ended based on the optimisation settings (Figure 4.4). (Goldberg 1989), (ABBAS 2014).

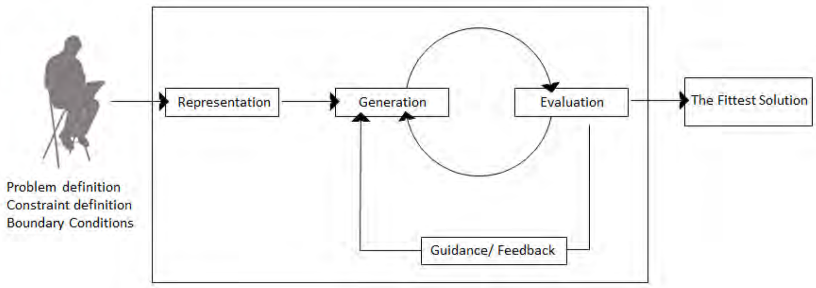


Figure 4.4 Digital Design Synthesis of GA. (Sastry, Goldberg et al. 2014).

Figure 4.5 Design Instances Generated by Genetic Algorithms (Retrieved from: http://gracefulspoon.com/blog/tag/evolution/, 12.05.2014)

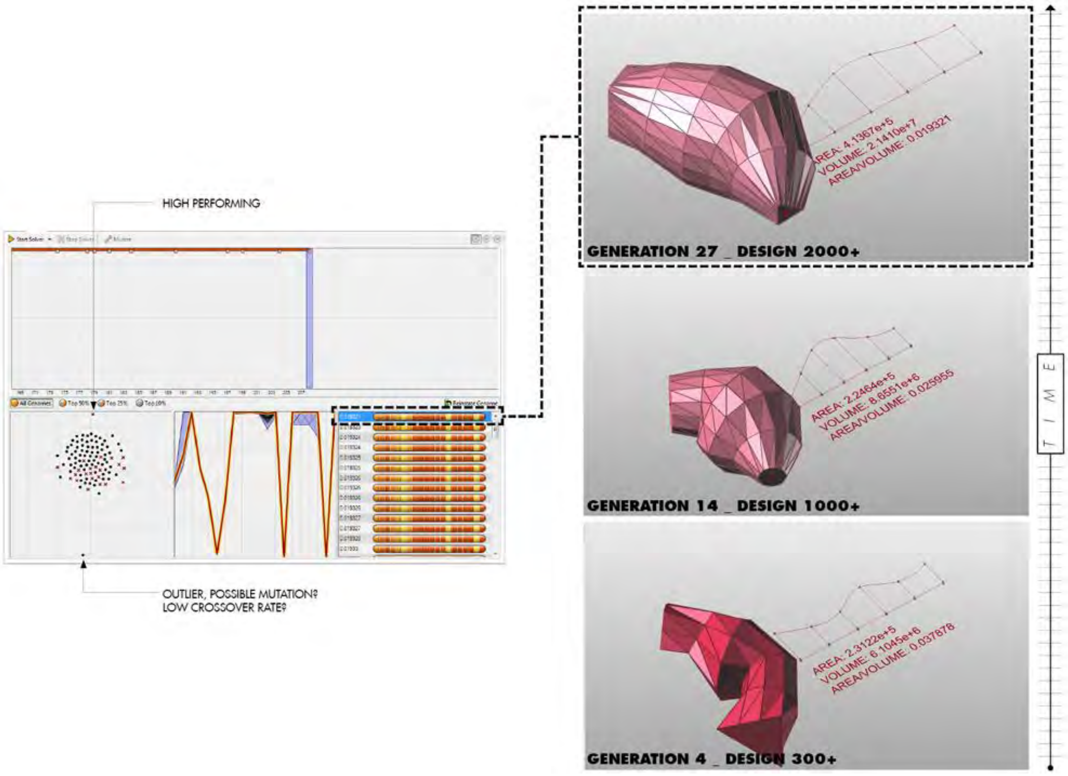


Figure 4.6 Performance fitness evaluation by Genetic Algorithms (Retrieved from: http://gracefulspoon.com/blog/tag/evolution/, 1.04.2016)

Genetic algorithms can be used in finding successful architectural solutions at the conceptual design phase; they are used to find acceptable alternative solutions for different design criteria, such as building forms, façade shading, and daylight harvesting. One study examined varying free-form ceiling geometry designs to optimise indoor daylight uniformity ratios (Rakha and Nassar 2011). Other researchers have focused on optimising the facade design and openings to achieve better daylighting levels and comfort, (Brotas and Rusovan 2013), (Ercan and Elias-Ozkan 2015) and (Rapone, Saro et al. 2013), and (Elkhatieb and Sharples).

Application of Building Performance-Based Design to Building Skin

With the current parametric design tools, architects can develop complex forms that are controlled by specific rules, parameters and variables in an organised geometric hierarchy that facilitate the investigation of a wide range of design solutions, resulting in innovative forms and patterns in building skin systems. Thus, parametrically designed building skin systems can combine functional and formal variables, consequently, will differ in design form based on the required performance, program, and the surrounding environmental condition (Shorey Jr 2015).

Building Performance Simulation (BPS) tools are powerful in testing and evaluating distinctive design's options primarily during the early conceptual stage. Moreover, contributed to achieving better improvements on the users and the environment by aiding designers in performing a succeeding designs for a particular required performance. However, the traditional approach of testing all possible alternatives manually is considered being very time-consuming, due to the need to modify or redraw the tested model the numbers of parameters involved in each simulation. Thus, regarding better results and time saving, it is more reasonable to consider using parametric and optimisation tools that can support overcoming the problems mentioned above.

Parametric tools can afford both geometric modelling and analysis functions within a controlled system. In the light of that, building heating and cooling load calculation, daylighting calculation, building energy management and control system design, building regulations, code checking, cost analysis and many other performance aspects can be measured. Moreover, evolution based computation can assist generating and evaluating a broad range of design alternatives and identify the optimal solutions (Ming, Anderson et al. 2012).

Thus, the main advantage of parametric tools is creating a set of relationship regarding the geometry parameters. Accordingly, the easy update of the overall geometry is promoted, resulting in a controlled environment for design exploration of new forms as the parameters various either manually, or automatically when genetic solver such as Galapagos is employed during the design exploration process. This results in facilitating the search for adequate design alternatives, according to pre-defined fitness criteria (Dino 2012).

Integrating parametric design with performance simulation, and Genetic Algorithms (GAs) tools have been found to be beneficial in solving many problems involving building skin designs. Therefore, the utilisation of daylight and energy-based optimisation functions has been examined in many studies to explore a broad range of design alternatives or to find the optimum solution for design problems, examples of these studies are discussed below:

(El Sheikh and Gerber 2011) used illuminance and luminous distribution of light in office space as performance indicators to optimise the design of external shading systems consists of independent louvres using evolutionary optimisation principles.

Moreover, (Gadelhak 2013) utilised daylight indicators such as the percentage of daylit area in the form-finding and shading optimisation of high-performance façades.

(Ercan and Elias-Ozkan 2015), utilised Parametric design, performance-based simulations, and evolutionary solver to generate the shading devices that optimise daylight while blocking out excessive solar heat gains.

Performance-Based Architectural Design: Available Combined Tools (Tools Box)

The Simulation of building performance is a demanding task and has been phrased as the art of performing the proper type of virtual experiment with the right model and the tool (Augenbroe 2011). The rapid progress of digital technology and its application in architecture have changed the field dramatically (Shi and Yang 2013). Software advances drastically enhance the design profession in the process. The more parameters that can be controlled and obtained, the more solutions generations the software can produce. The demand for integrating performance-based techniques into the early design stage requires a bidirectional exchange of data, where information flows back-and-forth between multiple interfaces.

The following section introduces parametric design, simulation, and optimisation tools for assessing the performance of Adaptive building skin. The proposed design tool adds to the current performance-based technology by making a particular contribution to the field of integrating performance into the early design phase. The contribution includes finding the best-possible skin configuration for better daylighting performance on any day of the year.

The following are tools that can be used in this study:

4.3.1.1.Parametric Modelling Tools (Grasshopper):

Grasshopper (Davidson 2012), is a graphical algorithm editor that allows the modelling of parametrically controlled simple and complex geometries. Grasshopper uses Rhinoceros© 3D modelling tools as an interface (Rhinoceros, NURBS-based three-dimensional modelling program; (McNeel 2014.)). Moreover, it is a widely used modelling tool among designers because of its flexibility in form generation integrated with Rhinoceros© 3D modelling.

Grasshopper allows the user to easily manipulate the dimensions of models by defining form-generating components, which can be optimised through the use of sliders and mathematical expressions. The Grasshopper interface is directly connected to the Rhino modelling tool so that changes made in the Grasshopper algorithm can be directly observed in the Rhino window. Moreover, Grasshopper assists architects to overcome the problem of the lack of scripting knowledge by enabling designers without scripting knowledge to create parametric forms. Moreover, affording components that are allowing custom scripts to be written in VB.NET (a version of Microsoft's Visual Basic that makes Web services applications easier to develop) or C# (a general object-oriented programming language for networking and Web development) (Lagios, Niemasz et al. 2010). Furthermore, the integrated Rhino/Grasshopper program has widely been applied because of its powerful modelling capability, intuitive interface, and abundance of plugins that greatly extend its functionality.

4.3.1.2.Parametric Integrated Simulation Tools:

Designers are increasingly utilising simulations in their designs (Galasiu and Reinhart 2008). With the aim of the integrating simulation tools with parametric tools, numerous scripts have been produced, for various features of building performance, such as structures, thermal and daylight performance. Various Grasshopper plug-ins were produced that connect the parametric geometry to simulation software such as

1. DIVA, which stands for "Design, Iterate, Validate and Adapt" (Solemma 2014), is a plug-in for Grasshopper that supports daylight and thermal performance analyses in Rhinoceros and its Grasshopper components (Jakubiec and Reinhart 2011) (Lagios, Niemasz et al. 2010). By integrating widely used and validated software, including RADIANCE, Daysim, Evalglare and EnergyPlus (Lagios, Niemasz et al. 2010, Jakubiec and Reinhart 2011). All modelling and daylight simulations could be carried out within the Rhino and Grasshopper environment, for the prediction of various radiant or illuminance calculations using sun and sky conditions derived from standard meteorological datasets. The results were dependent upon both the building's location and orientation, in addition to the facade composition and configuration (Mardaljevic 2008).
2. Honeybee:

   Honeybee connects parametric models to EnergyPlus, Radiance, Daysim and OpenStudio for energy and daylighting simulation in buildings (Roudsari, Pak et al. 2013).

3. Ladybug**:**

   Ladybug is an environmental plugin for Grasshopper3D (open source), which assists creating an architectural-conscious regarding environmental design. The plug-in imports standard EnergyPlus Weather files (. EPW) into Grasshopper and affords a variety of 3D interactive graphics to aid the decision-making process during the early design stages (Roudsari, Pak et al. 2013). For the purpose of this study, Ladybug was utilised for sun rays tracing.

4.3.1.3.Optimisation Tools (Genetic Algorithms (GA)):

1. Galapagos:

   Galapagos (Rutten 2014), is a genetic algorithm (GA) imbedded and runs in Grasshopper through the Rhino as an interface. Galapagos facilitates the exploration of different optimisation problems such as structures, thermal and daylight performance, without the necessary of scripting skills. Based on a predefined criterion, it creates an evolutionary loop that populates generations of possible solutions to random individuals. Then, based on the rule governing the selection of the optimum solution (parameters), the algorithm starts sending new parameters to the simulation program and receives the results, the previous steps are iterated till the optimum solution is reached.

2. Octopus:

   Octopus is a plug-in for multi-objective problem solving. As it allows the search for many goals at the same time, producing a range of optimised trade-off solutions between the limits of each objective (Vier 2014).

4.4. Selected Tools

One challenge for this research was achieving a smooth integration between modelling, simulation and optimisation tools for designing (TABS). This was due to many reasons: a) the form complexity of the designed system, b) The desire to explore an abundant number design solutions and c) The number of simulations and optimisation processes planned to be performed in this study.

For the aforementioned reasons, parametric tools were chosen as it allows the designer to generate a complex building skin geometry controlled by a number of variables, rules, and constraints that are defined by the designers. Moreover, the integrated Rhino/Grasshopper program was picked out as a design platform for this work as it has been widely used due to its powerful modelling capability, inherent interface, and richness of plugins that significantly outspread its functionality. In addition, the availability of Galapagos, which is a genetic algorithm (GA) plugin embedded in Grasshopper, which can be used for the optimisation processes.

Studying the technique of performance-driven architectural design based on Rhinoceros/Grasshopper is valuable for the following reasons.

- Performance-driven architectural design, while emphasising on performance optimisation, must simultaneously consider space and shape, two of the primary design considerations for architects. Therefore, the design workflow should incorporate modelling programs familiar to designers. Rhinoceros/Grasshopper is such a program. In which, design workflow and technique based on it would be friendly to designers.
- The robust modelling capability of Rhinoceros/Grasshopper makes it an adaptable platform for performance-driven design since it can handle various conceptual designs from linear to non-linear and from simple to complex.
- J. Mardaljevic defined the Climate-based daylight modelling (CBDM) as "the prediction of any luminous quantity (illuminance and/or luminance) using realistic sun and sky conditions derived from standardised climate data" (Mardaljevic 2006). Therefore, DIVA is a plug-in for Grasshopper and Rhino was chosen as it integrate widely used and validated software, EnergyPlus for thermal analyses and Radiance/Daysim for daylight calculations utilising realistic sun and sky conditions obtained from standardised climate data, and Ladybug, was chosen for the exploration stage. For these reasons, Rhinoceros / Grasshopper / Ladybug / Diva /Galapagos were chosen for modelling, exploring, evaluating and optimising the (TABS), in the following chapters.

4.5. Conclusion

Traditionally the conceptual phase of architectural design addresses only a rather limited selection of requirements (in most cases, functional and aesthetic aspects prevail). In contrast, the concept of performance-based architecture has recently emerged as a design approach in which building performance, becomes a guiding criterion (Kolarevic 2003). It aims to broaden the range of performance assessments in the conceptual phase, and on the other hand, to support their assessment based on early numeric evaluations (Becker 1999). By using performance-based design, the level of interdisciplinary, the level of complexity, and the key impact that geometry has on the realisation of the performance related goals naturally, increases.

The utilisation of digital technologies in the architecture allows to generate and evaluate a broad range of alternative design solutions (Henriques, Duarte et al. 2012), via combining parametric modelling tools with analytical tools, and consequently, opened up new advantages regarding performative aspects in building design (Kocatürk, Medjdoub et al. 2011).

In the context of parametric design, objectives such as performance, program, context, structure, economy, efficiency, and fabrication are controlling the guiding principles of algorithmic thought to fulfil the required criteria and consequently add meaning to both the output and the process.

The performance-driven parametric model allows designers to integrate parametric modelling, genetic algorithms (GA), with the recent advances in building performance simulation tools, into one integrated process governed by design objective to exploit design strategies that effectively improve building performance, and design decision by being in direct associate with the site and its surrounding environment (Huang and Niu 2016). Thus, the designer finds ways to utilise the site's natural resources as a means to improve the performance of the built environment and reduce the building's need for energy.

To sum up, employing a methodology that integrates parametric modelling tools (Grasshopper), parametric integrated simulation tools (DIVA), and Genetic Algorithms (GA) (Galapagos) fulfils many of the architect's nowadays problems such as:

- Guaranteeing high levels of environmental performance,
- Reducing the time needed for far-reaching trial and error processes.
- The automatic simulations' performing and results' sorting based on their performance, by setting a design problem and obtaining the optimised solutions regarding that problem, instead of setting model's changes for each simulation.
- Maintain a highly informed design decisions throughout the achievement of multiple successful solutions that are supported by data and evidence.

However, there are a variety of other option software platforms could be used to accomplish similar results, the previously selected tools were chosen based on their relevancy, availability, and personal skill.

The utilisation of these tools in modelling, exploring, evaluating and optimising the (TABS), in the following chapters.

Chapter Five

5. Design and Modelling of Territorial Adaptive Building Skin (Tabs)

5.1. Introduction

To that extent, the historical development of building skins and different strategies architects usually used for facades' treatment to improve building performance along with a special focus on daylighting was given in Chapter Two; moreover, the concept of adaptive building envelopes was introduced in Chapter Three.

The performance-based model and the utilisation of the advancements of parametric, generative and form finding (genetic algorithm (GA)) tools in addition to overviewing the capabilities of the building performance simulation tools with respect to Adaptive Building Envelopes were introduced in Chapter Four. This chapter is concerned with the (TABS), including general concept, objectives, system characteristics and sources of inspiration, in addition to the modelling and simulation toolbox and the design process of TABS.

5.2. Defining (TABS)

Several definitions of an adaptive building envelope have used, but for this thesis the following have been chosen as a general base for defining (TABS), Is the building skin that can adequately express the unique forces that are defining the surrounding context of the building, either tangible, or intangible, via utilising traditional pattern and local adaptation strategies as a source of inspiration, and have the ability to repeatedly and reversibly change its functions, features or form over time in response to varying performance requirements and variable boundary conditions. By doing this, the building skin effectively seeks to improve overall building performance along with reflecting its local cultural identity in an innovative way.

5.3. The Needs of (TABS) in Egypt

The current needs for TABS in Egypt can be discussed based on both functional and formal needs which are discussed as follows:

Functional Needs

Building envelopes are playing an indispensable part in protecting the building from external environmental elements, such as heat, cold, noise and air contamination.

Furthermore, the building skin plays a significant role in delivering natural daylight to indoor spaces (Brotas and Rusovan 2013).

Daylight strategies are fundamental to nourish human health, worker productivity and an effective work environment (El Sheikh 2011). In increase, natural lighting considered to be an indispensable factor in office buildings' design aiming for improving user productivity and indoor environmental quality, while cutting the building's energy consumption (artificial lighting, chilling and heating loads, etc.) (Ander 2003). Nevertheless, sunlight needs to be controlled regarding sufficiency vs. excess to live up to the occupant's comfort requirements. Therefore, architects have to look for ways to cut energy use without affecting the building user's comfort. Controlling the daylighting that accesses the building through its skin is one of the possible ways to improve the indoor environment, while reducing the energy consumed by artificial lighting, cooling and heating loads (Ander 2003). Office buildings are considered to be high-energy consumers compared to other building types (Westphalen and Koszalinski 1999). The Administration of the United States Energy Information (EIA) stated that the commercial and residential sectors used 40% of total energy consumption in 2012 (Administration 2015). In office buildings, 10% to 30% of the primary energy is consumed by lighting (Hee, Alghoul et al. 2015). Therefore, well-planned daylight strategies can provide energy savings, by minimising the artificial lighting use and decreases glare and other visual discomfort (Ander 2003), (Ruck, Aschehoug et al. 2000). As a result, the international society gives central attention to energy efficiency and occupant comfort; accompanied with an emerging demand to integrate sustainability–related performance approaches within design stages as daylighting and energy (Lagios, Niemasz et al. 2010).

However, building skin's solutions in most contemporary office buildings in Egypt do little to bring down energy requirement as they tend to stick to the International Style with large glass curtain walls. While fully glazed facades offer excellent prospects and offer great quantities of natural illumination, fully glazed office buildings in Egypt are experiencing inadequate daylighting levels during the working hours in the daytime in terms of illumination levels of task points that are out of the recommended range. In addition, there is an uneven distribution of daylighting and a high risk of glare. Moreover, a high demand for electric lighting to compensate for the insufficiency of daylighting depth into space and cooling loads due to the solar radiation accessing the space. (Etman, Tolba et al. 2013), (El Sheikh 2011).

The current technological advancement affords outstanding opportunities for providing better daylight performance and improving energy savings, by delivering daylight deeper into space, sustaining desired illumination levels, and achieving even luminous distribution and lower risk of glare. (El Sheikh 2011)

Thus, making an efficient office building envelope that interacts with its surrounding environment is one of the most important objectives for architects today (Etman, Tolba et al. 2013). This is especially true in Egypt, which is facing critical energy shortages accompanied by a significant increase in energy demands over the next decade as Egypt aims to develop economically. Therefore, energy savings is one of the primary targets for the Egyptian government (Sakr and Sena 2017).

Egypt's climate is characterised by high direct solar radiation and clear skies under the classification of hot desert arid climate (Peel, Finlayson et al. 2007). This is considered to be optimum sky conditions that contribute effectively to the utilisation of daylighting. In contrary, these weather conditions may cause excessive heat gain or visual discomfort (Sherif, El-Zafarany et al. 2012). Tracing the development of adaptation practice in architecture bioclimatic and ancient vernacular architecture revealed valuable lessons in term of taking the advantage of the available conditions in the surrounding environment in building design (Zhai and Previtali 2010).

Traditional shading devices such as louvers or overhangs are often unpractical for new complex building forms due to the difficulty of integrating these forms with highly articulated contemporary building design. Moreover, the contemporary importance of the architectural design on environmental performance has led to a renewal of attention in the ability for facades to be kinetically responsive (Ramzy and Fayed 2011). A recent development is to augment buildings with kinetic capability, allowing buildings to alter their physical shape in response to climate conditions (Kensek and Hansanuwat 2011).

All these facts highlight the need for updating the traditional approaches of the building envelope from acting exclusively as a passive barrier towards a building skin which acts as an active negotiator with the surrounding environment. Recent advances in materials, controls and system modelling now mean that building skin can be a dynamic element which acts as a negotiator with the external environment and an enhancer of the internal environment. As an approach to resolve this contradiction, one of many potential methods that achieved a promising efficiency is by integrating a shading system into the façade and controlling the building envelope configurations (El Sheikh 2011). Also, all of these aforementioned reasons raise the question about the possibility of using local traditional patterns as a source of divine guidance for designing a building ornamental skin integrated with louvers in one building skin system that are at the same time as a performative shading device to fulfilling the daylight standards.

This target could be accomplished by harnessing the capabilities of adaptive building skins as a mean to obtain a balance between the gathering of light and a sufficient amount of energy into the building while decreasing the unfavourable drawbacks such as overheating and glare.

Formal Needs (Searching for identity)

The building contextual identity can be well represented by the adequate consideration of both tangible and intangible forces that are forming the building's local context, with the aim of achieving particular objectives, such as energy efficiency and expressing its cultural influence (Pellitteri, Concialdi et al. 2008).

According to Martin oil wealth, along with social and political changes, have threatened Islamic culture and an identity crisis. The importation of Western technology, planning, design and constructional expertise. As a result, the new buildings in the Middle East are imitating the Western buildings that were designed for a different culture. Nowadays, many Middle Eastern architects are reacting to this crisis by reasserting their Islamic heritage. This points to the use of local geometry, local materials, and local architectural strategies to express the Islamic architecture. Moreover, examining the patterns of Islamic architecture revealed complex geometrical relationships, with a studied hierarchy of form and ornaments, and great depths of symbolic meanings.

(Ghiasvand, Akhtarkavan et al. 2008) explained three approaches that the contemporary Islamic architecture has taken:

1- Ignoring the past and produce Western-oriented architecture that is not addressing the Islamic identity.

2- Superficial representation of Islamic architecture.

3- Understanding the characteristics of Islamic architecture and utilising modern building technology as a tool for the expression of this spirit.

By following the third approach, Egyptian architects can harness the advantage of new technologies, materials and mass production techniques to explore the Islamic geometric patterns that can be evolved from this approach would have a local identity, a stylistic evolution and significance of the eternal principles of Islamic architecture. Moreover, it would be a real test of the architect's ability to combine the beauty and spirit of the ancient architecture interpreted in a modern expression harmonious with the current technological advances.

To sum up, it is necessary to consider the rich heritage of Egyptian Architecture in developing new office building skin in Egypt. In vernacular architecture much attention was spent on passive climate regulation, to achieve the most of the environment. However, with the introduction of modern architecture a major shortcoming of such a style is the negligence towards local climates and heritage, especially in a country like Egypt. Therefore, new design approaches that consider local issues, both climatic and socio-cultural, were essential. To do this relevant adaptation strategies had to be extracted from both Egyptian and Islamic cases to establish a toolbox of possible approaches. Then these strategies have to be "activated", so that a proper applicability study could be devised for utilising these strategies to maintain adequate performance during the entire year by affording a system that is culturally inspired by traditional patterns and adaptation solutions and dynamically responding to the fluctuating change environment condition.

5.4. Territorial Adaptive Building Skin and Daylight System Characteristics (analysis)

In the hot Egyptian climate, controlling solar radiation gain is essential for both visual and thermal performance. Otherwise, there is excessive heat gain in addition to illuminance levels greater than recommended levels. Therefore, a study was carried out in Chapter Two that overviewed the essential knowledge of the existing shading and daylight redirecting systems and traditional local architectural practice, and the capabilities of the current technologies regarding Adaptivity in architecture was reviewed in Chapter Three; moreover, the current advancements regarding parametric design, Genetic Algorithm (GA), and Building Performance Simulation (BPS) tools, that influenced the architectural design process were explored in Chapter Four. Each chapter helped build-up an awareness about the needs and requirements of developing an innovative system that harnesses the capabilities of current technologies while obtaining lessons from the accumulated local architectural and adaptation practice to design an optimised (TABS). This would be a system that integrates the advantages of both the shading system and daylight redirecting system and capable of repeatedly and reversibly changing its configuration to adequately enhancing the daylight performance while reducing overheating and the risk of glare, and consequently, reduce the energy demands for office space's operation, along with reflecting its local cultural identity. Based on the discussion in Chapter Three regarding the adaptive building envelope system analysis, Table 5.1 summarises the characteristics of the (TABS).

Table 5.1 Characteristics of the (TABS)

No	System characteristics	Feature
1	Adaptive application area	Opaque envelope elements (south façade)
2	Adaptive behaviour	Climate: Solar radiation - daylight availability and control solar heat gains; People: Responding to the required performance based on the occupants' preferences
3	Time scales	Hours
4	Scale of adaptation mechanism	Macro scale
5	Control	Closed loop system
6	Relevant Physics	Optical (B)
7	Source of inspiration	Traditional pattern / Biomimicry

5.5. Designing a (TABS)

Introduction

The performance of daylighting systems is associated with various parameters, such as the type, size, and location of shading and daylight redirecting systems, and the availability of direct, diffuse and reflected solar radiation. The daylight-deflection is the process of re-directing light into space or back into the outdoor environment. On the other hand, shading systems are utilised to block direct sunlight. However, the use of both strategies in a combined scheme is possible, and may prove more efficient as this integration allows for adequate daylight optimisation inside space due to a combined configuration of blocking unnecessary light and harvesting it in an appropriate way that improves the occupants' working environment. Moreover, affording better distribution of the illuminance during the daytime, and improving daylight penetration depth inside space, while still blocking solar radiation to reduce heat gains and glare (Ruck, Aschehoug et al. 2000).

As a result, the amount of artificial lighting can be diminished, and cooling demands can be reduced. Moreover, by harnessing the advancements of current technologies these systems can be dynamic and consequently, can be applied to adapt to different conditions throughout the year and maintain the required performance. Furthermore, these adaptive skins have become a main area of research, utilising many terms, strategies and shapes from biology and tradition as a source of inspiration.

All of these aforementioned reasons raise the question about the possibility of recalling traditional patterns and solar screens in an innovative way as a source of inspiration for designing a cultural-functional adaptive building ornamental skin integrated with a louver system in one building skin. At the same time, such a skin could act as a performative shading and daylight redirecting device and a possible means to represent the country's identity in a modernised way along by carrying out the aforementioned multi-objective measures.

Consequently, this stage is concerned with designing a TABS that is adaptive and inspired by biomimicry and cultural tradition in order to fulfil the objectives of this research.

The demonstrated system is designed as a double layered system to integrate the advantages of both of the shading and daylight redirecting systems.

The ornamental perforated dynamic screen consists of a grid of dynamic patterns forming the external panel of the fully glazed façade, and the internal panel of the fully glazing façade consists of horizontal louver system as a daylight redirecting syetem, The process of designing the demonstrated TABS consists of three stages: the first stage explains relevant adaptation strategies from Islamic architecture and local adaptation strategies in hot climate areas to establish a toolbox of possible approaches in the face of climate change as a sources of inspiration. The second step demonstrates the process of designing and "activating" the utilised Islamic pattern and the third step is concerned with integrating the louvers system with the designed pattern.

Sources of Inspiration

The designed pattern is culturally motivated by a traditional architectural feature in Egypt and the Middle East called "Mashrabiya" (Figure 5.1), and by biomimicry that is inspired by plant adaptation strategies to grow in bright sunshine or shade. Adaptation plays a significant role in the vernacular architecture which, to a certain extent, can be considered as the accumulated result of a static adaptation process in which spatial and formal solutions were modified after thousands of years of evolution.

5.5.1.1.Traditional Architectural Feature

Vernacular architecture has examples of static adaptation in which ornamentation is used to solve multi-task problems and qualify space with attributes. An example can be found in Islamic Architecture with the use of Mashrabiya screen walls. Which is a traditional Islamic and Arabic motif of the wooden lattice screen, it was made for creating an interesting façade, an efficient shading system, reducing solar gain, reducing glare, and providing privacy, in addition it represents the identity of the Egyptian culture (Mahmoud and Elbelkasy 2016), which is one of the main objectives of designing TABS.

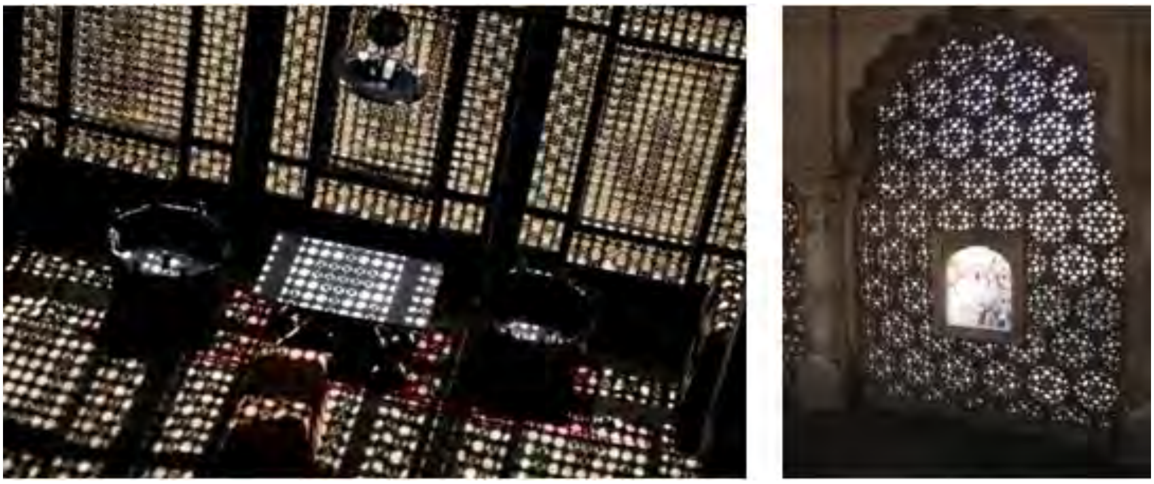


Figure 5.1 Examples of Mashrabiya

Many previous studies discussed the performance of Solar Screens and their associated design parameters and geometric configurations. The strategies adopted for utilising these screens was either allocated in the front or integrated with the fenestration glazing. Regarding the screen opening forms and perforation ratio, (Aljofi 2005), examined the impact of the different geometric configuration of the solar screen's opening cells, such as circular, elliptical, rectangular, diamond and square shapes in the daylight performance inside a space. The results showed that regarding the daylight factor, in all the cells' shapes, the central zone of space received the highest level of the reflected daylight, as the daylight factor in this area was ranging from 10% to 23%, and less than 12% on the sides. Moreover, the circular shapes contributed less to the daylight performance inside the space. Furthermore, a higher perforation ratio is recommended to increase the light reflected in the space.

Regarding the utilisation of solar screens for different orientations, a study by (Sherif, El-Zafarany et al. 2012) suggests that the utilisation of solar screens on the south, west and east facades of buildings can support larger window to wall ratios (WWR) while minimising the risk of overheating.

The utilisation of Solar Screens in providing daylighting, while maintaining the privacy levels desired in the cultures of the Middle Eastern countries was examined in a study by (Sherif, Sabry et al. 2010). A group of different screen perforation ratios of wooden Solar Screens was evaluated regarding the daylighting performance inside a living room using the Radiance software. The results showed that a balance between daylighting and visual privacy could be obtained.

5.5.1.2.Biomimicry

Besides the inspiration of Islamic traditional perforated solar screens “Mashrabiya”, adaptation also finds a significant background in biomimicry. Biomimicry is a way of understanding the process of creative problem solving through analysing adaptation strategies of a living organism and using it in solving problems (Volstad and Boks 2012). The Sun is a dominant source of energy for living creatures. Thus, during millions of years of evolution, creatures have utilised many adaptation strategies to optimise different kinds of performances, such as plants in term of controlling the amount of radiation gain to their system (Poorter and Werger 1999), (Ezcurra, Montaña et al. 1991), and (Ehleringer and Forseth 1980).

Some plants show evolutionary adaptations to grow in sunshine or shade. For example, the leaves of trees often show developmental adaption to different conditions - the exterior leaves of the canopy grow under conditions of direct sunlight, while leaves within the interior part of the tree are adjusted to the shade made by surrounding leaves. These adaptations include differences in leaf anatomy and shape. Moreover, the leaf surface is responsible for regulating the movements of water vapour, O_2 and CO_2 through them, via opening and closing pores, called stomate, usually found on the bottom side of the leaf. Opening and closing of stomata are controlled by cells called guard cells. (See Figure 5.2)

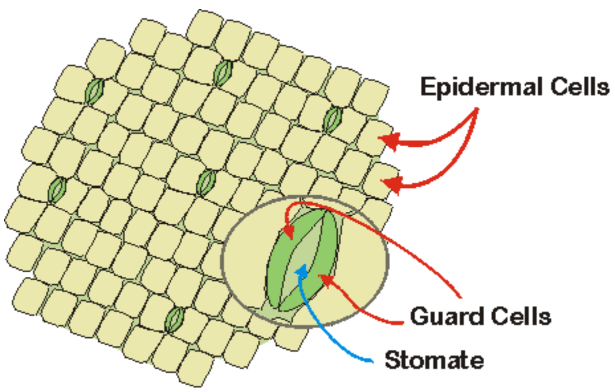


Figure 5.2 Stomate exists as the small opening between the pairs of guard cells.

Guard cells can react to a diversity of environmental stimuli by opening and closing the stomate. Stomatal valve changing in response to water and carbon dioxide exchanges is an example of dynamic mechanisms. Also, due to functional adaptations to environmental conditions, there is a variation in morphologies on surface structures around these valve cells. Stomata are effective for the interchange of gases for breath and photosynthesis, support the loss of water vapor for cooling.

Therefore, leafs are continuing adjusting the apertures of their stomata in response to conditions and changes in parameters such as light intensity, water and carbon dioxide availability. So, the stomatal form variables are affected by both internal variables such as carbon dioxide concentration and the water level and the external inputs such as humidity or water availability, temperature, atmospheric carbon dioxide concentration and light intensity (Lopez, Rubio et al. 2015).

According to (Badarnah and Kadri 2015), Biomimicry as a source of inspiration has become appealing in recent years, but researchers are still discussing on how to build a systematic methodology to be explained in general terms where the main objective is to transform biological processes into a functional element for engineering or architectural application. One of the challenging tasks for architects and designers is to identify the natural systems that achieve the same function as the design purpose, and even more challenging is abstracting the principle of biological mechanisms usually when there is a lack of biological knowledge. There are other challenges in implementing the bio ideas into a direct application, like choosing the right strategy from the many options available or an incompatibility of scales in size and the conflicts with the basic design concept. (Badarnah and Kadri 2015).

According to (Bogatyrev and Bogatyreva 2014), four principles should be followed for adapting natural processes to technology. The first is a simplification, which means that it is necessary to reduce the complexity of biological systems and to specify the main function that is needed.The second principle is interpretation, where the design has to follow the main function that was conceived along with the desired result. The third principle is to provide an ideal result, and the final is the contradiction, translating the objective into a problem-solving process.

Designing the Pool of Solutions

Parametric modelling in supporting performance-oriented design in early design stages has critical impacts on the final design decisions and consequently on the building performance over their lifetime of dynamic structure forms. Parametric modelling is the process of making a geometric representation of design with components and attributes that have been parameterized. Moreover, parametric modelling has the capability to represent both geometric entities and their relationships, based on the so-called associative geometry, which is structured in a hierarchical chain of dependencies, built during the preliminary parameterisation process. Based on the established hierarchy, some geometric attributes are expressed through independent parameters, which act as inputs to the model, while other attributes receive data from them and are dependently variable. This structure is maintained to be consistent, even if the model is manipulated and variations of the independent parameters generate different geometric configurations of the model. The different solutions are called 'instances' (Turrin, von Buelow et al. 2011). Each instance describes an individual set of transformations based on the values assigned to the parameters, allowing design variations and yielding different configurations (Barrios 2005).

In the case of adaptive skins such as the demonstrated system (TABS), these instances forms' variations provide the capability to adapt to varying conditions and scenarios based on the required criteria over the building lifetime. Moreover, the conceptual design of TABS requires managing embedded additional tasks while using parametric modelling and computational search techniques such as identifying the proper geometric means of adaptability, the appropriate configurations within predefined geometric features and the reliability of the dynamic designed system.

The first task is concerned with the description of the changes in various geometric features that affect the performance trend of design during contextual changes, such as changing environmental conditions, principally when the analysed performance is a complex geometry that is affected by multiple phenomena.

The second task aims to identify more specifically the configurations that can achieve the desired performance and to track the expected number of needed reconfigurations, as well as their patterns during the life span of the building to maintain responding effectively to the pattern of changes in the context. The final task deals with the description of technical means, to define reconfigurable systems. Reconfigurable systems can also be determined based on the capacity of their geometric configuration to change. Investigating predefined systems tends to aid the engineering knowledge integration into the architectural design process.

Also, for dynamic architecture, parametric modelling in support of performance oriented design affords the automatic generation and performance evaluations of a broad range of alternative design solutions based on a predefined range of independent parameters by utilising computational search techniques, such as genetic algorithms (GA). Furthermore, controlling the independent model parameters and organising the chain of geometric correlations considered as key points to define solution spaces significant for the analysed performance via building performance simulation tools (BPS). These movements' variations can be utilised as a design pool of solutions for the GA-based optimisation of the system behaviour, by considering different configurations to optimise the adequate configuration that fulfilled the required performance for each condition (Turrin, von Buelow et al. 2011). (Figure 5.3)

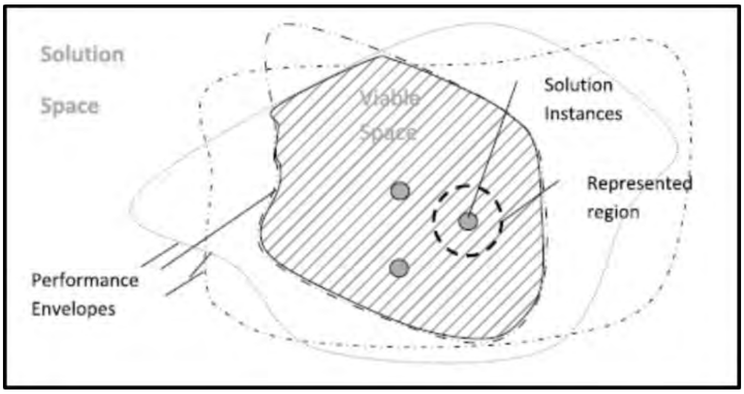


Figure 5.3 Pool of solutions (solutions space)

Therefore, a parametric system is proposed to generate multiple TABS configurations through providing a wide range of values that are controlling the parameters of each point of the skin geometries. Moreover, the problem of adapting the TABS to the context is a matter of manipulating its form in response to internal and external conditions. In the context of the current study, this problem was simplified using a case study. The internal conditions depend on the particular use intended for the office space, which has an important impact on spatial and daylighting requirements.

The relevant external conditions for lighting analysis are mainly the geographical location, time of the day and year, and weather conditions, which impact on the direction and the amount of available sunlight. So, the problem becomes one of finding an adequate configuration for the pattern and louvers which are the subsystems of the TABS, and the set of values that control variables of the shape that produce adequate indoor lighting conditions. The configuration of the TABS is determined by a small set of variables, including basic form, tessellation, opening ratio, inclination angles and geometry dimensions such as (length, width and depth).

To control the universe of possibilities and focus the study on lighting aspects, the basic form was limited to TABS system and the manipulation of the corresponding variables determines the specific shape and dimensions of the TABS.

Mechanisms for Environmental Adaptation

The designed pattern used in this study was inspired by the previously discussed strategies. The goal is to design a TABS system that is inspired by the principles of existing vernacular and biomimicry concepts to improve performance according to local conditions. The conceptual idea is based on designing a system that is culturally inspired by the Islamic solar screen “Mashrabiya” and biomimicry inspired by the adaptation strategies of plants in hot, dry climates. Such plants can dynamically alter their physical shape in response to climate conditions to maintain predefined performance criteria throughout the year. These kinetic mechanisms for environmental adaptation are essential as can now be found in building skins in recent architectural design practice.

This approach to designing architectural skins comprises the adoption of kinetic mechanisms for environmental adaptation and responsiveness. The term ‘‘kinetic architecture” was introduced by (Zuk and Clark 1970), in the early 1970s when dynamic spatial design problems were investigated in mechanical systems (Ramzy and Fayed 2011). The concept of kinetic architecture investigates a building’s capacity for motion. However, more consideration of the response to environmental conditions is required. There is a critical need to focus such novel technologies toward an important architectural responsibility; namely, sustainable strategies in buildings. Industry and research efforts are moving quickly in this area. A common approach is to augment buildings with kinetic capability, allowing buildings to alter their physical shape in response to climate conditions (Beesley, Hirosue et al. 2006).

Another approach is to augment physical space with sensing capability. Current intelligent kinetic systems arise from the isomorphic convergence of three key elements: mechanical engineering, embedded computation and responsive architecture.

According to (Moloney 2011), the motion has four geometric transitions in space: move, rotate, scale, and motion through material deformation. Move explains the motion of an aspect in a vector direction, rotation enables the movements of an object around all axis, while scaling represents expansion or contraction in size. The geometric transitions in place - move, rotate, and scale - are the three basic kinetic types. Combinations of these, like movement and rotation, will create a rolling movement – see Figure 5.4.

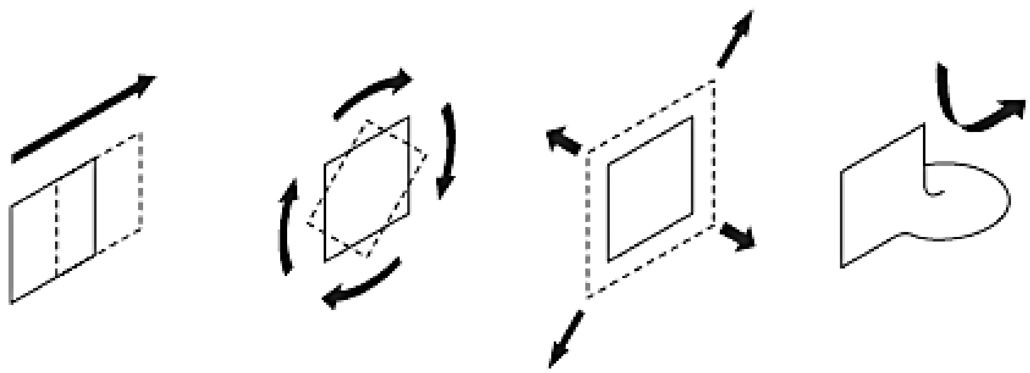


Figure 5.4 Four geometric transitions in space (442/ Moloney, 2011)

For each of these kinds of movement, one can identify three degrees of freedom, depending on how the position or orientation of an object changes on one, two or three coordinate axes. Geometric constraints can be applied to limit an object's degree of freedom (Moloney 2011), (Schaeffer and Vogt 2010).

This approach will be the foundation of various kinetic motions at the design stage and on which this research proceeds to test and evaluate possible configurations to optimise daylight performance.

For the current study a typical south facing space in Cairo, Egypt, measuring 10x8x4 m, was generated as a computer model. Using parametric design tools (Grasshopper) a three-dimensional geometric configuration of facade pattern inspired by the aforementioned strategies is proposed as an outer skin for the TABS.

The flexibility of the parametric model with all its variables provided a wide variety of shapes by altering its elements' (depth, the ratio of openings, scale, extrusion and inclination angles, etc.). Skin pattern morphology also depends on the design concept, as its realisation can be made in X, Y, and Z directions or any combinations of these. The idea was to have a variety of pattern configurations and a wide range of facade perforation ratios ranging from fully opened to fully closed. The advantages of these models can be summarised as:

- Attractive, complex form.
- Wide variety of folding states which ensures the ability of the TABS system to provide adequate daylight during the whole year and at the same time provide self-shading.
- Providing solid and transparent combination on one module

The importance of providing this wide range of variations is due to the objective of optimising the performance of the system at twelve times during the entire year, which represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st of March (vernal equinox); 21st of June (summer solstice); 21st of September (autumnal equinox)) and 21st of December (winter solstice).

Thus, the fluctuating environmental condition during the year and the contradictions between different objectives requires more flexibility and a wide range of capabilities embedded in the system to provide a group of candidate solutions for each objective and, consequently, help the genetic algorithm to identify the intersected domain of successful solutions which satisfies all the objectives and as a result identify the suitable solution for each time and maintain the required performance during the entire year. Thus, designing an efficient pool of solutions is the main objective of this stage and considered being the keystone of the whole process.

The Designed Pattern

5.5.1.3.The Complex Geometry of the Dynamic Solar Screen

By harnessing the advancement of parametric tools, a three-dimensional geometric pattern is designed. The idea was to design TABS system consisting of 40 units, with each unit measuring 1 x 1 m, for a south facing building skin which would have the ability to adjust its geometric configurations in reply to the surrounding environment based on the desired predefined design criteria. The patterns' parts have the ability to gradually open in horizontal or vertical directions depending on the time and the required performance based on predefined criteria based on the previously mentioned adaptation strategies of the "Mashrabia" and "stomate". Figures 5.5, 5.6, 5.7, 5.8, 5.9 and 5.10 show the development of the pattern and the way of integrating the horizontal and vertical louvers with pattern.

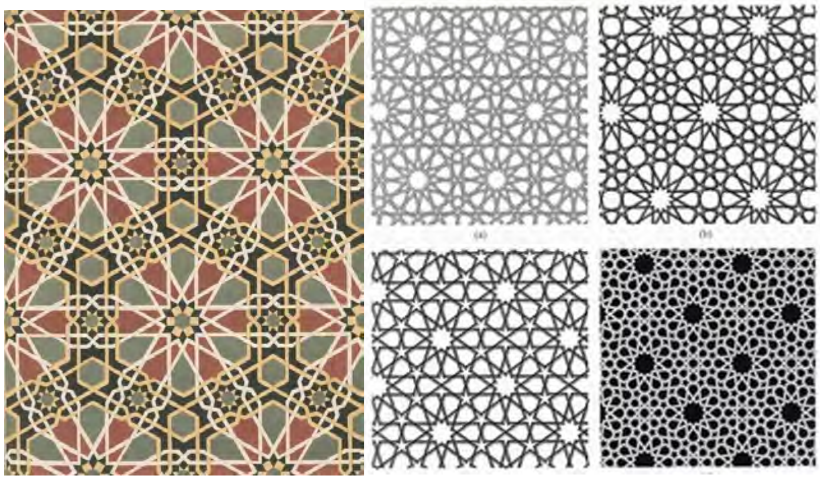


Figure 5.5 Islamic decorations

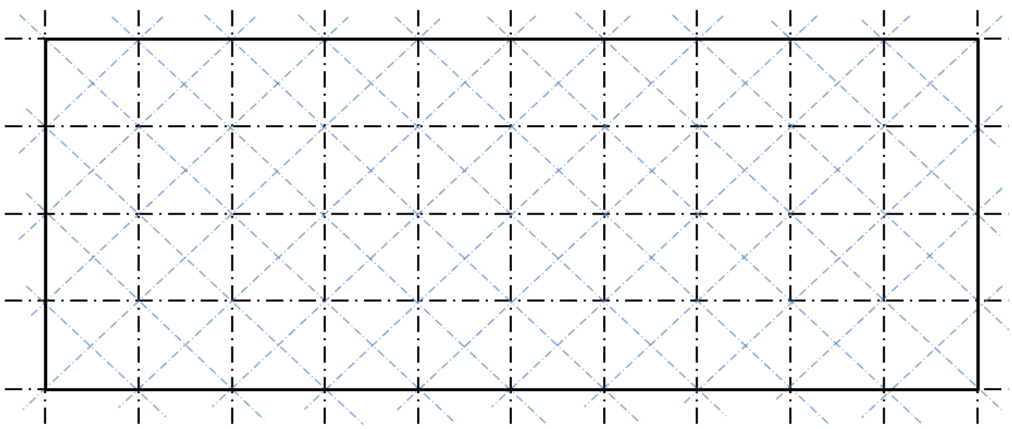


Figure 5.6 TABS units arrangement

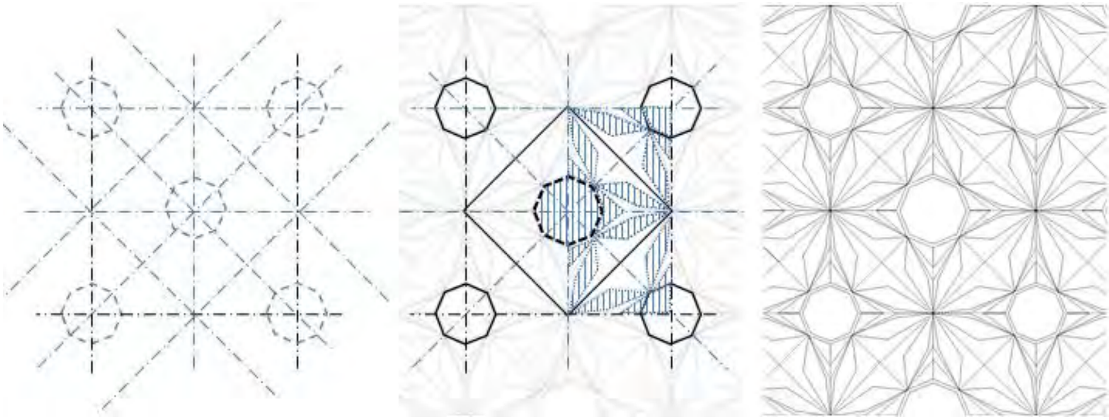


Figure 5.7 shows extracting the concept of a pattern

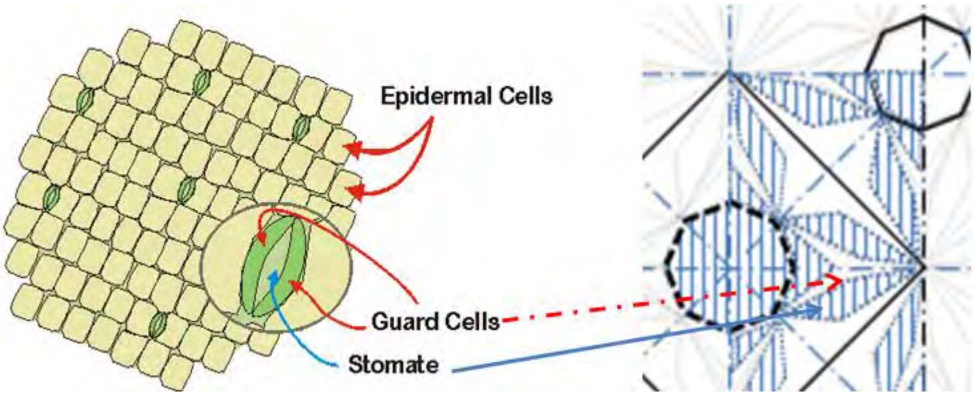


Figure 5.8 Stomata mechanism concept

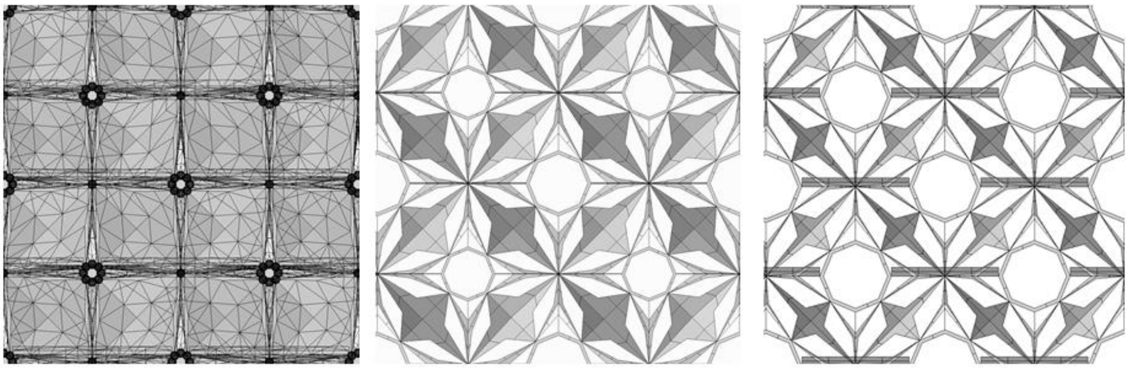


Figure 5.9 shows the TABS system opening ratios ranging from fully closed to 80%cm opening ratio (step size= 10%).

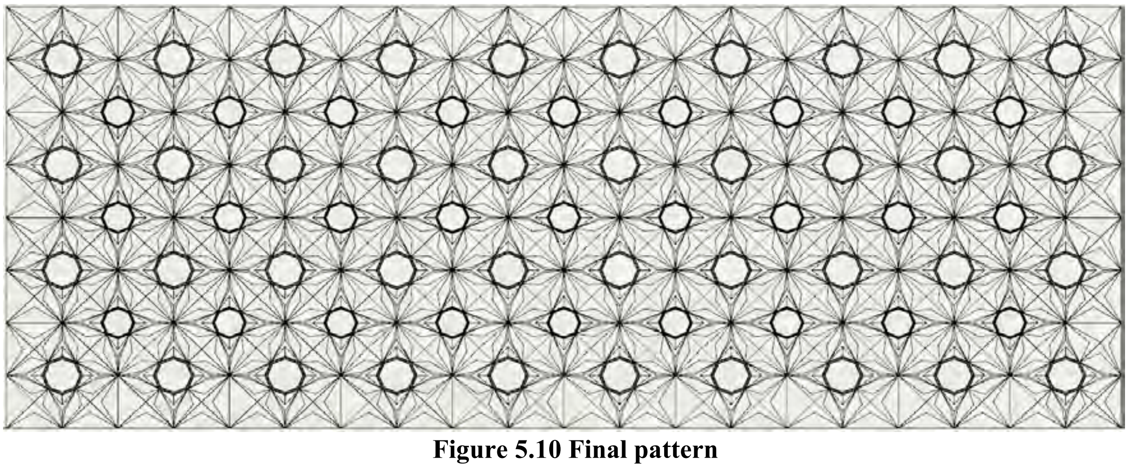


Figure 5.10 Final pattern

5.5.1.4.Integrating Louvers with Pattern

The main objective of this stage is to integrate the louver system with the complex geometric pattern without affecting the aesthetic values of the whole system.

In the light of that, two groups of horizontal and vertical louvers distributed behind the pattern along the boundaries and main axis of the Octagon shape in the centers and corners of the pattern's units, dividing each unit to four sub-units in a way that ensures redirecting the daylight that passing through the shading geometric patterns towards the ceiling to enhance the daylight distribution inside the space, to improve the daylight in the rear area of space as well as to prevent direct sunlight from hitting the task plans and the area near to the window to partially prevent overheating and risk of glare. The main points and rotation of the louvers were chosen as connections points with the Octagons to aesthetically not affecting the skin design.

Both Horizontal louver and Octagon shapes can extend in the internal direction with various depths, while TABS's redirecting subsystem are capable of having different inclination angles in both directions (Upwards and downwards). The vertical louver was decided to be fixed with 0° inclination angle and minimum depth (0.1) for the purpose of increasing the system's structural firmness and as vertical barriers between units. However, the vertical louvers have an insignificant impact on the south orientation (Ruck, Aschehoug et al. 2000), its parameters were considered as a fixed design parameter due to its geometric configurations. (See Figure 5.11 and Figure 5.12)

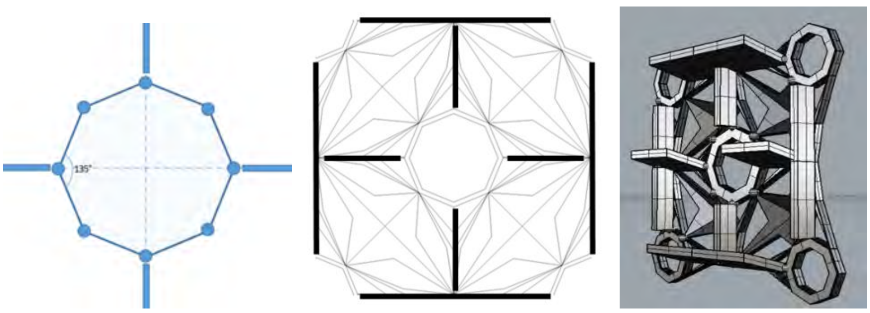


Figure 5.11 The integration of louvers with a pattern on the axis of the Octagon shape

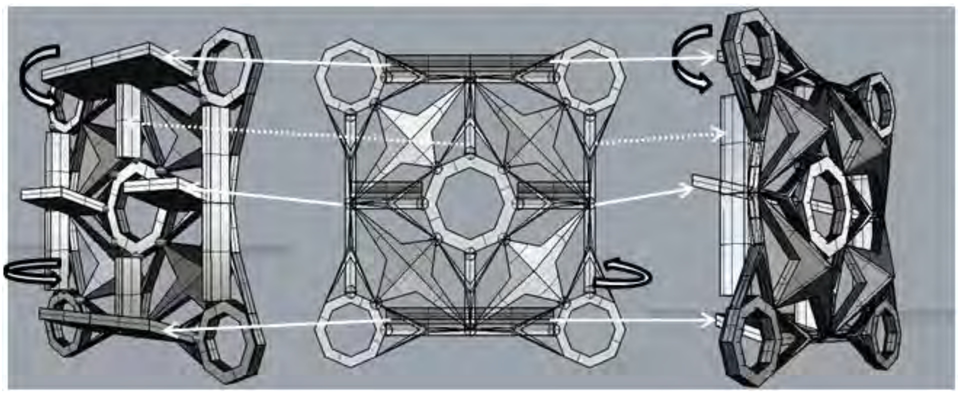


Figure 5.12 Integration of louvers with a pattern in one system

The advantages of these models can be summarised as:

- Interesting complex form.
- A wide variety of folding states which might enable the (TABS) system to provide adequate daylight during the whole year and at the same time provide self-shading.
- Providing solid and transparent components in one module.

5.6. Exploration Stage

For the exploration stage, an open source environmental plugins for Grasshopper3D called Ladybug was used to help in creating a conscious regarding the environmental architectural design. Ladybug imports standard EnergyPlus Weather files (.EPW) into Grasshopper and affords a variety of 3D interactive graphics to aid the decision-making process during the early design stage. Thus, the main objective of this stage was to understand the behaviour of daylight at all the examined times and its interaction with the designed system using interactive visualisation for sun rays tracing (Roudsari, Pak et al. 2013).

Systematically generating design alternatives in a 3D modeller allows both a quick visualisation of different alternatives and the emergence of un-conceived geometric configurations often based on the high number of possible combinations of the variables; both of which favour the revealing of new design directions, and the disclosing of previously un-expressed design aspects. This has great potential for the designer to evaluate visual aspects and explore the variations for aesthetic criteria.

Visualization of Sun Paths and Sun Ray Tracing

A standard EnergyPlus Weather file (.EPW) for Cairo was imported to Ladybug to visualize the sun's rays on 21st March at 9.00am, 12.00pm and 3.00pm (vernal equinox); 21st June at 9.00am, 12.00pm and 3.00pm (summer solstice); 21st September at 9.00am, 12.00pm and 3.00pm (autumnal equinox) and 21st December at 9.00am, 12.00pm and 3.00pm (winter solstice). The objective of exploration stage is to understand the behaviour of sun path, sun rays tracing and the impact of using different configurations of patterns opening ratios and louvers system with different tilt angles in daylight harvesting and supporting lower solar radiation's penetration in the office space while also mitigating the negative impacts of introducing excessive amount of natural lighting into space and excessive heat gain affecting thermal comfort..

These studies are summarised in Tables 5.2 and 5.3.

Model description:

Table 5.2 Model Parameters used for space in all simulations

Parameters used for space in all simulations	
Space Dimensions and Materials	
Space Dimensions	10.00 * 8.00 * 4.00
Glazing ratio	100%

Table 5.3 TABS subsystem's parameters used for the exploration stage (redirecting).

Parameter	Possible Values
Louver rotation angle	-30, -15, 0, 15, 30, and 45.
Depth	0.2 m
Octagons radius	0.15 m
Depth	0.2 cm

Table 5.4 TABS subsystem's parameters used for the exploration stage (Shading)

Parameter	Alternatives		
	High PR and extrusion depth	Medium PR and extrusion depth	Low PR and extrusion depth
Perforation ratio (PR)	75%	65%	40%
Extrusion	0.25 m	0.15 m	0.025 m

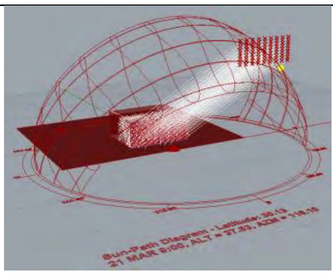
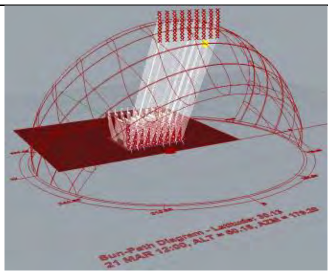
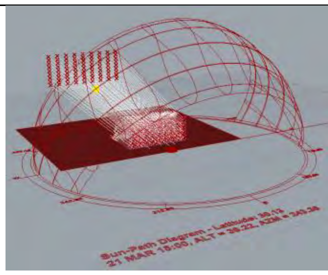
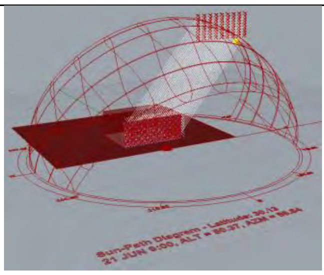
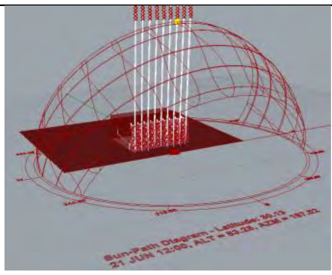
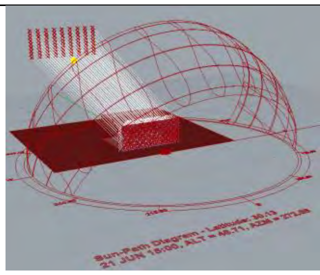
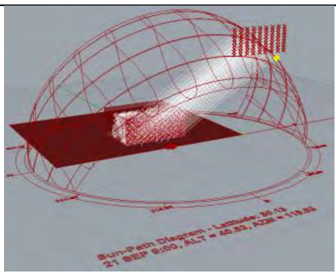
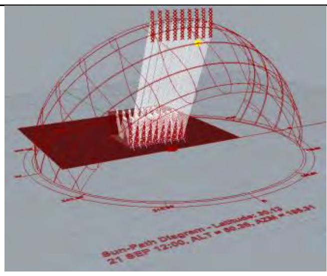
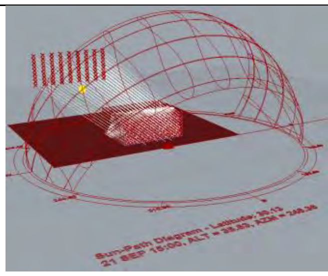
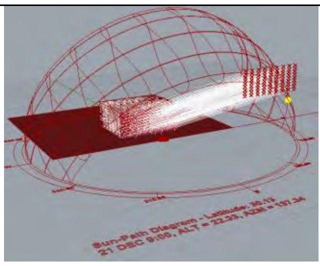
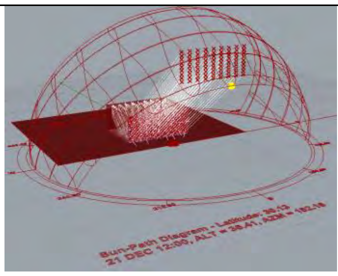
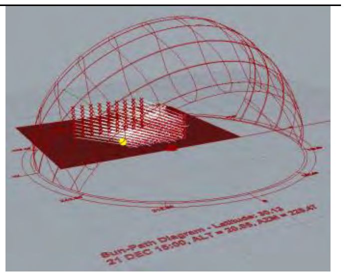
During the exploration stage, an open source environmental plugin for Grasshopper 3D called Ladybug was used to help in creating a conscious regarding the environmental architectural design and to get a sense of how sunlight is interacted and reflected by the TABS geometries by visualising the sun path and tracing the sun rays forwards through these geometries at certain times of the year. Note that this component assumes that all sun light is reflected off of these geometries specularly (as if they were a mirror).

Therefore, a standard EnergyPlus Weather file (.EPW) for Cairo was imported to Ladybug to visualize the sun's positions and rays on 21st March at 9.00am, 12.00pm and 3.00pm (vernal equinox); 21st June at 9.00am, 12.00pm and 3.00pm (summer solstice); 21st September at 9.00am, 12.00pm and 3.00pm (autumnal equinox) and 21st December at 9.00am, 12.00pm and 3.00pm (winter solstice) and a wide range of patterns opening ratios and louvers system with different tilt angles were explored. The utilisation of this plugin was helpful during the exploration stage (only) to decide the domain of the possible beneficial values of each design parameter of the TABS geometric configurations to be utilised in the next stage during the analysis and optimisation stages.

- Table 5.5 presents the Sun path visualisation at all the examined times.
- Tables 5.6, 5.7, 5.8 and 5.9 show examples of the sun rays tracing analyses of different tilt angles of the internal TABS subsystem (daylight redirecting system) in March, June, September and December respectively. While Tables from 5.10, to 5.21, show examples of the sun rays tracing analyses of the external TABS subsystem (shading system).

To sum up, the objective of exploration stage is to understand the behaviour of sun path, sun rays tracing and the impact of using different configurations of patterns opening ratios and louvers system with different tilt angles in daylight harvesting and supporting lower solar radiation's penetration in the office space.

Table 5.6 Sun path tracing visualisation

Time						
Month	9 am		12 pm		3 pm	
21st Mar						
	ALT.	AZM.	ALT.	AZM.	ALT.	AZM.
	37.53	116.10	60.15	179.20	38.22	243.36
21st Jun.						
	ALT.	AZM.	ALT.	AZM.	ALT.	AZM.
	50.37	88.34	83.25	187.52	48.71	272.06
21st Sep.						
	ALT.	AZM.	ALT.	AZM.	ALT.	AZM.
	40.53	118.53	60.38	185.31	35.83	246.36
21st Dec.						
	ALT.	AZM.	ALT.	AZM.	ALT.	AZM.
	22.33	137.34	38.41	182.18	20.05	225.47

Visualization

Tables 5.6, 5.7, 5.8 and 5.9 show examples of the sun rays tracing analyses of the internal TABS subsystem (louver system) in March, June, September and December respectively. While Table from table 5.10, to Tables 5.21, show examples of the sun rays tracing analyses of the external TABS subsystem (shading system).

Table 5.7 Results of sun rays tracing in March for base case and

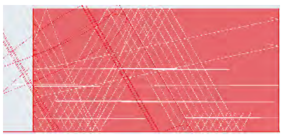
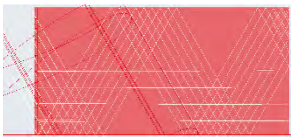
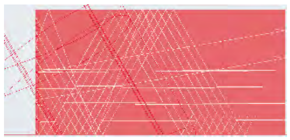
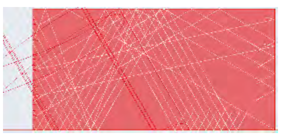
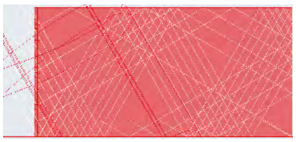
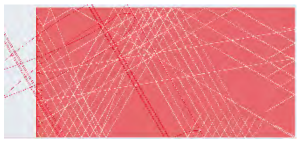
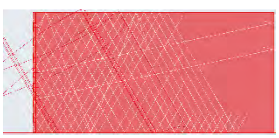
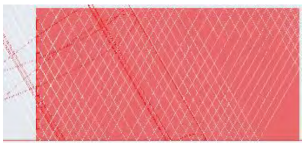
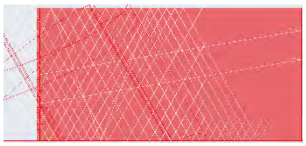
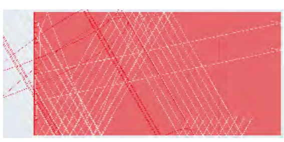
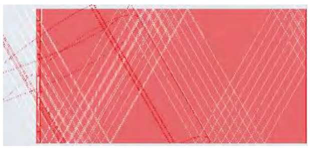
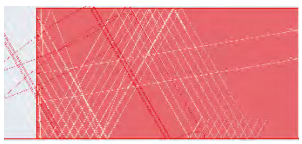
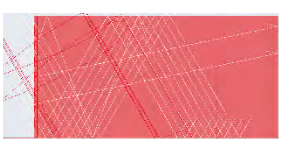
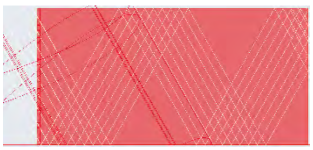
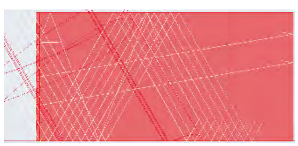
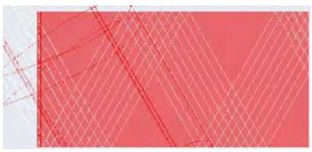
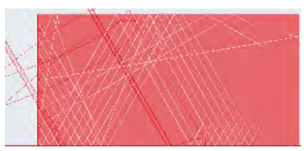
Month		March		
	H	9	12	3
	Base Case			
Angle Θ	-30°			
	-15°			
	0°			
	15°			
	30°			
	45°			

Table 5.8 Results of sun rays tracing in June

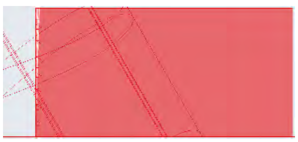
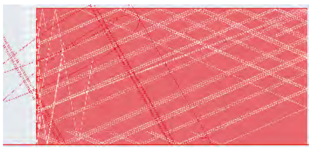
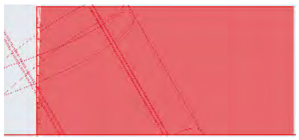
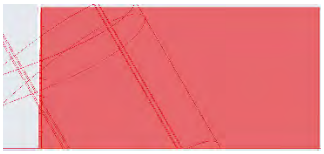
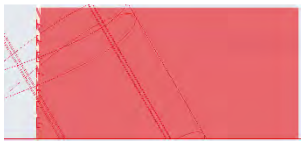
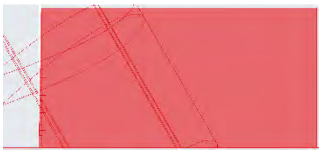
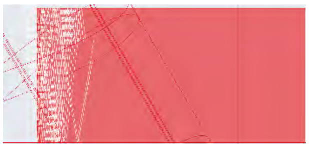
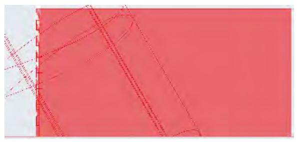
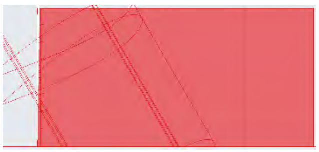
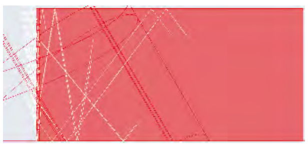
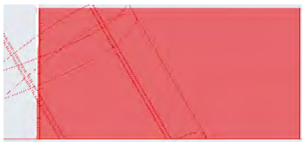
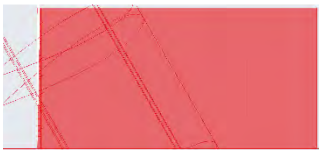
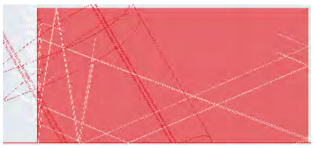
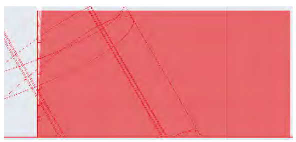
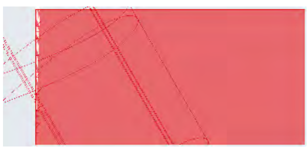
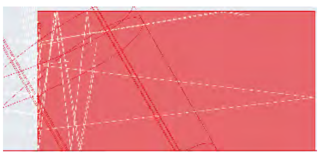
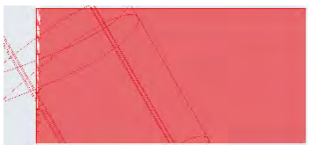
Month		June		
H		9	12	3
	Base Case			
Angle Θ	-30°			
	-15°			
	0°			
	15°			
	30°			
	45°			

Table 5.9 Results of sun rays tracing in September

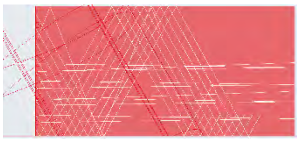
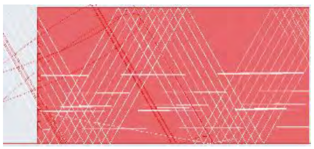
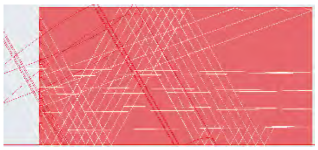
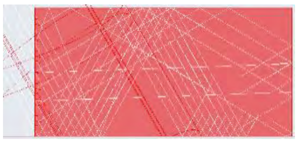
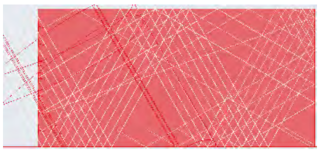
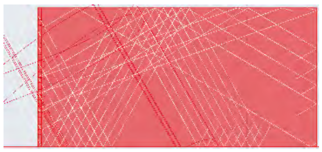
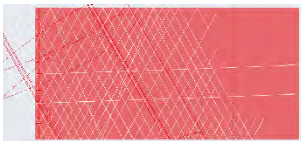
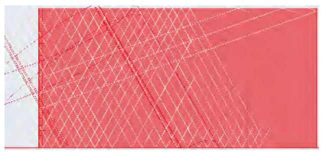
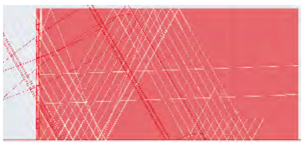
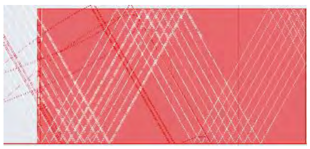
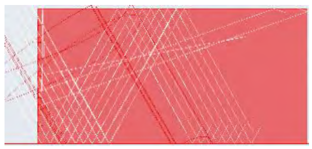
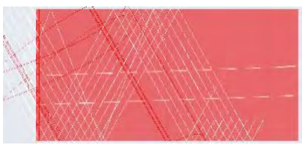
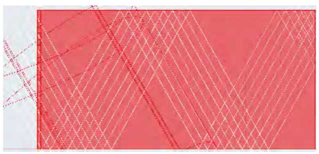
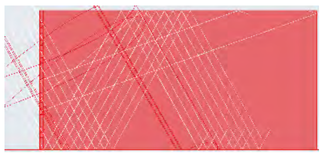
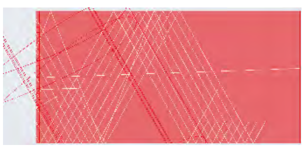
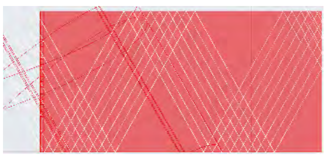
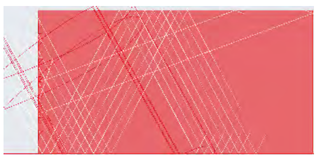
Month		September		
	H	9	12	3
	Base Case			
Angle Θ	-30°			
	-15°			
	0°			
	15°			
	30°			
	45°			

Table 5.10 Results of sun rays tracing in December

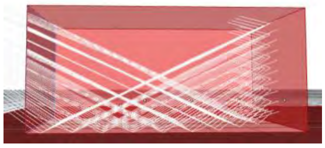
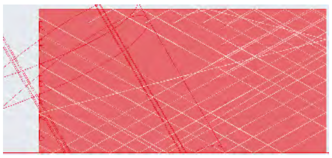
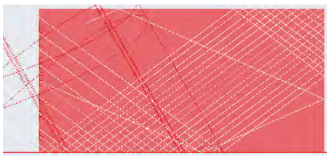
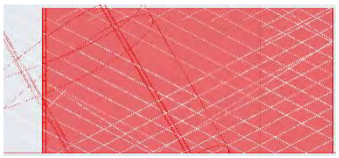
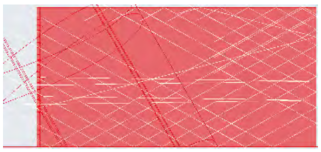
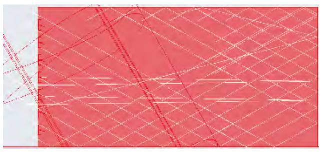
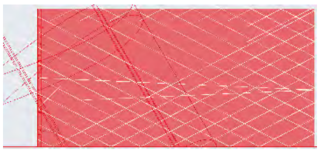
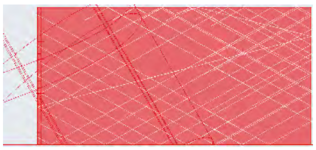
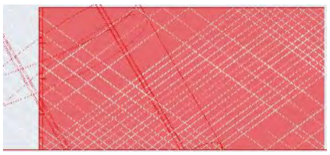
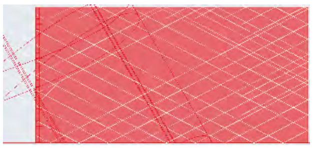
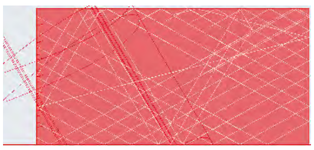
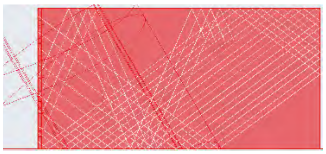
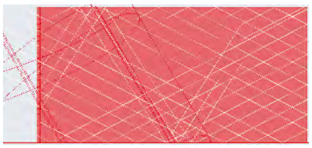
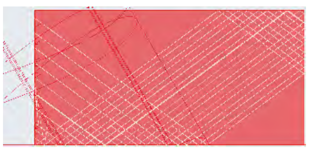
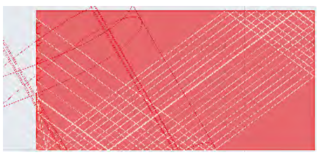
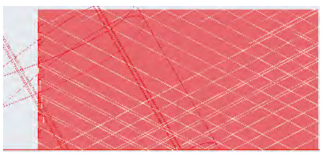
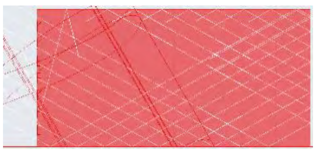
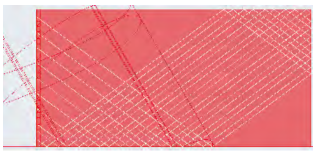
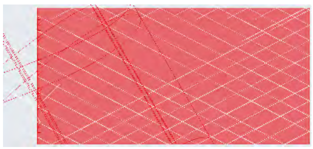
Month		December		
H		9	12	3
	Base Case			
Angle Θ	-30°			
	-15°			
	0°			
	15°			
	30°			
	45°			

Table 5.11 Results of shading system sun rays tracing in 21st March 9 am

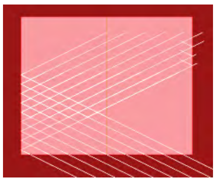
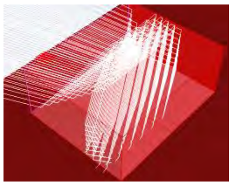
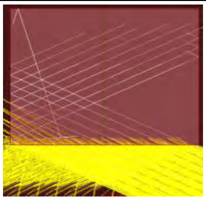
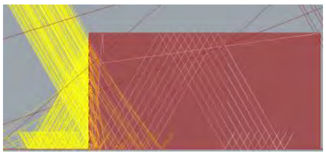
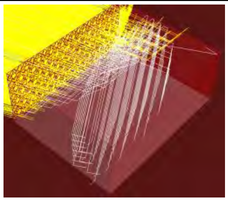
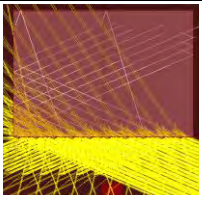
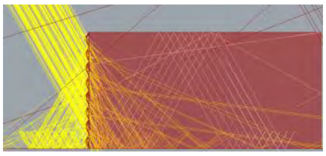
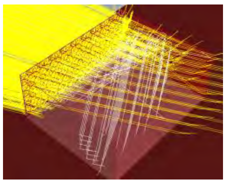
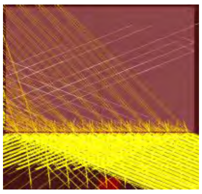
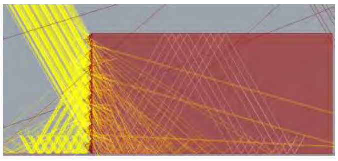
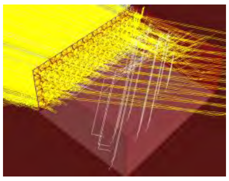
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60%) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.12 Results of shading system sun rays tracing in 21st March 12 pm

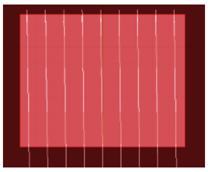
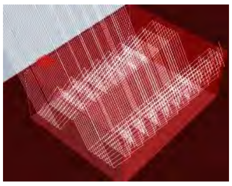
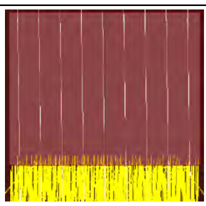
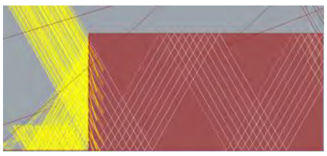
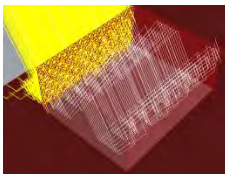
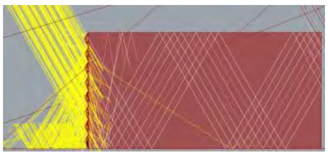
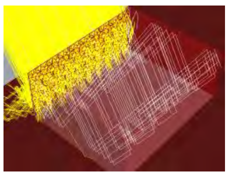
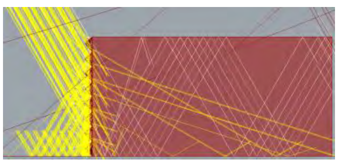
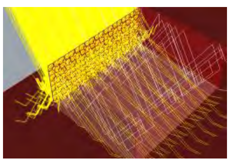
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60%) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.13 Results of shading system sun rays tracing in 21st March 15 pm

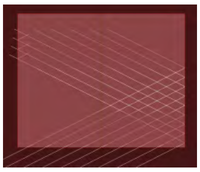
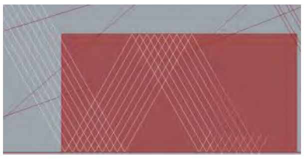
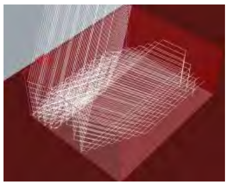
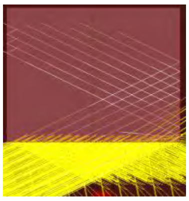
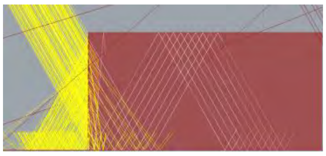
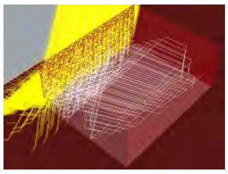
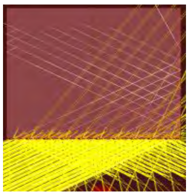
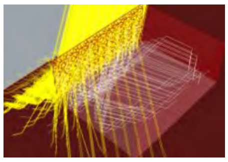
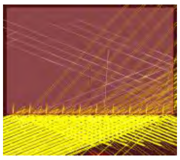
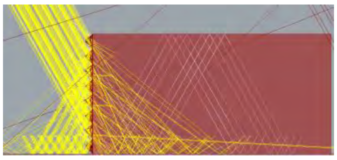
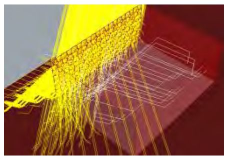
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60%) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.14 Results of shading system sun rays tracing in 21st of June 9 am

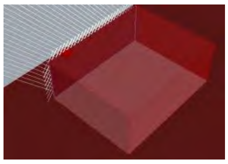
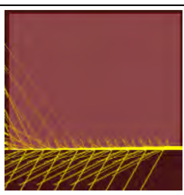
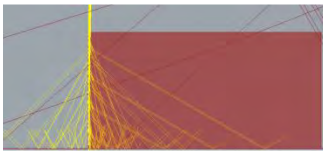
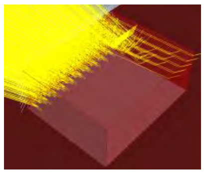
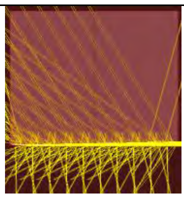
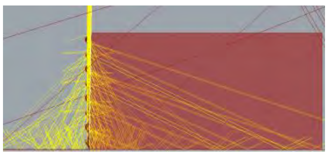
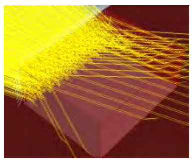
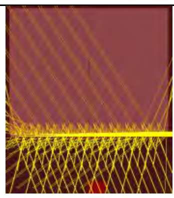
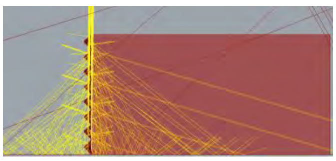
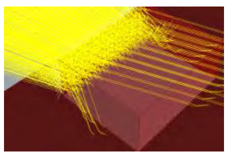
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60%) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.15 Results of shading system sun rays tracing in 21st of June 12 pm

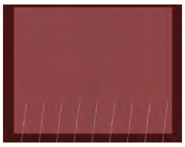
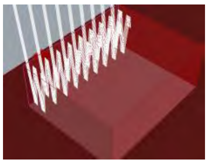
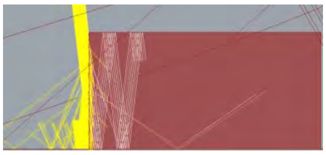
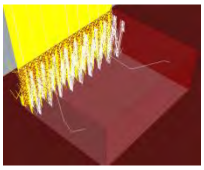
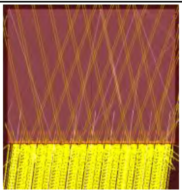
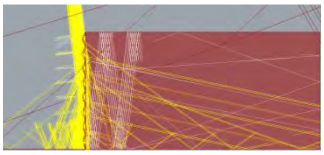
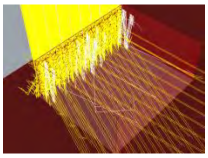
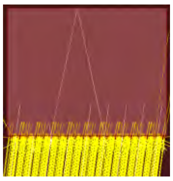
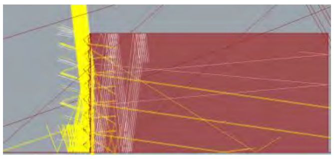
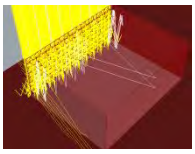
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60%) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.16 Results of shading system sun rays tracing in 21st of June 15 pm

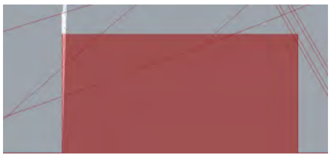
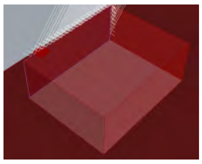
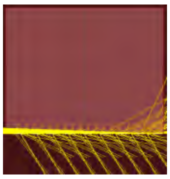
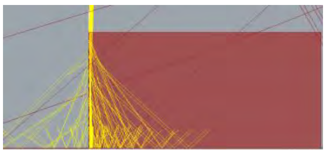
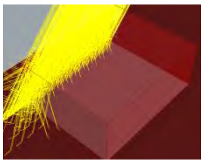
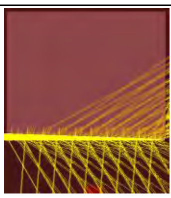
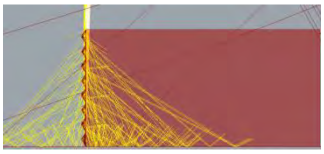
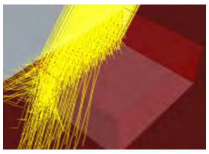
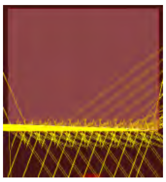
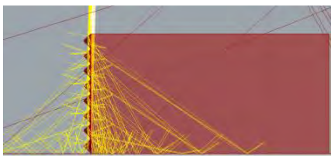
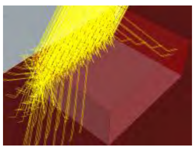
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.17 Results of shading system sun rays tracing in 21st of Sep. 9 am

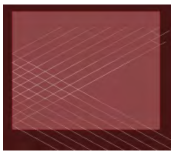
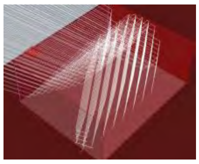
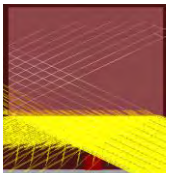
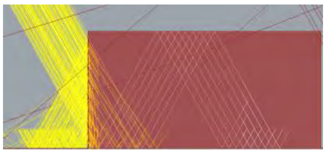
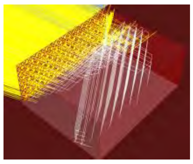
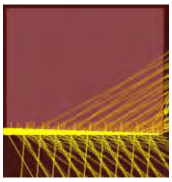
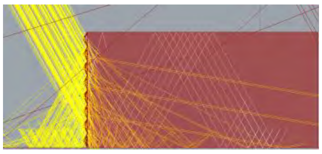
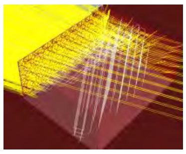
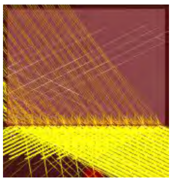
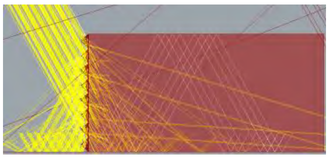
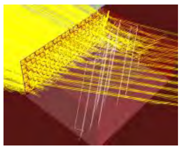
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.18 Results of shading system sun rays tracing in 21st of Sep. 12 pm

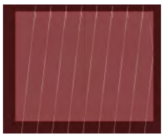
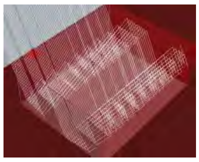
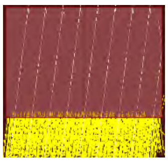
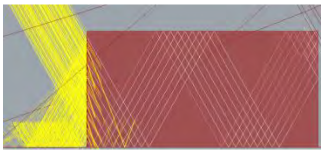
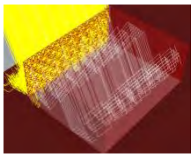
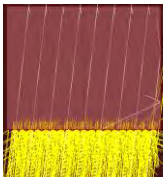
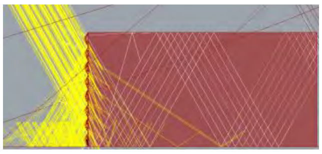
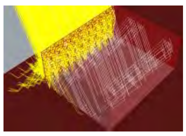
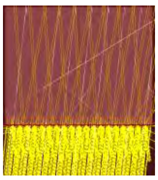
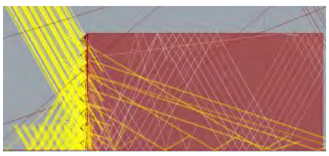
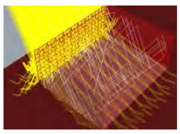
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.19 Results of shading system sun rays tracing in 21st of Sep. 15 pm

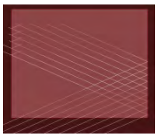
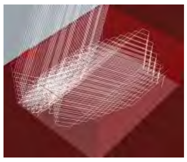
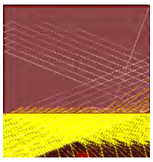
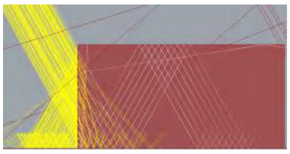
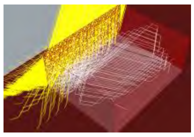
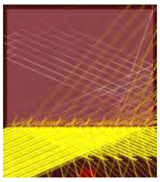
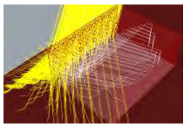
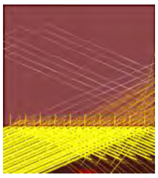
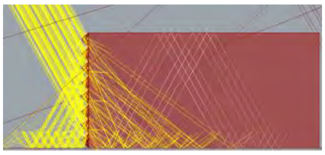
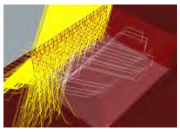
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.20 Results of shading system sun rays tracing in 21st of Dec. 9 am

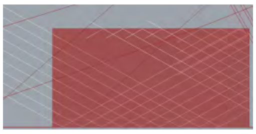
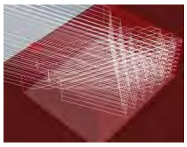
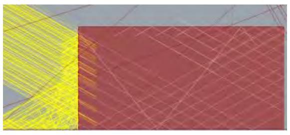
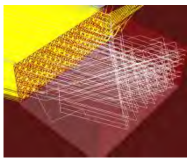
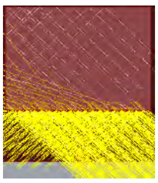
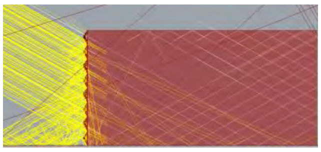
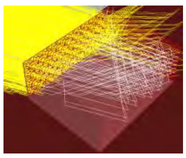
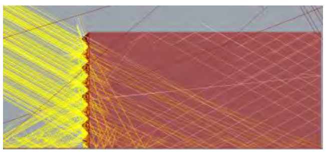
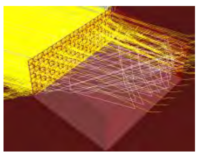
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.21 Results of shading system sun rays tracing in 21st of Dec. 12 pm

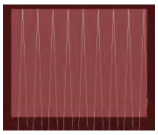
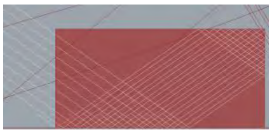
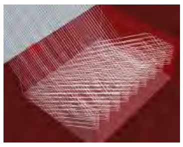
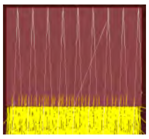
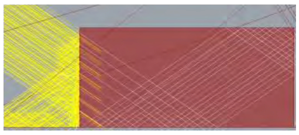
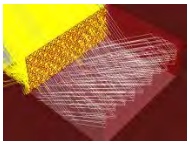
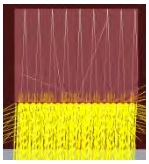
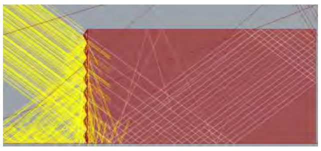
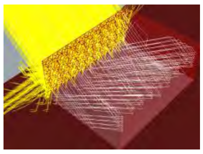
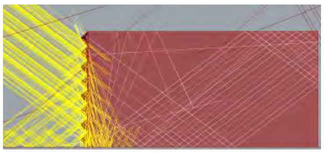
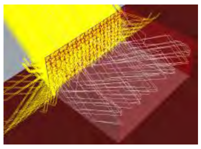
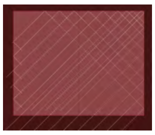
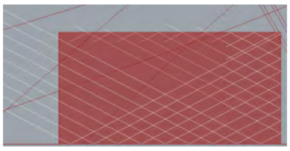
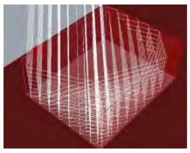
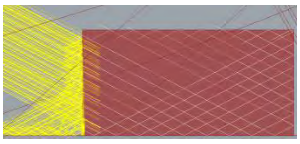
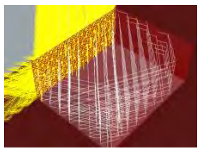
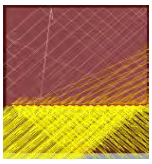
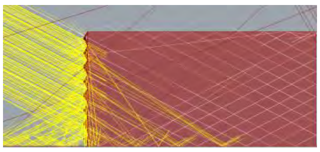
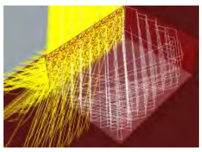
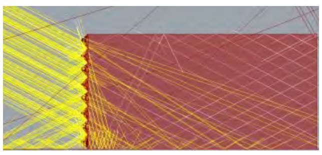
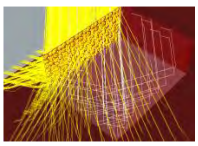
Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Table 5.22 Results of shading system sun rays tracing in 21st of Dec 15 pm

Case	Plan	Side view	Perspective
Base case			
High PR (75%) and (0.025m) Extr.			
Mid. PR (60) and (0.15m) Extr.			
Low PR (40%) and (0.25m) Extr.			

Exploration stage results and discussion:

Based on the sun ray visualisations at all the examined times, it was identified that:

5.6.1.1.Base case without TABS

March

The base case indicated excessive sun rays entered space and concentrated in the area near to the window at all the explored times (21st of March at 9 am, 12 pm, and 15 pm), which indicates a high potential for excessive heat gains, an inadequate daylight performance and high risk of glare due to the potential expected high illuminance levels.

June

The base case indicated excessive sun rays entered space and concentrated in the area near to the window at 21st of June at 12 pm, on the other hand, almost no direct sun rays entered space (21st of March at 9 am, and 15 pm), which indicates a high potential for excessive heat gains, an inadequate daylight performance and high risk of glare due to the expected high illuminance levels only at 21st of June at 12 pm.

September

The base case indicated excessive sun rays entered space and concentrated in the area near to the window at all the explored times (21st of March at 9 am, 12 pm, and 15 pm), which indicates a high potential for excessive heat gains, an inadequate daylight performance and high risk of glare due to the potential expected high illuminance levels.

December

The base case indicated excessive sun rays entered space and reaching the near, middle and rear area of space at all the explored times (21st of March at 9 am, 12 pm, and 15 pm), which indicates a high potential for excessive heat gains, an inadequate daylight performance and high risk of glare due to the potential expected high illuminance levels.

5.6.1.2.TABS subsystems

Daylight redirecting system

March

- Louvers with – 30° (downwards) failed in preventing the direct sun rays from reaching the area near to the window, in addition, it reflected the sun rays in a horizontal direction which increase the potential of glare.
- Louvers with -15° and 0° was effective in reflecting the sun rays to the ceiling, however, -30 shows higher potential regarding delivering daylight to the rear area of space.

- Louvers with 15°, 30°, and 45° (upwards) was effective in preventing sunrays from reaching the area near to the window; however, they failed in delivering daylight to the rear area of space.

June

- Louvers with -30° and -15° was effective in reflecting the sun rays to the ceiling and prevent sunrays from reaching the area near to the window, however, -30 shows higher potential regarding delivering daylight to the rear area of space.
- Louver with 0° was effective in reflecting the sun rays to the ceiling and prevent sunrays from reaching the area near to the window, however, it failed in delivering daylight to the rear area of space as all the rays reflected from the ceiling are concentrated in the near area to the window.
- Louvers with 15°, 30°, and 45° (upwards) was effective in preventing sunrays from reaching the area near to the window, however, they failed in delivering daylight to the rear area of space.

September

- Louver with -30° failed in preventing sunrays from reaching the area near to the window. Moreover, it failed in delivering daylight to the rear area of space.
- Louvers with -15° and 0° succeeded in preventing sunrays from reaching the area near to the window. Moreover, they succeeded in delivering daylight to the rear and the middle area of space, respectively.
- Louvers with 15°, 30°, and 45° (upwards) failed in both, preventing sunrays from reaching the area near to the window and in delivering daylight to the rear area of space.

December

- Louvers with -15°, -30°, and -45° (downwards) failed in both, preventing sun rays from spreading across space and in delivering daylight to the rear area of space.
- Louvers with 0° and 15° succeeded in both, preventing sun rays from spreading across space and in delivering daylight to the rear area of space.
- Louvers with 30°, and 45° (upwards) was effective in preventing sunrays from reaching the area near to the window; however, they failed in delivering daylight to the rear area of space.

Regarding the Octagons it was noticeable that due to their shallow depth, the direct sun rays were passing through and between the gaps of the shallow depth of Octagons shapes and the louver even when the louver inclination angle was successful in preventing direct sun rays from reaching the area near to the window or delivering daylight to the rear part of space by reflecting the sunrays to the ceiling. Therefore, increasing the Octagons depth will contribute in preventing direct sun rays from reaching the area near to the window and potentially could improve the daylight distribution and depth. Likewise, increasing the domain of the louver depth's possible values will be efficient, especially for low sun angles.

Shading system

In general the visualisation of the three explored screens (High PR (75%) and (0.025m) Extrusion), (Mid. PR (60) and (0.15m) Extrusion), and (Low PR (40%) and (0.25m) Extrusion), during the twelve explored times, indicated that, the lower the sun position is, the lower PR and deeper extrusion are effective, such as in March, September and especially in December at 12 pm where the sun is almost facing space, and the sun rays deeply penetrating space and reaching the rear part of space. Consequently, require a low PR to control the excessive amount of sun rays that penetrates space and deeper extrusion to increase the possibility of the screen's self-shadowing. For March, and September at 9 am, and 15 pm when space is exposed to the sun rays from South-East and South-West directions, respectively, (Mid. PR (60) and (0.15m) Extrusion), and (Low PR (40%) and (0.25m)) or a combination of them could be effective for these times. For December, the minimum PR is recommended for all times. Finally, the narrower the sun angle facing space the higher the PR and the shallower extrusion could be effective such as for Summer times as the visualisation of sun rays tracing indicated that, (Mid. PR (60%) and (0.15m) Extrusion) could be effective at 12 pm, while the (High PR (75%) and (0.025m)), could be effective at 9 am, and 15 pm, due to the high sun positions.

5.6.4 Exploration stage recommendations

1. Increasing the domain of the possible values of the louver (depth and inclination angles), as it's expected to positively contribute to improving the daylight distribution and depth while reducing the direct sun rays from reaching the internal space.

2. Increasing the domain of the possible values of the Octagons (depth and radius), as it's expected to positively contribute to improving the daylight distribution and depth while reducing the direct sun rays from reaching the internal space.

3. Separating the parameters controlling the perforation ratio of the shading system, by splitting the patterns to main and secondary groups to add more capability and help the system to successfully optimise the illuminance levels at different task plans allocated inside space and prevent direct sun rays from entering space at certain positions.

4. Separating the parameters controlling the boundary rows of the shading system to add more capability and help the system to prevent direct sun rays from entering space at certain times such as at summer season with the high sun rays angles or at 9 am, and 15 pm when space is exposed to the sun rays coming from South-East and South-West directions, respectively.

5. Increasing the domain of the possible values of the shading system's extrusion, to add more capability and help the system to achieve the required performance at different examined times.

5.7. Modifying the Parametric Design Model

Based on the recommendations of the exploration stage, the (TABS) parameters and geometric configuration's characteristics modified to be utilised in the following stage.

The final TABS parameters and domain values are described in Table Table 6.6

5.8. Conclusion

This chapter has introduced Territorial Adaptive Building Skin (TABS) as a system which is "theoretically" able to modifying its configuration through the motion of elements to improve building performance. The simple movement of louvers, or complex transformable patterns, are examples of this type of dynamic façade. Moreover, (TABS) has the ability to respond to the changing environmental condition during the four seasons, utilising predefined performance criteria, whilst maintaining an architectural link with cultural identity – for example, producing a variety of geometrical patterns inspired by traditional Islamic patterns and vernacular architectural solutions. This chapter described the initial development and testing of just such a (TABS) system, and examined the impact on sunlight distribution in a room from having louvers that could have a variety of geometries. The objective of the following chapters is develop and test a methodology a more complex arrangement of this kind of adaptive building skin.

Chapter Six

6. Performance Simulation and Optimisation Methodology of (TABS)

6.1. Introduction

As this work tries to demonstrate that providing adequate daylight, making a visually stimulating and healthful interior environment of buildings as well as directing the cultural identity can be achieved by incorporating a well-designed Territorial Adaptive Building Skin that is capable of efficiently negotiating with its surrounding environment and addressing its cultural identity as an official representative's negotiator.

This chapter introduces a methodology for performance simulation and optimisation of TABS, aiming for examining this integrated performance. Moreover, in order to understand the impact of the TABS system on visual comfort and daylight availability in office spaces the performance of the TABS is examined in this chapter in comparison to other traditional building skin solutions, such as a fully glazed base case, an optimised WWR (AOWWR), and an annual optimised static building envelope (AOSBE), on the basis of the simulation and optimisation strategy as illustrated in Figure 6.1. The characteristics of these simulations, the performance indicators and tools used in the analysis. In addition, Specific assumptions and motivations for each case are presented. Moreover, performance metrics, which are used to assess daylight levels and visual comfort, were discussed in this chapter.

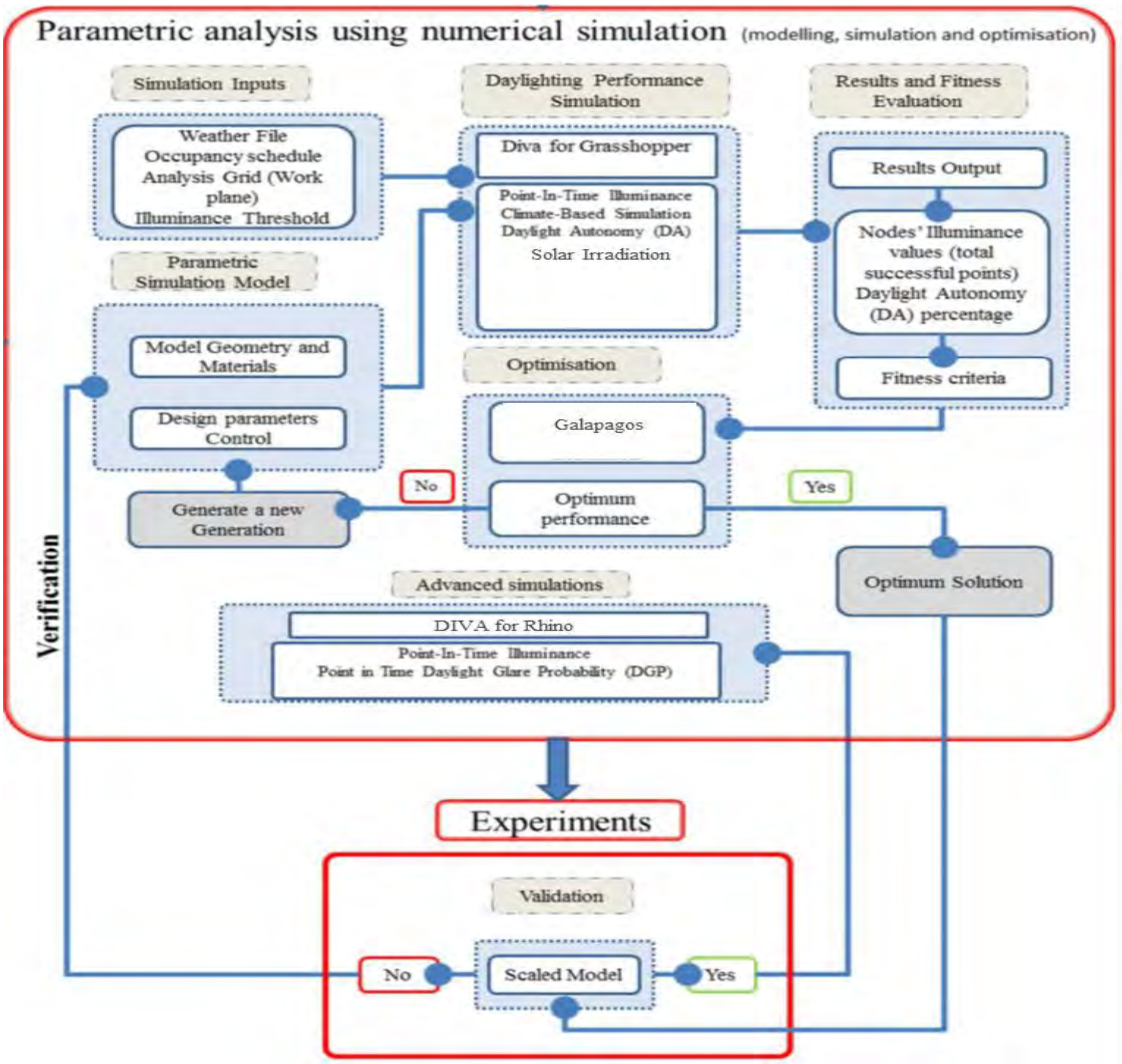


Figure 6.1 Simulation strategy of TABS

6.2. Overview

The methodology proposed in this research employed a parametric modelling, building performance simulation and Genetic Algorithm tools for optimising the performance of a parametrically modelled (TABS) for a south facing office space in Cairo, Egypt, based on predefined required criteria, at twelve different times during the entire year, which represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice), to ensure a pleasant and productive environment for space users. In addition to identifying the optimal WWR (AOWWR) and the optimal configuration of an annually optimised static building envelope (AOSBE), based on the same criteria to compare their performance to the TABS performance at the same examined times.

Therefore, with the aim of studying the effectiveness of the TABS in comparison to other traditional approaches, a number of computer simulations were carried. The main objective of the process and the developed parametric algorithm was to evaluate the performance of TABS in integrating different motions in response to dynamic daylighting and search for an optimal solution for TABS configurations.

Within the context of this study, all cases were developed using Rhino and Grasshopper. Rhinoceros (Rhino), NURBS-based three-dimensional modelling program; (McNeel 2014.), Grasshopper (Davidson 2012), is a graphical algorithm which allows for the parametric modelling and scripting and serves as an extended parametric modelling to the Rhino. Grasshopper allows the user to easily manipulate the dimensions of models by defining form-generating components, which can be optimised through the use of sliders and mathematical expressions. The Grasshopper interface is directly connected to the Rhino modelling tool so that changes made in the Grasshopper algorithm can be directly observed in the Rhino window. Simulations were conducted using Diva a plug-in for both Rhino and Grasshopper. DIVA (Design, Iterate, Validate and Adapt) (Solemma 2014), a plugin for the Rhinoceros and Grasshopper environment, was utilised in this study as it supports a series of performance evaluations by using validated tools, including RADIANCE, Daysim, Evalglare and EnergyPlus software (Lagios, Niemasz et al. 2010), (Reinhart, Lagios et al. 2012). All modelling and daylight simulations carried out within the Rhino and Grasshopper environment, for the prediction of various radiant or illuminance calculations using sun and sky conditions derived from standard meteorological datasets; the results were dependent upon both the building’s location and orientation, in addition to the facade composition and configuration (Mardaljevic 2008). Galapagos (Rutten 2014), is a genetic algorithm (GA) imbedded and runs in Grasshopper through the Rhino as an interface, Galapagos is used in this study for cases’ problem solving. Based on a predefined criterion, and finally, TT Toolbox: a plugin for Grasshopper using a Galapagos listener component that recorded all fitness performances and TABS configurations; and exported these data to Excel sheets (Tomasetti 2015).

The Grasshopper parametric definition is used to bridge the gap between the early design stage and the performance of the building, regarding daylighting (Mahmoud and Elghazi 2016). Moreover, used to identify the input parameters of the building skin and set the evaluation criteria for daylighting assessment; and pass these to the daylighting simulation tool, Diva, to simulate the process of daylighting and sends the results back to Galapagos for evaluation until an optimal solution is reached.

The tools selection was based on the possibilities for integrating them together to run at the same time to get real time feedback. Rationalising the logic processing in the form of parameters is the key element for the success of the simulation process. The geometries of all cases were created as a parametric model guided by the performance values associated with daylight, radiation control and glare and analysed using a simulation tool, then evaluated and sorted by a genetic algorithm to show best solutions according to the fitness value of each design alternative based on predefined design criteria. The aim was to develop a design strategy that could achieve building performance higher than the level achieved by trial-and-error designs.

A methodology to achieve these objectives was proposed in this study to respond to dynamic daylighting conditions to reach a better daylight quality in indoor spaces.

The workflow of the process can be described as follows:

6.3. Model setup

The location, dimensions, properties and occupancy schedule of space are discussed in the following sections.

Location

The case study was chosen to be located in the city of Cairo, Egypt (30° N- 31° E). Cairo is characterised by a clear sunny sky for almost all the year round (Peel, Finlayson et al. 2007). Also, as Cairo is the capital of Egypt and the centre of industrial and administration work in Egypt, many fully glazed office buildings were built in the last few decades following the International Style.

Weather data

Simulations use weather files to retrieve data for a specific building's location. For the purpose of this study, the simulations were conducted using the standard EnergyPlus Weather (.EPW) files of Cairo (Energy 2014).

Occupancy Schedule

The occupancy schedule was chosen to be from 9:00 am till 5:00 pm, for five working days/week, which are the official working hours for the governmental sector as well as many private companies in Egypt.

Work plane

The reference plane on which daylighting performance was evaluated, was chosen to have a height of 0.76 m. Three groups of nodes were used for daylighting analysis as described below:

a. Task points: 9 points

b. Daylight depth: 8 points (1 point for each meter depth)

c. Luminous distribution: a grid of points that is divided into 0.425 m intervals (0.425 x 0.425m) (Al-Ashwal and Budaiwi 2011).

Furniture

For the purpose of examining different shading systems, furniture was eliminated from the simulation, for quicker and easier runs and more controlled simulation environment in addition to ensuring similarity between the simulation and the scaled model during the validation process, which is described in the following chapter.

6.4. Cases dimensions and Simulation parameters

Base case

The virtual office generated for this study was a fully glazed, generic, south oriented space without shading, with spatial dimensions of 10 m wide by 8 m deep rectangular space, with a 4 m ceiling height. These dimensions represent an average space that can hold nine workstations. The office space was assumed to have a fully glazed window that was 10 m wide and 4 m high (see Figure 6.2). The office space was assumed to have an open horizon and no obstructions to neutralise the effect of the context and surroundings on daylighting performance. Within the context of this study, the base case was evaluated at twelve chosen times during the year to be compared in terms of performance with the other optimised systems. Four representative days of the year were chosen: March 21, June 21, September 21 and December 21, at three times of the day, 9:00 am, 12:00 pm, and 3:00 pm. These dates and times were chosen so that a fairly accurate idea of the performance could be taken into account by encompassing the sun's highest and lowest altitude and a range of azimuth angles throughout each day. The parameters and materials used for all cases in all simulations are shown in Table 6.1. All cases' parameters used in optimising processes are explained with different ranges. (See Table 6.6)

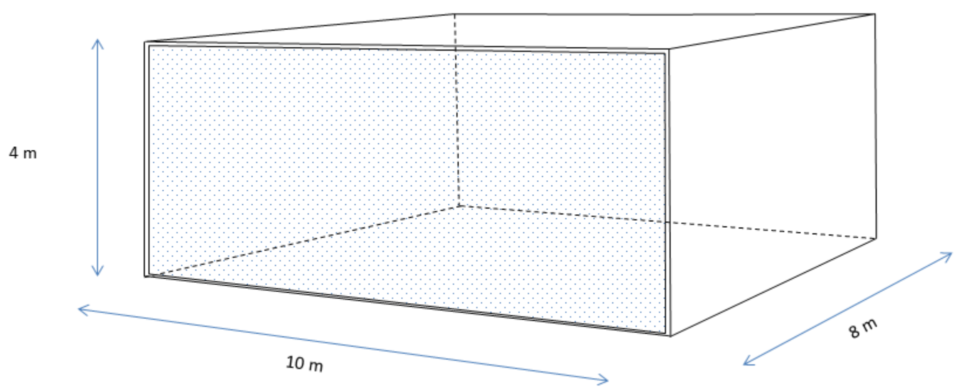


Figure 6.2 Isometric view of the base case office room

Table 6.1 Dimensions and material properties of the tested office space (all cases)

Space Dimensions and Materials		
Floor level		Zero level
Space area (m2)		80
Space dimensions (m)		10 * 8 * 4
Walls (All cases)	Reflectance	50%
	Material	Medium coloured walls
Ceiling (All cases)	Reflectance	90%
	Material	White coloured ceiling
Floor (All cases)	Reflectance	20%
	Material	Wooden floor
Ground (All cases)	Reflectance	20%
Window Dimensions and Materials (All cases except WWR)		
Width (m)		10
Sill (m)		0
Lintel (m)		4
Glazing	Transmittance	DoublePane_ LowE_65
TABS and opaque part of south wall in the case of WWR	Reflectance	Metal diffuse

Modelled. Cases (optimisation)

Different daylighting strategies were investigated for the south orientations. Three optimisation processes were carried out for Annual optimised window to wall ratio (AOWWR), Annual optimised static building envelope (AOSBE) and “(TABS). Figure 6.3 illustrates the systems applied to the base case.

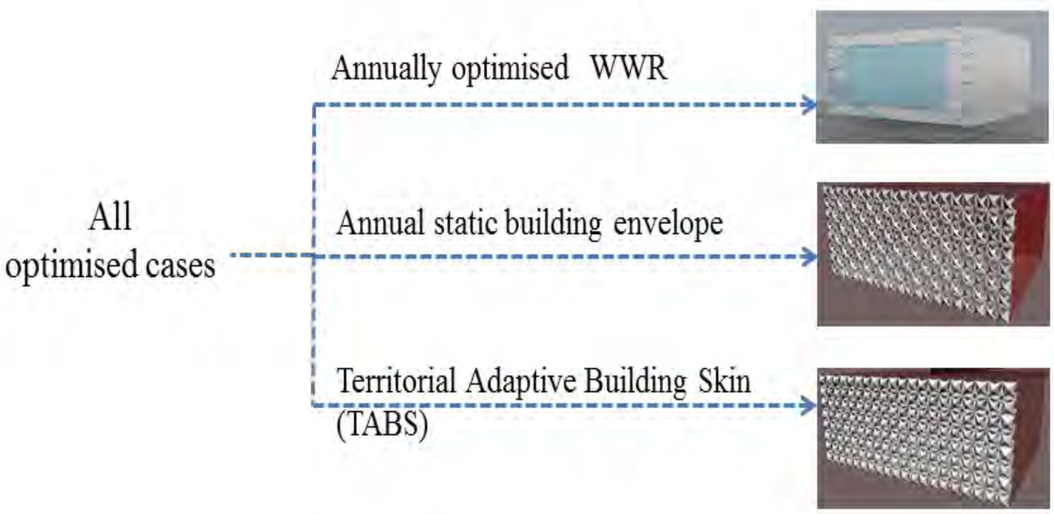


Figure 6.3 All optimised cases

6.4.1.1.Case 1: Annually Optimised WWR (AOWWR)

First, an optimisation process was performed to achieve the optimum window to wall ratio (AOWWR) that met a required annual performance. Second, the optimised design was evaluated at the twelve chosen times given previously. Dimensions and material properties are described in

Table 6.1, and all the parameters and possible values used in the simulations and optimisation process are described in Table 6.6.

6.4.1.2. Case 2: Annually Optimised Static Building Envelope (AOSBE):

First, an optimisation process was performed to achieve the optimum annual performance of an annual static solution (Static version of TABS). Second, the optimised design was evaluated at the twelve chosen times given previously.

6.4.1.3. Case 3: Optimisation of (TABS):

TABS is a system that can be applied to almost any building type, as the technology is in continuous development. Developing the specifications of the TABS has to satisfy multiple and competitive requirements, including, aesthetical, performance efficiency and reflecting it is contextual identity by dynamically responding to the environmental changes as a mean to maintain adequate performance during the entire year. In this evaluation, the properties and configuration of the TABS were selected to deal with the dynamic environmental conditions in different seasons during the entire year, while maintain the required criteria and to be a fair forecast of what is possible in the predictable future. The TABS was designed as a double layered system to integrate the advantages of the both ornamented perforated screen (shading system) and louvers (daylight redirecting system).

The ornamental perforated dynamic shading system formed the external panel of the fully glazed façade while the dynamic horizontal louver system, form the internal pane of the fully glazing façade. Iterative optimisation processes were performed to achieve the optimum 'twelve' system configurations that fulfil a predefined criterion at twelve chosen times during the entire year to be compared in terms of performance with the base case and other optimised static modelled systems ((AOWWR), and (AOSBE)).

6.5. Performance Indicators and Daylighting Metrics

Both quantitative goals, such as required illuminance threshold, and qualitative measures, such as the occurrence of glare, are important in daylighting design. Many daylight metrics have been developed over the years for the purpose of setting a scale for designers to use when comparing the aspects of daylighting design. Each metric differs and has a variety of strengths and weaknesses. As the aim of the different metrics is to help designers to distinguish well daylit, and comfortable spaces. Identifying the objective and the performance indicators are essential for deciding the suitable metrics to use.

The core purpose of this application study was to gain insight into the interplay between the TABS geometric configurations, daylight and solar radiation. For this function, sunlight needs to be controlled in terms of sufficiency vs. excess to satisfy the occupant's visual comfort requirements. Thus, it is important to show the performance indicators that constitute the basis for comparisons between the performance of the TABS and other cases included within this study. In the light of that, this thesis considered six indicators (task-plane illuminance, daylight distribution, illuminance contrast ratio, daylight penetration depth, glare and solar irradiation), based on the recommended office illumination levels discussed in Chapter Two. All indicators are described in Table 6.5 and can be summarised as follows:

Task-Plane Illuminance

The objective was to achieve 500-2000 Lux at nine nodes in the centre of nine task points placed in a representative office room at the height of 760 mm from the floor. (See Figure 6.4)

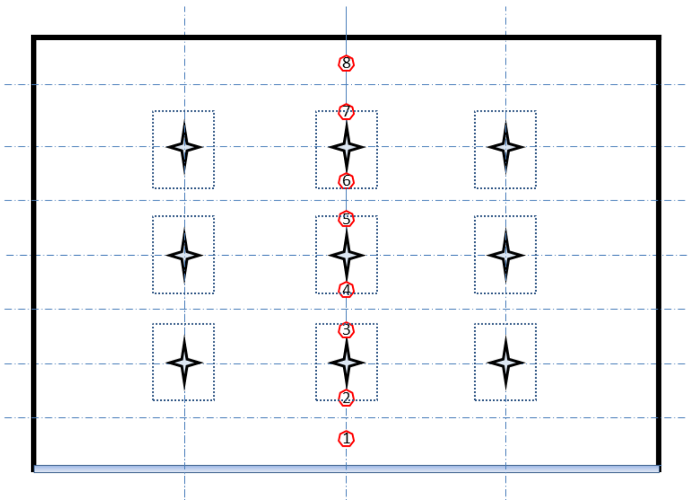


Figure 6.4 Measuring nodes for illuminance in middle of nine working plans and eight points in the central axis of space.

Daylight Distribution

Simulations for daylighting performance was to be studied for all studied cases - the base case, annual (AOWWR), optimisation of annual static envelope and Territorial Adaptive Building Skin TABS. The simulation and optimisation processes conducted in this study were based on three illumination evaluation levels in the floor area were used: ‘‘daylit”, ‘‘partially daylit” and ‘‘Overlit” areas. The ‘‘daylight” area achieves illuminance levels between 300 lux and 3000 lux for the floor area; ‘‘Overlit” area achieves illuminance greater than 3000 lux for the floor area with potential glare; ‘‘Partially lit” area achieves illuminance below 300 lux for the floor area. Regarding this performance indicator, the simulation parameters were set to measure daylight illuminance sufficiency for the room; DIVA parameters were set to calculate the percentage of analysis points that achieves illuminance levels between 300 lux and 3000 lux for the floor area. Where 80 % of the area should be.

Daylight Penetration Depth

The objective was to achieve a range of 300-3000 Lux at eight nodes in the central axes of space at the height of 760 mm from the floor (as an indication of light penetration depth inside the 8 m space depth). As a means to achieve daylight penetration of at least twice (2X) the window head height.

Illuminance Contrast Ratio

For a comfortable visual environment within the occupant's field of view it is important to maintain a limiting ratio between maximum and minimum illuminance values in a space. Studies with artificial lighting suggest that this ratio should not exceed 10:1 (Rea 2000). The objective of this study was to not exceed this ratio between the maximum and minimum illuminance value at the 17 points (eight nodes in the central axes of space and nine nodes at the centre of the task points) distributed across the space.

Glare

As mentioned above, the objective was to maintain a range of 500-2000 Lux at nine nodes in the centre of nine task points as a means to reduce the potential of the high level of glare when illuminance levels are more than 2000 Lux (Reinhart and Wienold 2011), (Wienold 2009). However, due to the range of 300-3000 Lux at 8 nodes in the central axes of space (as an indication of light penetration depth). Therefore, regarding this performance indicator, the annual Daylight Glare Probability DGP, and point in time DGP metrics were utilised as a further analysis to make sure that the occupants were not suffering from an unpleasant level of glare. A camera position was chosen from the perspective of the user to detect the glare occurrence on each examined time and annually. A fisheye camera was located at the user's eye level targeting the window and the working plane. Finally, a DGP of less than 35% was the criterion set for TABS performance in this study.

Solar radiation gain

A vertical grid of points located 200mm behind the TABS facade system was established to determine the incident solar radiation which had passed through the TABS facade. The grid consisted of 40 points covering the entire 10 m x 40 m high south facade (see Figure 6.4). The primary objective was to achieve the greatest solar radiation reduction for the successful solutions compared to the solar gains experienced in the base case.

6.6. The evaluation metrics used for each case

Within the context of this study many daylighting metrics were used for different cases based on the objectives of the study; all metrics used during this study are described in the following section:

Base case

For the fully glazed base case office space without treatment the metrics used are described as follows:

1. Point in Time illuminance (SPT) to measure the illuminance of 9 task points inside space and 8 points in the middle axis of space representing space depth at twelve times during the entire year, which represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21^{st} March (vernal equinox); 21^{st} June (summer solstice); 21^{st} September (autumnal equinox)) and 21^{st} December (winter solstice), using DIVA for Grasshopper.
2. Annual Daylight Glare Probability (DGP), (using DIVA for RHINO).
3. Point in Time Daylight Glare Probability (DGP) at the twelve examined times during the entire year, (using DIVA for RHINO).

Optimisation of Annual Window to Wall Ratio (AOWWR)

For the (AOWWR) the metrics used are described as follows:

1. Annual daylight autonomy (DA) for optimising the illuminance of 9 task points inside space and 8 points in the middle axis of space represents space depth, with Minimum Threshold 500 Lux to be at least 50% of the occupied hours (using DIVA for Grasshopper), for finding the optimum annual WWR.
2. Point in Time illuminance (SPT) to measure the illuminance of 9 task points inside space and 8 points in the middle axis of space represents space depth at the twelve examined times during the entire year, using DIVA for Grasshopper.
3. Point in Time illuminance (SPT) for evaluating the daylight illuminances ranges inside space between 300 Lux and 3000 Lux (daylit) of all space with nodes' grid spacing 0.425m (using DIVA for RHINO), at the twelve examined times during the entire year.
4. Annual Daylight Glare Probability (DGP), (using DIVA for RHINO).
5. Point in Time Daylight Glare Probability (DGP) at the twelve examined times during the entire year, (using DIVA for RHINO).

Optimisation of Annual Static Building Envelope (AOSBE):

For the Annual optimised adaptive static envelope the metrics used are described as follows:

1. Annual daylight autonomy (DA) for optimising the illuminance of 9 task points inside space and 8 points in the middle axis of space represents space depth, with Minimum Threshold 500 Lux to be at least 50% of the occupied hours (using DIVA for Grasshopper), for finding the optimum (AOSBE).
2. Spatial daylight autonomy (sDA) and (ASE) with Minimum Threshold 300 Lux 50% of the annual occupancy hours and maximum 10% of the area receiving direct daylight for more than 250 hours per year to examine the capability of the selected solution to fulfil the LEED requirements.
3. Point in Time illuminance (SPT) to measure the illuminance values of 9 task points inside space and 8 points in the middle axis of space represents space depth at the twelve examined times during the entire year, using DIVA for Grasshopper.
4. Point in Time illuminance (SPT) for evaluating the daylight illuminances ranges inside space between 300 Lux and 3000 Lux (daylit) of all space with nodes' grid spacing 0.425m (using DIVA for RHINO), at the twelve examined times during the entire year.
5. Annual Daylight Glare Probability (DGP), (using DIVA for RHINO).
6. Point in Time Daylight Glare Probability (DGP) at the twelve examined times during the entire year, (using DIVA for RHINO).

Territorial Adaptive Building Skin TABS:

For the optimised TABS the metrics used are described as follows:

1. Point in Time illuminance (SPT) for optimising the illuminance of 9 task points inside space to be Minimum 500 Lux and maximum 2000 Lux, and 8 points in the middle axis of space represents space depth to be between 300 Lux and maximum 3000 Lux (using DIVA for Grasshopper), at the twelve examined times during the entire year.
2. Point in Time illuminance (SPT) for evaluating the daylight illuminances range inside space between 300 Lux and 3000 Lux (daylit) of all space with nodes' grid spacing 0.425m (using DIVA for RHINO), at the twelve examined times during the entire year.
3. Point in Time Daylight Glare Probability (DGP) at the twelve examined times during the entire year, (using DIVA for RHINO).

For in-depth analysis and to achieve a further understanding of the contribution of each subsystem in reaching the optimised performance.

The same simulations of the previous stage were carried out for the (Territorial Adaptive Building Skin TABS) Subsystems:

A. TABS's shading subsystem
B. TABS's redirecting subsystem

Table 6.2 The evaluation metrics used for each case

Daylighting metric	Sky Type	B.C	AOWWR	AOSBE	TABS	TABS's shading subsystem	TABS's redirecting subsystem
Single Point in Time Illuminance (SPT)	**CIE Clear sky With sun.**	●	●	●	●	●	●
Daylight Autonomy (DA)	**CIE Clear sky With sun.**		●	●			
Spatial daylight autonomy (sDA) and (ASE)	**CIE Clear sky With sun.**			●			
Annual Daylight Glare Probability (DGP)	**CIE Clear sky With sun.**	●	●	●			
Point in Time Daylight Glare Probability (DGP)	**CIE Clear sky With sun.**	●	●	●	●	●	●

Table 6.3 Optimisation and simulation processes of all cases

Case		Process	Software	Time											
				Mar.			Jun.			Sept.			Dec.		
		Evaluation / Optimisation	**DIVA for Grass. /Rhino**	**9**	**12**	**15**	**9**	**12**	**15**	**9**	**12**	**15**	**9**	**12**	**15**
Base Case															
1	Point in Time illuminance (17 measuring nodes)	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
2	Solar radiation	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
3	Point in Time illuminance (grid of measuring nodes (0.425*0.425 m))	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
4	Annual glare (DGP)	Evaluation	Rhino.	●											
5	Point in Time glare (DGP)	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
TABS															
1	Point in Time illuminance (17 measuring nodes)	Optim.	Grass.	●	●	●	●	●	●	●	●	●	●	●	●

2	Solar radiation	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
3	Point in Time illuminance (grid of measuring nodes (0.425*0.425 m))	Evaluation	DIVA for Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
4	Point in Time glare (DGP)	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
TABS's subsystems (Shading and Redirecting)															
1	Point in Time illuminance (17 measuring nodes)	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
2	Solar radiation	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
3	Point in Time illuminance (grid of measuring nodes (0.425*0.425 m))	Evaluation	Rhino	●	●	●	●	●	●	●	●	●	●	●	●
4	Point in Time glare (DGP)	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
Annual optimisation of static building envelop (AOSBE)															
1	DA 500 lux	Optim.	Grass	●											
2	Spatial daylight autonomy (sDA) and (ASE)	Evaluation	Rhino	●											
3	Point in Time illuminance (17 measuring nodes)	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
4	Solar radiation	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
5	Point in Time illuminance (grid of measuring nodes (0.425*0.425 m))	Evaluation	Rhino	●	●	●	●	●	●	●	●	●	●	●	●
6	Annual glare (DGP)	Evaluation	Rhino.	●											
7	Point in Time glare (DGP)	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●
Annual optimisation of Window Wall Ratio (AOWWR)															
1	DA 500 lux	Optim.	Grass	●											
2	Point in Time illuminance (17 measuring nodes)	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
3	Solar radiation	Evaluation	Grass.	●	●	●	●	●	●	●	●	●	●	●	●
4	Point in Time illuminance (grid of measuring nodes (0.425*0.425 m))	Evaluation	Rhino	●	●	●	●	●	●	●	●	●	●	●	●
5	Annual glare (DGP)	Evaluation	Rhino.	●											
5	Point in Time glare (DGP)	Evaluation	Rhino.	●	●	●	●	●	●	●	●	●	●	●	●

6.7. Tools Box (Simulation software and modelling tools)

Due to the complexity and size of the simulations performed in this study, it was essential to choose tools which allowed for smooth integration between the modelling tool and simulation tool.

Within the framework of this thesis, the performance of daylighting inside office spaces is studied through the use of simulation tools that are capable of handling multi-inputs, as well as considering more than one variable at a time.

Parametric models facilitate developing complex building geometry with a number of variables, patterns, and constraints that are specified by the architects. Several design software tools offer parametric modelling features. Of these software choices, the integrated Rhino/Grasshopper program has widely been applied because of its powerful modelling capability, intuitive interface, and abundance of plugins that greatly extend its functionality.

It also furnishes a ready-to-use GA plugin, Galapagos, which can be used for optimisation. Hence, this case study uses Rhino/Grasshopper as the design program. The following is the current tools and used in this case study:

1. Rhinoceros (Rhino), NURBS-based three-dimensional modelling program; (McNeel 2014.).

2. Grasshopper (Davidson 2012), is a graphical algorithm plug-in for Rhino which allows for parametric modelling and scripting and serves as an extended parametric modelling to the Rhino. The Grasshopper interface is directly connected to the Rhino modelling tool so that changes made in the Grasshopper algorithm can be directly observed in the Rhino window; therefore Grasshopper was used for all cases modelling.

3. DIVA (Solemma 2014), a plugin for the Rhinoceros and Grasshopper environment: used in this study as it supports a series of performance evaluations by using validated tools, including RADIANCE, Daysim, Evalglare and EnergyPlus software (Reinhart, Lagios et al. 2012). All modelling and daylight simulations carried out within the Rhino and Grasshopper environment, for the prediction of various radiant or illuminance calculations using sun and sky conditions derived from standard meteorological datasets; the results were dependent upon both the building's location and orientation, in addition to the facade composition and configuration (Mardaljevic 2008).

Table 6.4 Radiance simulation parameters.

Ambient Bounces (-ab)	Ambient Divisions (-ad)	Ambient Sampling (-as)	Ambient Resolution (-ar)	Ambient Accuracy (-aa)
2	1000	20	300	0.1

Due to the complexity of the TABS external sub-system geometry and the number of simulations performed in this study, in which runtime was very long and the number of runs was very large, some simplification regarding the ambient bounces parameter of RADIANCE was assumed. As the ambient bounces were selected to be the minimum (ab = 2) (to reduce the extraordinary long processing time that resulted from the complication of the TABS configurations. The effect of this assumption on the accuracy of the results was tested in two steps where the deviation of results from the commonly assumed bounces (ab-6) was measured. First, using DIVA for grasshopper, to measure the illuminance values' deviation in the near, mid, and far zone of space from the window, via one point allocated in the middle of each zone. Second, using DIVA for Rhino (point-in-time illuminance with illuminance range (Min. 300, and Max. 3000 Lux)), to measure the overlit area and the mean illuminance values' deviation in the whole space. Two optimised (TABS) designs were selected for this testing: optimised (TABS) designs of the 21st of June at 12 pm, and 21st of December at 12 pm, as a representation of summer and winter seasons.

The results showed that the deviation in both steps was very limited. In the first step, the average deviation of illuminance values was only 13–18% in the near and mid zones respectively and reached 39% in the far zone.

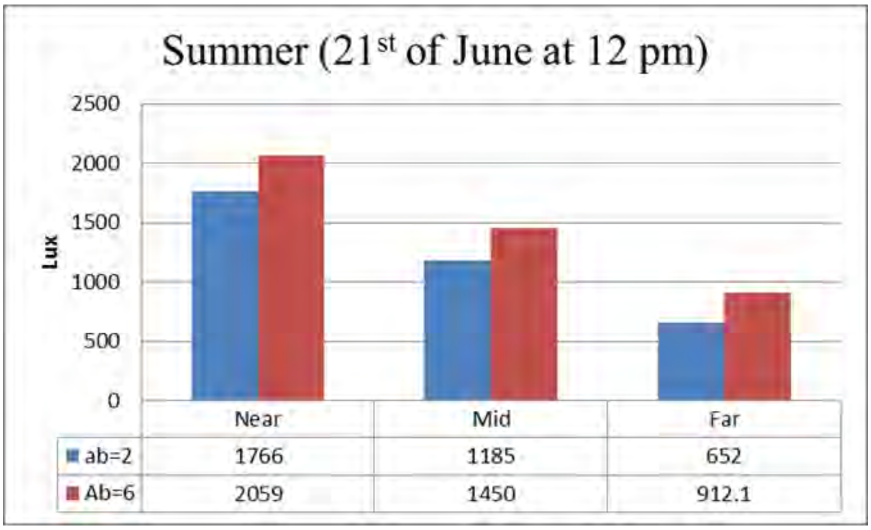
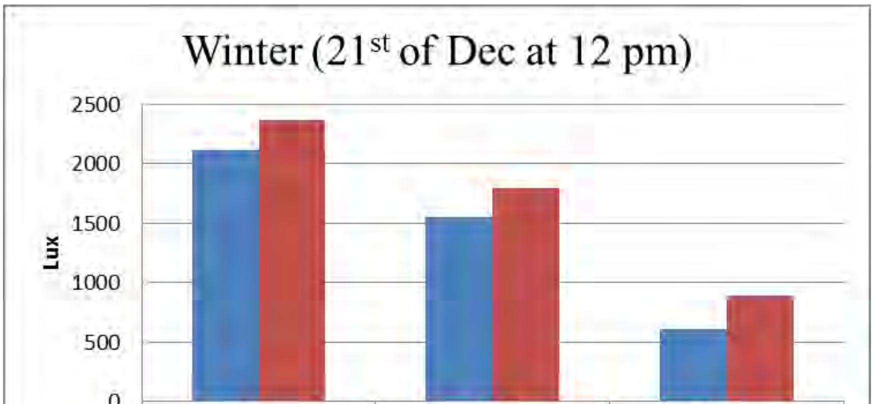


Figure 6.5 Comparison between the result of TABS in Summer season (21st of June at 12 pm) with two ambient bounces (ab = 2 and ab = 6).



	Near	Mid	Rear
ab=2	2113	1551	604
Ab=6	2361	1793	887

Figure 6.6 Comparison between the result of TABS in Winter season (21st of Dec. at 12 pm) with two ambient bounces (ab = 2 and ab = 6).

In the second step, the results showed only 0–0.08%, increasing in the “overlit” area, and 21-32%, rising in the Mean illuminance values for summer and winter screens, respectively. The effect of this deviation on research conclusions “under two conditions” was considered unimportant in comparison with the processing time saved as the time required for each iteration using ab=6, is 37 times the time required for the iteration using ab=2. The first condition, giving less priority to select alternatives that achieved task point illuminance values close to the upper threshold (2000 Lux) during the selection of the successful solution of each examined time during the optimisation process using Diva for Grasshopper. The second condition, all the twelve final optimised TABS solutions should achieve 80% daylit area of space (300-3000 Lux) using DIVA for RHINO (point-in-time illuminance), with RADIANCE ambient bounces parameter (ab- 6). Otherwise, the solution is not considered, and the optimisation process should be repeated to find another successful solution.

4. Galapagos (Rutten 2014), is a genetic algorithm (GA) imbedded and runs in Grasshopper through the Rhino as an interface, Galapagos is used in this study for cases’ problem solving. Due to the large number of the optimisation processes endured during this study, and the intention to identify a group of successful solutions, rather that identifying the absolute optimum solution for each time an intermediate number of individuals per generation was used (35 out of 50 recommended). Despite this reduction of the evaluated alternatives for each optimised times, a minimum of 1000 design alternatives were generated and evaluated for each time to identify a group of successful solutions.

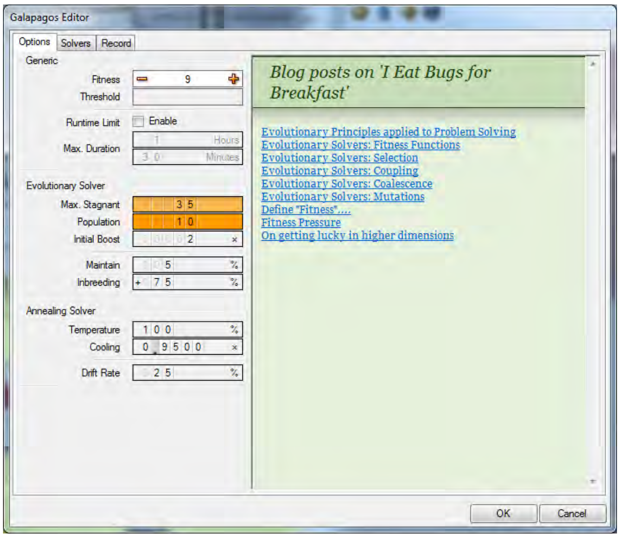


Figure 6.7 Galapagos parameters setting

5. TT Toolbox: a plugin for Grasshopper using a Galapagos listener component that recorded all gene/ fitness configurations; (ii) Excel Writer, that exported data to Excel sheets as Galapagos ran, and (iii) Excel Reader/ Listener, that kept a live link to an Excel spreadsheet and automatically detected changes for advanced analysis (Tomasetti 2015).

Within the context of this study, all cases were developed using Grasshopper. Simulations were conducted using Diva a plug-in for both Rhino and Grasshopper. DIVA is used to interface Radiance, Daysim and Evalglare for performance evaluation. All tools utilised within this study are shown in Figure 6.8.

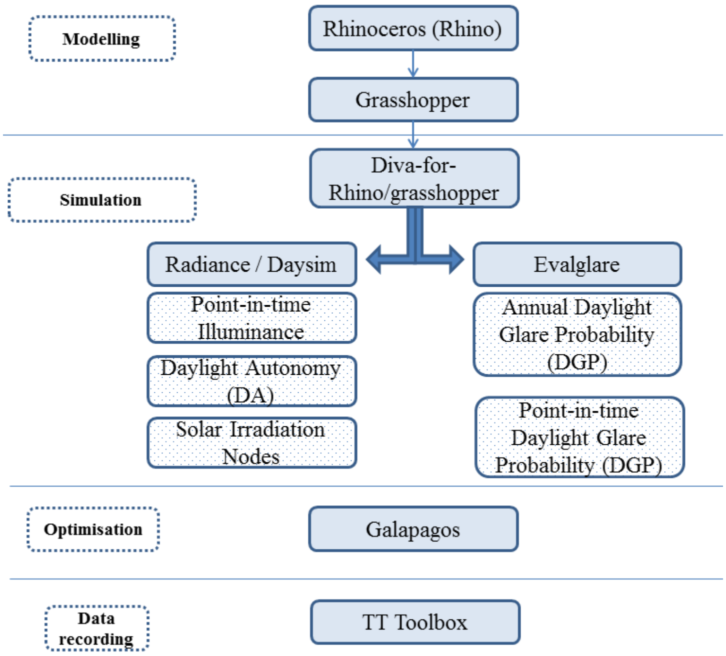


Figure 6.8 Modelling, Simulation, optimisation and data recording tools used.

6.8. Process Workflow

6.8.1. Setting a criterion

Aiming for creating a visually pleasing and productive environment for office building occupants, architects can focus on a number of objectives during the early design stages, for example, maximising indoor environmental merits like daylight, air quality, and thermal comfort in addition, minimising energy demand (lighting, heating, cooling), solar radiation, operational carbon emissions and construction cost (Singh and Kensek 2013). Thus, the main focus of this research is oriented to maximise the daylight quality and to minimise the excessive heat gain by solar radiation as well as minimising the risk of glare (see Table 6.5).

Table 6.5 The criteria applied in this study.

No	Indicator	Performance
1	Task points illuminance	Minimum 500 Lux and max 2000 Lux for the task points nodes
2	Daylight illuminances distribution	Illumination level between 300 Lux and 3000 Lux (daylit) for at least 80% of all space (Grid spacing 0.425) at all the examined times.
3	Contrast ratio	1:8
4	Daylight depth	2x of window head height, with illuminance values between 300 Lux and 3000 Lux of 8 points in the middle axis of space represents space depth.
5	Glare	Imperceptible glare (less than 35%)
6	Solar radiation	Minimum

6.8.2. Model preparation (simulation parameters and procedures)

TABS must respond to particular environmental conditions which are site specific. For this study in Cairo [30° 2' N, 31° 14' E] the weather file from Cairo International Airport was used for the daylighting and radiation analysis.

The TABS analysis tool was developed as a parametric model in which variable geometries are actuated algorithmically, simulating intelligently-evaluated independent TABS system configurations. The design of the TABS originated in the software Grasshopper to control each variable parametrically. All variables for TABS alterations are defined; The examined system consist of a parametrically designed 3d pattern controlled by 11 parameters and integrated with horizontal louvers controlled by 2 parameters to fulfil a predefined criterion at different twelve times during the entire year, which represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice) and to ensure a pleasant and productive environment for space's users. Table 6.6 shows the range of parametric changes in the various TABS parameters as they were altered to try and achieve the predetermined lighting and solar criteria i.e. optimisation).

The TABS geometry model was connected to the daylighting analysis software DIVA. The DIVA plug-in for the software RHINO and Grasshopper environments supports a range of performance evaluations, using validated tools incorporating Radiance, Daysim, Evalglare and Energy Plus software.

All variables were controlled automatically through the algorithms to start generating the TABS alterations based on the results of the simulations of daylight and solar radiation levels in the office. This framework permits the quick visualisation of daylight results from a parametric design model where numerous design alternatives for daylight performance can be examined.

Table 6.6 Parameters used in the simulation and optimisation processes

No.		Cases' parameters	Action		Possible Values
1		Base case	-	BOR	Fully glazed no shading
2		(AOWWR)	WWR	WWR	10 % to 90 % WWR
3		(AOSBE) and (TABS) parameters			
	1	Extrusion of all Small Patterns (ESP)	Extrusion	ESP	0, 0.025, 0.05 m
	2	Extrusion of all Main Patterns (EMP)	Extrusion	EMP	0, 0.05, 0.1, 0.15, 0.2, 0.25 m
	3	Opening Ratio of Small Patterns rows 1,3,5,7 (ORSP1)	Opening ratio	ORSP1	20 to 90 %
	4	Middle Main Pattern Opening Ratio (MMPOR)	Opening ratio	MMPOR	10 to 70 %
	5	Opening Ratio of Small Patterns rows 1,3,5,7 (ORSP2)	Opening ratio	ORSP2	20 to 90 %
	6	Boundaries Patterns Opening Ratio (BPOR)	Opening ratio	BPOR	10 to 70 %
	7	Upper and Right rows Opening Ratio (UROR)	Opening ratio	UROR	0 to100 %
	8	Lower and Left rows opening Ratio (LLOR)	Opening ratio	LLOR	0 to100 %
	9	Octagons Depth (OD)	Depth	OD	0.01, 0.1, 0.15, 0.2, 0.25, 0.30, 0.35, 0.40, 0.45, 0.5 m
	10	Main Octagons Radius (MOR)	Radius	MOR	0.05, 0.12, 0.15, 0.18, to 0.20 m
	11	Secondary Octagons Radius (SOR)	Radius	SOR	0.05, 0.12, 0.15, 0.18, to 0.20 m
	12	Horizontal Louvers Depth (HLD)	Depth	HLD	0.01, 0.1, 0.15, 0.2, 0.25, 0.30, 0.35, 0.40, 0.45, 0.5 m
	13	Horizontal Louvers Inclination Angle (HLIA)	Rotation	HLIA	-60°, -45°, -30°, -15°, 0°, 15°, 30°, 45° and 60°
	14	Vertical Louvers Depth (VLD)	Depth	VLD	0.1m
	15	Vertical Louvers Inclination Angle (VLIA)	Rotation	VLIA	0°

Two groups of nodes were generated: the first group is horizontal nodes located at (0.76m) above the finish floor, consist of seventeen points representing the nine task points and eight points in the central axis of space as an indication of daylight.

The second group is a vertical grid of points, located (- 20 cm) behind the X system inside space to measure solar radiation, 40 points covering the 100% glazing area (10m x 4m) distributed as 1 point for each m^2 (See Figure 6.4 and Figure 6.9).

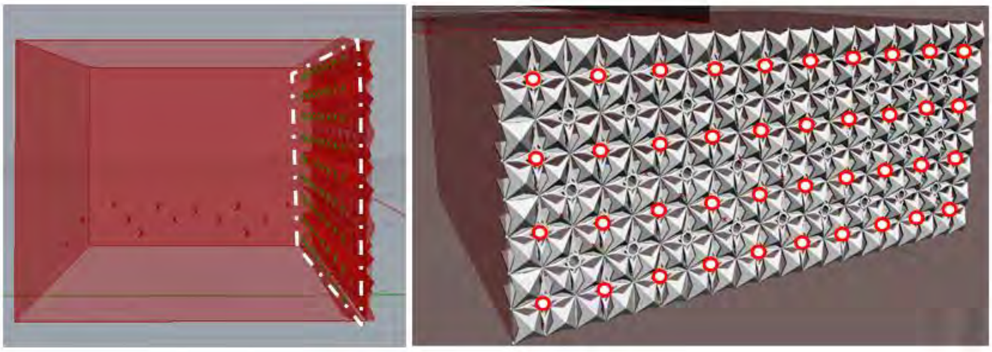


Figure 6.9 Measuring nodes for solar radiation analysis

All surfaces, materials and nodes were defined and linked to the DIVA plug-in for both Illuminance and solar radiation analysis.

The definition generated in Grasshopper can be divided into eight groups: Office space geometry, TABS geometry, DIVA components, TABS controlling parameters, Performance dashboard, illuminance and solar irradiation measuring nodes, performance control, optimisation component and data recording (see Figure 6.10).

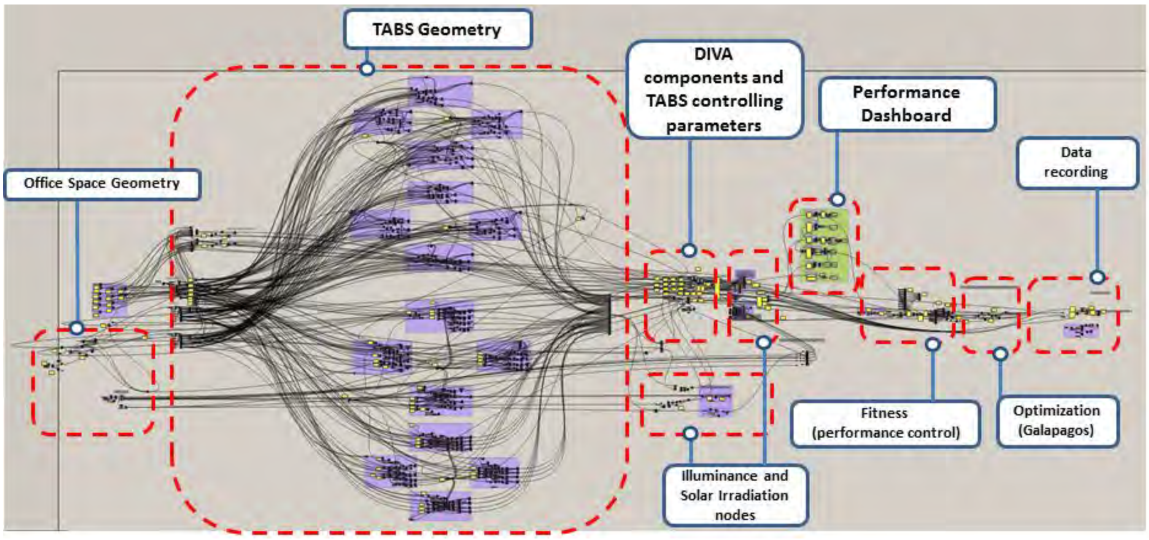


Figure 6.10 Grasshopper definition

6.8.3. Form Generation and Evaluation

The algorithm that evaluated space was based on three particular criteria:

(1) 100 % of the nine nodes of working plans are within desired illuminance range (500-2000 Lux). (Task point's illuminance, Daylight illuminances distribution and glare performance indicators)

(2) Illuminance contrast ratio between the highest and the lowest node's values is less than 1:8. (Performance indicators: illuminance contrast ratio and glare)

(3) 100 % of the eight nodes (in the central axes of space) are within the range 300-3000 Lux; as an indication of the daylight depth (2x). (Performance indicators: Daylight illuminances distribution and daylight depth - see Figure 6.8.

The main objective was to achieve 100 % of the 17 calculation points within the range of acceptable illuminance values. To make more control over the definition, dispatch components were used to extract the values of both of the 9 task points nodes and 8 nodes in the central axis of space in two separate lists, and A series of "list item" components are used to extract the values of each node, achieved the required illuminance level inside the space, then the 'mass addition' component was used to count the accepted nodes' values, the total should be '17' In the case of accepted solutions. In contrast, the solution is considered rejected if the total value is less than '17'.

For the illuminance contrast ratio all the illuminance values have been organised in a descending order using the "list item" component, the first point having an index of '0' and the last value having an index of '16'; the lowest values are divided by the highest value, if the result is within 1:8 ratios, the solution, is considered acceptable and sent for solar radiation calculation (40 measuring nodes), else, it is considered rejected (see Figure 6.11).

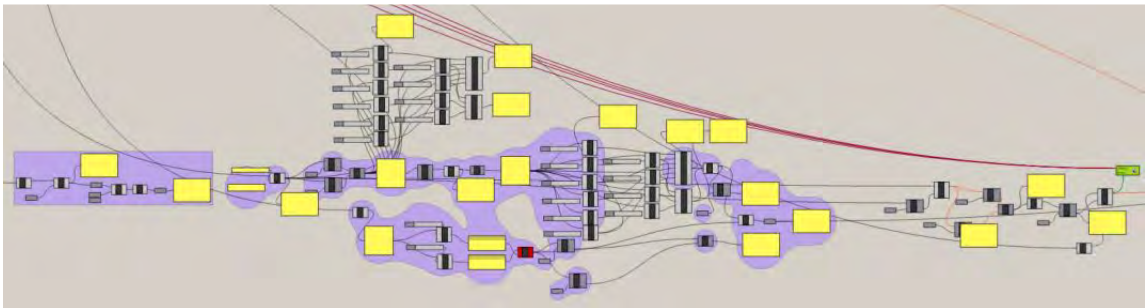


Figure 6.11 Performance indicators and control

A performance dashboard includes all the required performance indicators, was designed to facilitate the evaluation of each design alternatives. In the light of that, only solutions that fulfil all the performance indicators were considered. (See Figure 6.12)

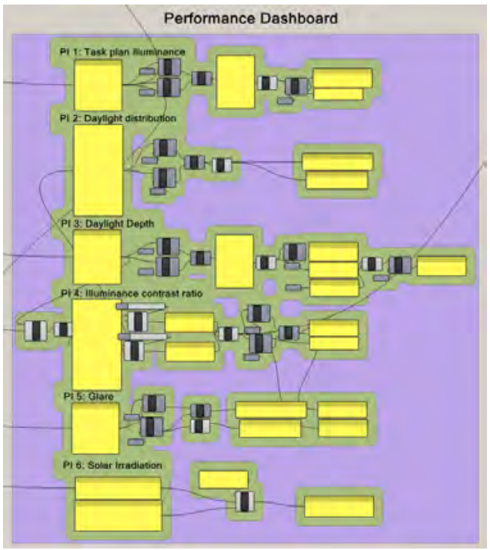


Figure 6.12 Performance dashboard

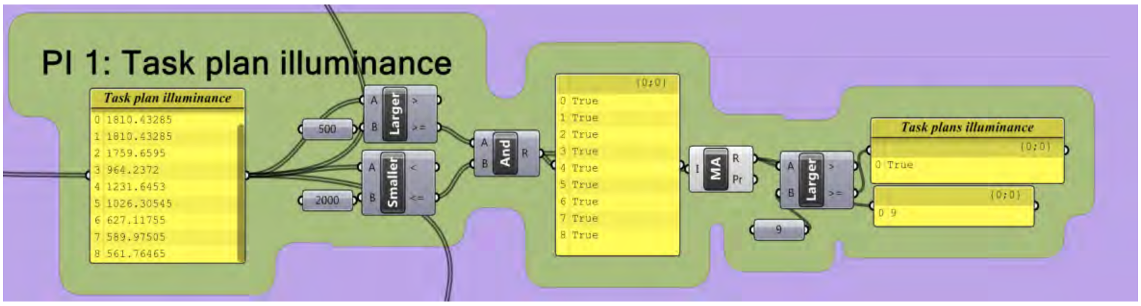


Figure 6.13 Performance indicator 1: Task-plans illuminance

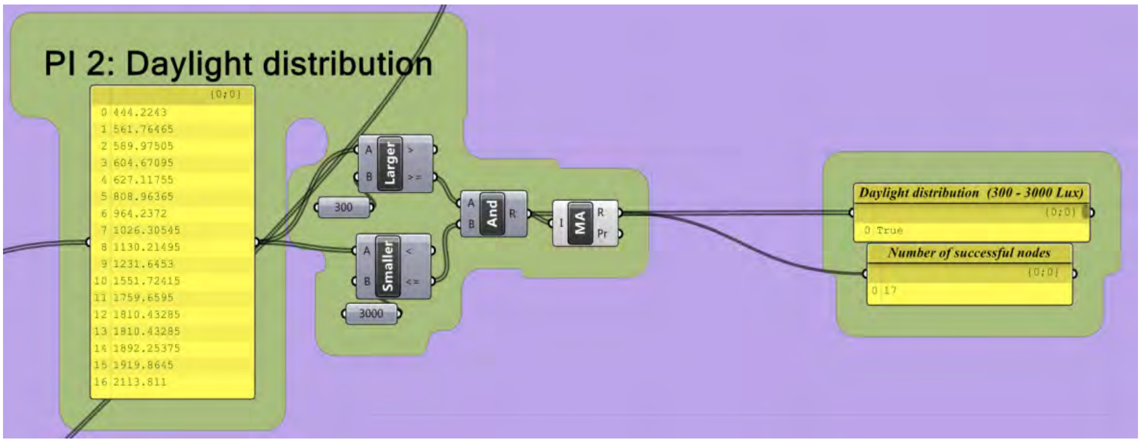


Figure 6.14 Performance indicator 2: Daylight Distribution

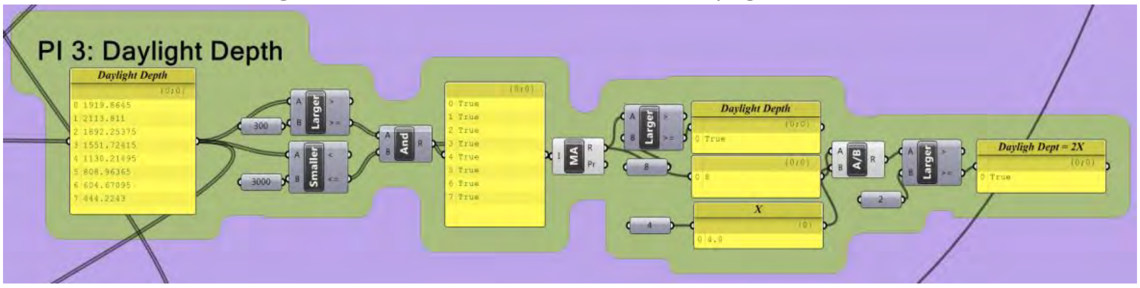


Figure 6.15 Performance indicator 3: Daylight penetration depth

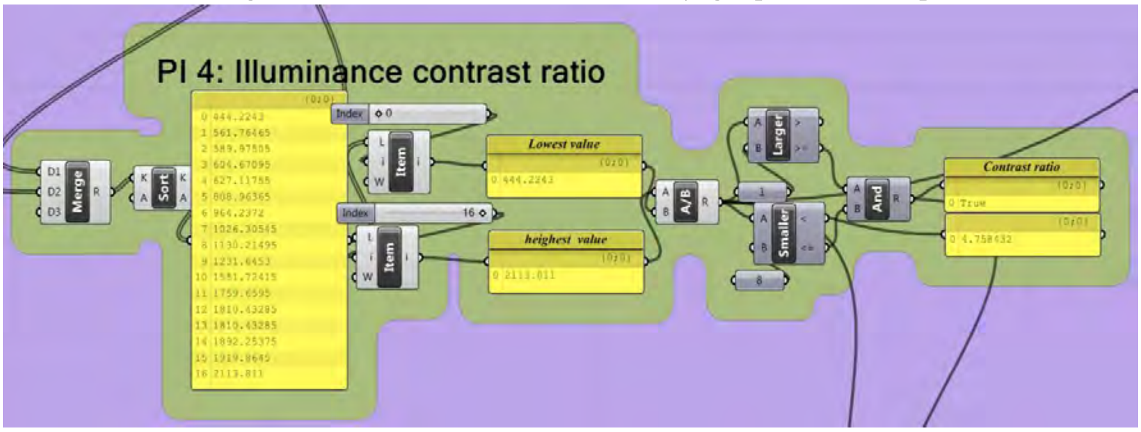


Figure 6.16 Performance indicator 4: illuminance contrast ratio

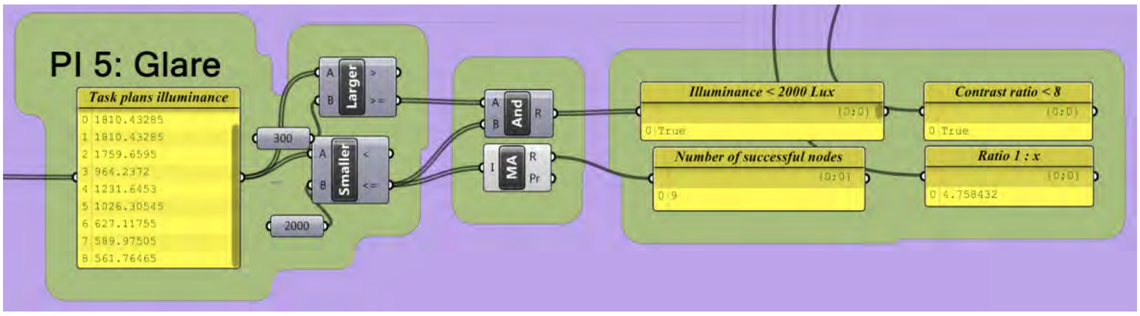


Figure 6.17 Performance indicator 5: Glare

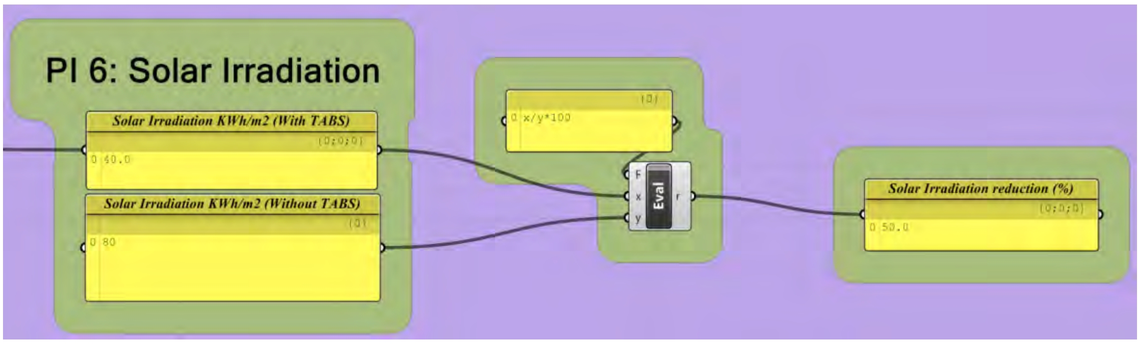


Figure 6.18 Performance indicator 6: Solar irradiation

6.8.4. Applying the heuristic algorithm

In this step, the designer determines the suitable optimisation algorithm and setting the function controlling the selection of accepted solutions; then, the heuristic algorithm will manage the flow of parameters and performances between the simulation and the modelling software, the algorithm takes the parameters of the TABS with their performance of the simulation program. For this purpose, Galapagos was used. By using this genetic algorithm, a wide range of alternatives can be explored and evaluated.

Galapagos has been integrated into the definition in search of the best TABS configuration at specific dates and times. The genetic algorithm works on finding a group of successful solutions that fits the predefined criteria. Galapagos works on maximising the number of Task-pans nodes that achieve (500- 2000 Lux) to identify a group of successful solutions that all the 9 Task plans illuminance values are within the required illuminance range. The algorithm operates by randomly generating numerous TABS configuration, evaluating a different combination each time. Then, based on the rule governing the selection of the optimum solution (parameters), the algorithm starts sending new parameters to the simulation program and receives the results, the previous steps are iterated till the optimum solution is reached (See Figure 6.19 and Figure 6.20).

Finally, these optimised solutions fulfilled the criteria witch is the illuminance level of all 9 Task points inside space between 500 Lux and 2000 Lux, and daylight depth 2x (the illuminance level of 8 points in the central axes of space between 300 Lux and 3000 Lux) and minimum solar radiation.

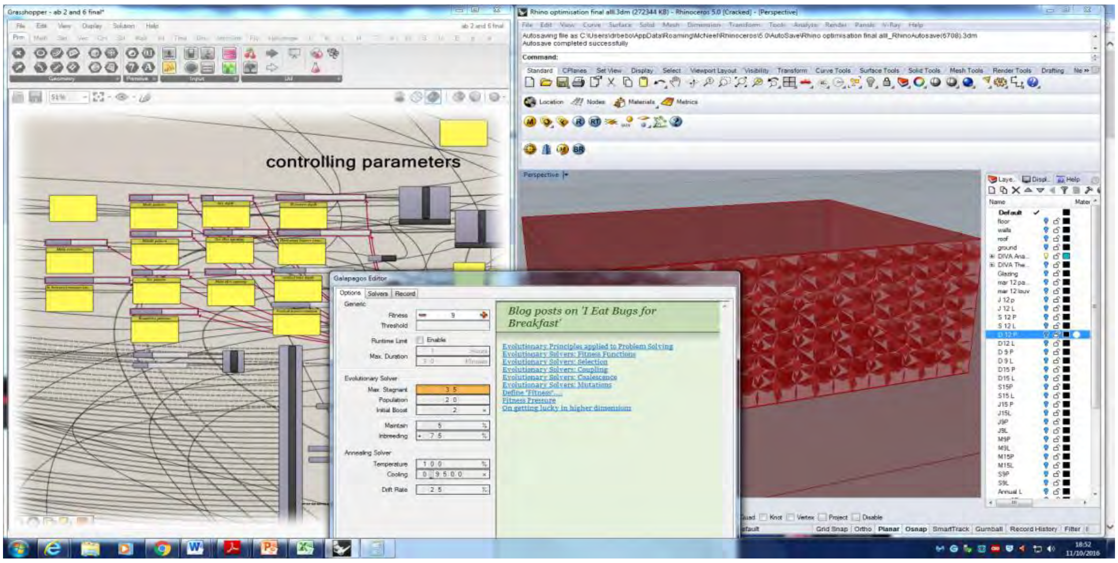


Figure 6.19 Galapagos settings for optimising the illuminance values of 9 task plans

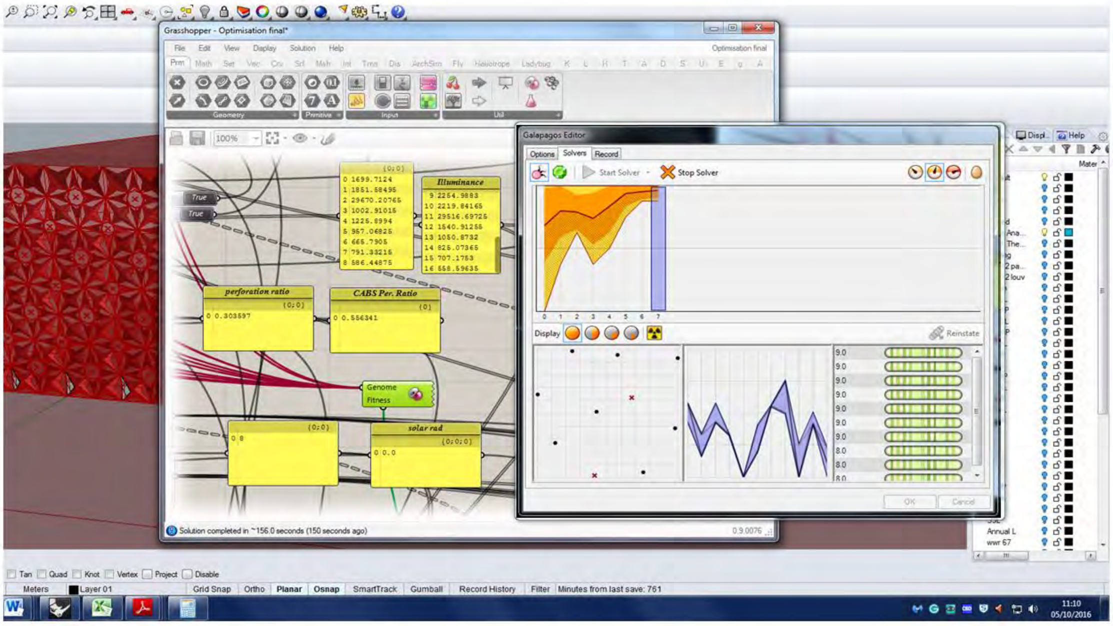


Figure 6.20 The successful alternatives results from the Galapagos *Data recording*

Finally, a group of TABS configurations that fulfilled the predefined criteria have been reached. TT-Toolbox was used for data recording of all the simulated alternatives in Excel sheets (see Figure 6.21).

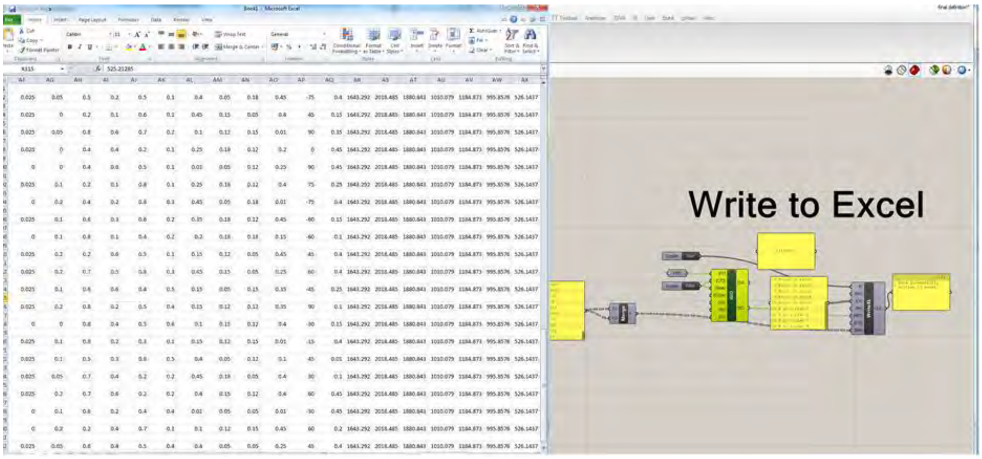


Figure 6.21 Data recording

6.8.5. Fine tuning selection based on architectural preference

Finally, a set of TABS configurations that maximised the quality of daylighting within the predefined criteria and have the lowest solar radiation gain were distinguished. All the optimum group of solutions [population] was examined and compared architecturally, and finally, only twelve solutions were selected as one solution for each time, (9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice).

Moreover, even though, External View wasn't part of the design criteria during the optimisation process. This factor was considered during this stage, as a priority was given to the successful solutions with the maximum perforation ratio and louver with inclination angle between -30° to 30° and minimum depth.

6.8.6. Advanced simulation and data verification

The twelve TABS solutions (one solution for each time), annually optimised WWR (AOWWR), and Annually optimised static building envelope (AOSBE) were achieved. However, all the optimised TABS solutions were optimised using Point-in-Time illuminance evaluation, while (AOWWR) and (AOSBE) were optimised using Annual daylight autonomy (DA). Therefore, to adequately compare their performance, advanced simulations were essential using DIVA for Grasshopper / Rhino in three main phases (1, 2, and 3), using the same evaluation metric and times, to facilitate the performance comparison between them regarding each performance indicator.

Moreover, the TABS solutions were optimised as a whole system, therefore, for a better understanding of each system's performance and their contribution to the whole system performance regarding each performance indicator, additional simulations carried out using DIVA for Grasshopper / Rhino in phase (4). All four phases are described in the following sections (see Figure 6.22).

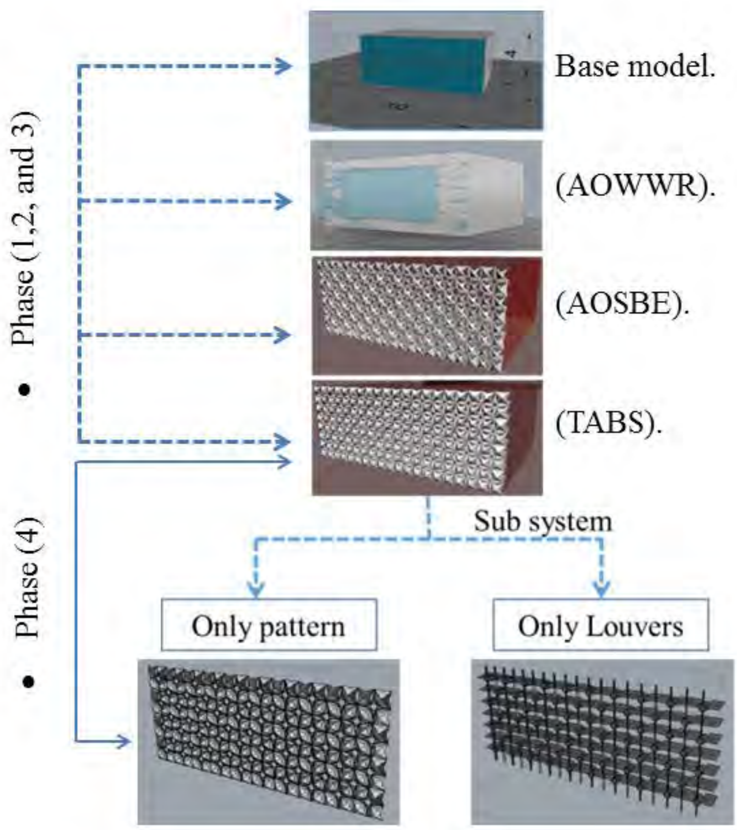


Figure 6.22 Advanced simulation phases

6.8.6.1. Phase One:

TABS successful solutions (twelve solutions) compared using Point-in-Time illuminance DIVA for Grasshopper at the same twelve times, with:

- Base model.
- Annually optimised WWR (AOWWR).
- Annually optimised static building envelope (AOSBE).

6.8.6.2. Phase Two:

Advanced simulations were carried out for all space using DIVA for RHINO, which has a more capabilities for results' verification and in-depth analysis, so, all the successful solutions are “baked” to Rhino for enduring point in time illuminance simulations in DIVA for Rhino, and compared to other cases using the same conditions (material, space dimension, weather file and time) - see Figure 6.23).

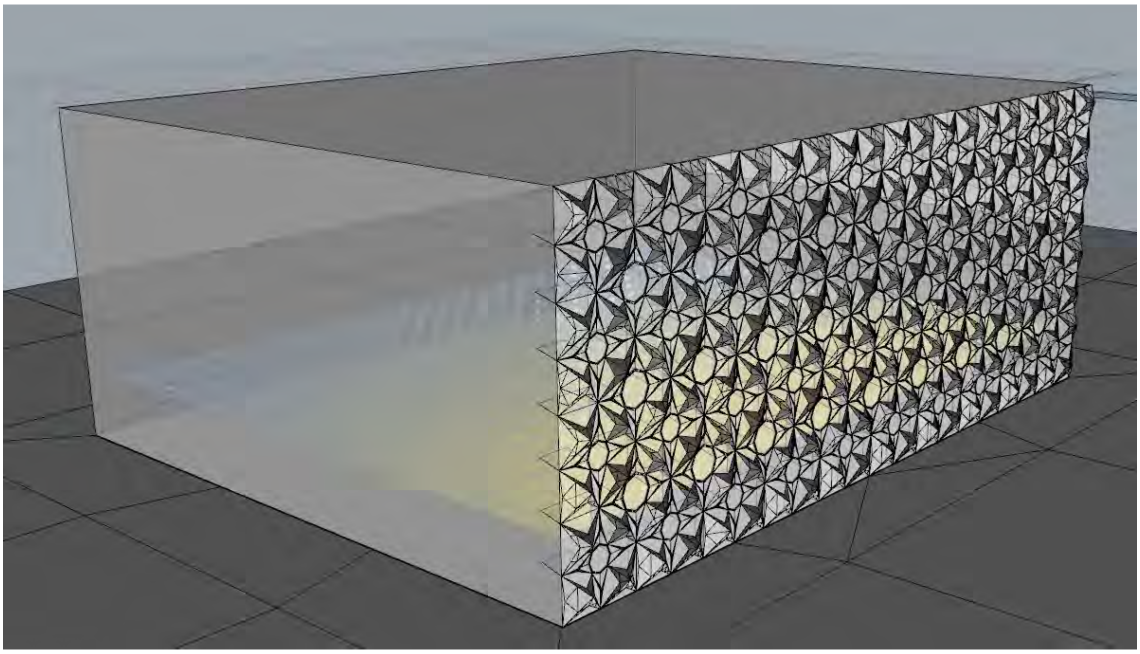


Figure 6.23 Point in time illuminance simulation in DIVA for Rhino (500 nodes)

A point in time illuminance analysis was carried out for all cases at all the twelve examined times to examine the daylight performance within all space by calculating the illuminance values of grid nodes spacing 0.42 m (500 nodes) to make sure that at least 80 % of space received illuminance between 300 lux and 3000 lux, Three zones described space area as follows: 'daylit', 'partially daylit' and 'over lit' areas. Firstly, the 'daylit' area percentage is reported when illuminance levels fall between 300 and 3000 Lux at the examined time. Secondly, the 'partially daylit' area is measured when less than the minimum illuminance of 300 Lux that represents the insufficiency in daylight. Finally, the 'over lit' area is when daylight illuminance goes above 3000 Lux that represents the insufficiency in daylight. However, the upper limits of 3000 Lux according to some studies indicate potential for heat gain or glare, and so the upper limit is selected to be 3000 Lux according to more recent studies (Mardaljevic, Andersen et al. 2012). Therefore, all cases were tested regarding glare in the next step for all the optimised solutions at the same examined times.

6.8.6.3. Phase Three: Daylight Glare Probability (DGP)

For glare calculations, a point-in-time glare simulation in DIVA was carried out, and the visual comfort of a user under the simulated conditions at the camera viewpoint examined. The Daylight Glare Probability (DGP) metric is used in the simulations, which considers the overall brightness of the view, the position of 'glare' sources and visual contrast.

DIVA for Rhino uses Evalglare to calculate the Daylight Glare Probability (DGP) from a luminance image based on total vertical eye illuminance and contrast.

The process can be summarised as follows:

- An annual glare simulation with an hourly calculation for the Base case, (AOWWR), and (AOSBE) was done.
- Point in time Glare probability simulations from a point in the middle of space at height 1.3 (sitting position and looking towards the window) at all the twelve examined times were done, and compared against the glare performances at the same twelve times:

  a. Base case.

  b. (AOWWR).

  c. (AOSBE).

  In this stage, glare is considered to be intolerable if DGP is larger than or equal to 45% of the time, disturbing when it is between 40% and 45%, perceptible when it is between 40% and 35%, and imperceptible when it is less than 35%.

6.8.6.4. Phase Four: TABS Subsystems Evaluation

To evaluate the performance of the TABS subsystems, further analysis was carried out to evaluate the individual performance of each subsystem, using the same simulations parameters utilised to evaluate the whole TABS system at the twelve examined times. As a means to identify the contribution of each subsystem in achieving the required performance, based on the six performance indicators. The following simulations were carried out at twelve times during the entire year, which represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice):

- Point in Time illuminance using DIVA for Grasshopper to measure illuminance values at the 17 points in space.
- Point in Time illuminance using DIVA for Rhino to measure the illuminance values of a grid of nodes spacing 0.42 m.
- Point in Time Daylight Glare Probability (DGP)

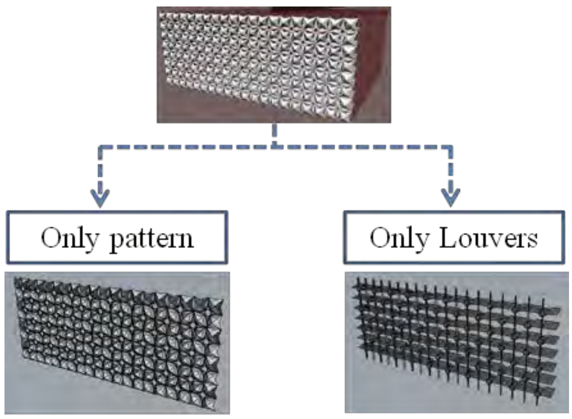


Figure 6.24 TABS sub-systems

6.9. Conclusion

This chapter introduced a methodology for assessing performance simulation and optimisation of TABS. In addition, the impact of the TABS system on visual comfort and daylight availability in office spaces was examined in comparison to other traditional building skin solutions, such as a fully glazed base case, an optimised WWR (AOWWR), and an annual optimised static building envelope (AOSBE). Finally, performance metrics, which are used to assess daylight levels and visual comfort, were discussed in this chapter.

Chapter Seven

7. Territorial Adaptive Building Skin (TABS) Model Validation

7.1. Introduction

Thus, the validity of the simulation model plays a crucial role in proving the validity of the performance predictions and associated decisions in support of the design process (Sargent 2005). Especially, for innovative technologies such as adaptive building envelopes which, usually faces a general lack of accepted model strategies due to the possible inaccuracy in a model's reliability. The building performance simulation's efficiency is the art of accomplishing the precise type of virtual experiments with the accurate model and tools (Augenbroe 2011). Until now, the TABS model had only been tested under the controlled conditions of the simulation environment generated by the software. Checking the reliability of the hugely complicated computational procedures is an important task. Therefore, two scaled models of optimised TABS were created and tested experimentally in an artificial sky.

In this chapter, the validity of the TABS model is tested by an empirical validation study. The intention at this stage was to evaluate the validity of the specific assumptions concerning the TABS model and not to question the validity of the algorithms of the software tools.

Verification and Validation (V&V) studies are essential parts of every TABS model design process. According to (Pace 2004), in general, the definitions of the verification and validation (V&V) are mainly concerned with answering two main questions: "Did I build the thing right? "and "Did I build the right thing?", which can be described as follows:

Verification:

Did I build the thing right?

Which is about making sure that the built model and simulation have fully satisfied the designer's intent as indicated in the specifications. This step has two aspects: first, design (only, all the selected specifications are included in the model or simulation design).

Second, implementation (only, all the selected specifications are included in the model or simulation as built).

Design and Implementation (the same use of the same specifications during both of the model or simulation design and model or simulation as built, respectively).

Validation:

Did I build the right thing?

Which is about the demonstrated model or the simulation ability to fulfil its intended use adequately. This step has two aspects: First, conceptual validation; when the predicted fidelity of the conceptual or simulation model is evaluated. Second, results validation; after comparing the results of the implemented model or simulation with an appropriate reference to prove that the model or simulation can in real fulfilling the intended use.

One of the earliest paradigms of the associations among V&V activities and model or simulation development the "Sargent Circle" produced in the 1970s by Dr Robert Sargent of Syracuse University. Figure 7.1 is an evolution of the paradigm developed by Sargent in 2001 (Pace 2004).

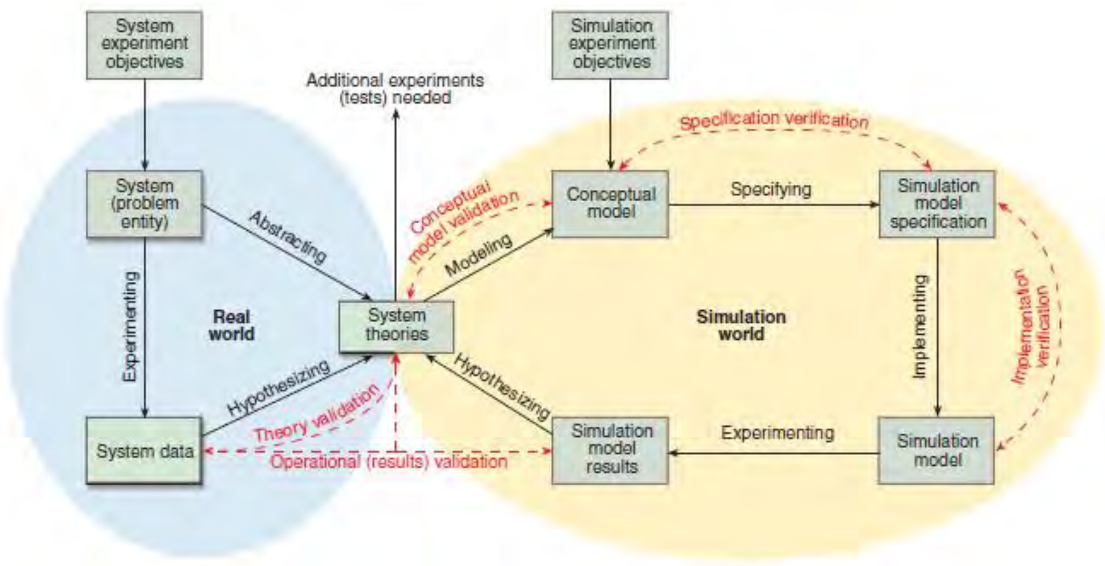


Figure 7.1 Real-world and simulation-world relationships in developing system theories and simulation models with verification and validation (Pace 2004).

Thus, with the aim of using the computer models with confidence and prove the results' reliability, a process called empirical validation was carried out by comparing the results of the simulations with the results of the experiment (Judkoff and Neymark 1995).

7.2. Methodology

According to (Judkoff, Wortman et al. 1983), the efficiency of a whole-building energy simulation program can be evaluated by:

• Empirical Validation—in which results from software are matched with observed data from a real building, test cell, or laboratory experiment.

• Analytical Verification - in which results from software are compared to results from a known analytical solution or an accepted numerical method under very simple, highly constrained boundary conditions.

• Comparative Testing - in which a program is compared to itself or other programs.

Within the context of this study, the empirical validation studies were chosen, and can be summarised in the following three main steps:

First: using the adequate experimental setup for monitoring the boundary conditions and the performance of a test object.

Second: Making a simulation model of the experimental setup and test environment, and undertaking simulations using the measured climatic data;

Third: Comparing measured performance with predicted performance and deciding upon the validity of the model. Figure 7.2 shows the process workflow.

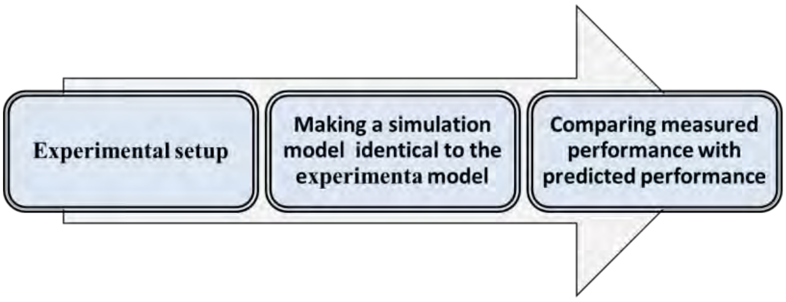


Figure 7.2 Empirical validation study process workflow

By carefully following the steps above, the potential of ensuring an accurate validation process is higher. In the end, if the comparison between the measured performance and the predicted performance are within an accepted certain boundary, then it proves that the validation process gives satisfactory confidence about:

1) The model reliability in predicting performance in new situations.
2) The simulation program is capable of modelling the component's characteristics correctly when it is subject to random dynamic outdoor conditions.

The details of all the steps above are described in the following sections:

7.3. Experimental Setup:

The building model's geometrical dimensions, configuration and surface properties assumed for the prediction stage are crucial parameters that should be considered to confirm that they are adequately close match to the real building, similarly, the reflection/transmission of the surfaces assumed in the building model are a competent representation of those in the actual building. (Mardaljevic, Brembilla et al. 2016). Accordingly, considering these parameters in both the simulation and the physical scale model within this study is essential.

Therefore, creating an adequate scaled model close match to the simulation model regarding the geometrical configuration and dimensions as well as surfaces reflections is the key aspect at this stage. The scaled model was chosen to be 1:20 with dimensions 500x400x200mm, based on the recommendation of researchers at University College London's Artificial Sky, as the model, should be within the range of 1m by 1m. Moreover, according to (Bodart, Deneyer et al. 2007), this scale is suitable for the objective of the study (see Table 7.1).

Table 7.1 Scale choice as a function of daylight design purpose.

Scale	Objectives
1/200 to 1/500	For preliminary design and concept developing. To give an entire sense of the massing of the project. To study the shadows generated by the future building or from a neighbouring building.
1/200 to 1/50	To study direct sunlight penetration into a building. To study diffuse daylight in a big space.
1/100 to 1/10	To consider a detailed refinement of spatial components. To have highly detailed inside views. To study accurately diffuse and direct daylight penetration.
1/10 to 1/1	To integrate crucial industrial elements. To study daylighting devices that cannot be decreased in scale. To proceed to a final evaluation of advanced daylighting systems through monitoring and user assessment.

The TABS is a geometrically intricate surface, and it was decided that 3D printing of the TABS model was the critical due to the complexity of its geometry. Thus, many digital fabrication tools were tested to find the suitable way for achieving an accurate physical model with full details. The Z-Corp powder printer was selected for the 3D printing of the façades. The selected printer spreads thin layers of powder across a bed, then applies glue to where the part is to be built; the part is then depowdered by the author; the build volume was 240 x 200 x 200mm, and the printed parts had a minimum thickness of 2 mm and maximum thickness 5mm. Thus the model was scaled and modified in Rhino and divided into three parts for accomplishing the 3D printing process.

Using the methodology described in Chapter Six, two optimisation processes for two selected times (out of twelve examined times within this thesis), was carried out to find the optimised TABS designs of the 21st June at 12 pm, and 21st December at 12 pm, as representation of the Cairo summer and winter seasons for the 3D printing of TABS for the validation process. Figures 7.3 to 7.5 show the 3D printing process.

Figure 7.3 Printing setup

Figure 7.4 Printing process and the first stage of depowdering the printed screen

Figure 7.5 Final stage of depowdering the printed screens

A fibreboard test-box with dimensions 500x400x200mm was fabricated as a representation of the office space behind the TABS system. The dimensions of the fibreboard box were scaled by a factor 1:20.

The material select depends on the study's purpose. For an actual quantitative luminance and illuminance study, as the case in the current study, it is crucial to pick a scale model material having a reflection coefficient and lightness very close to the full-scale material's values. Overvaluation of the reflection, the factor can lead to significant errors. For instance, if the wall had a reflection coefficient ρ of 50 %, and the scale model had white walls with ρ=85% then the measurements made in the scale model can overvalue the results of about by 150% to 200 %, for a point at the rear part of space (Bodart, Deneyer et al. 2007).

Therefore, the internal surfaces of the box (floor, ceiling, and walls) were painted using a special painting with reflectance values matching with the simulation model to assess the TABS system daylighting performance correctly. The material and reflectance values utilised in both simulation and validation process are described in Table 7.2.

Figure 7.6 Painting process

Figure 7.7 Final model

Table 7.2 The model materials and reflectance used in simulation and validation is described in the following table:

Space Dimensions and Materials			
		Simulation	Validation
Walls (All cases)	Reflectance	50%	45%
	Material	Medium coloured walls	Medium coloured painted fiberboard
Ceiling (All cases)	Reflectance	90%	87%
	Material	White coloured ceiling	White coloured painted fiberboard
Floor (All cases)	Reflectance	20%	24%
	Material	Dark wooden flooring	Dark coloured painted fiberboard
Screen	Reflectance	90%	87%
	Material	Metal diffuses	White coloured painted fiberboard

Artificial sky:

All measurements took place at the Bartlett artificial sky at University College London (Figure 7.8). The Bartlett Sky simulates daylight for scale models of buildings to evaluate the impact of ambient and directional light on lighting design. The Bartlett Artificial Sky is a 5m diameter geodesic dome comprising 270 diffused luminaries, managed by a control system based on the required sky types. A wide range of sky conditions can be generated, in addition to a sun simulator. The sun is represented by a 50W halogen lamp reflected by a parabolic mirror which makes the light into parallel beams. The sun is on a rotatable track which can be programmed to create almost any solar position for the time of day/year in the northern or southern hemisphere. The orientation of this façade is south, no significant obstructions that block direct solar radiation are present.

Figure 7.8 The Bartlett daylight simulator for scale models of buildings

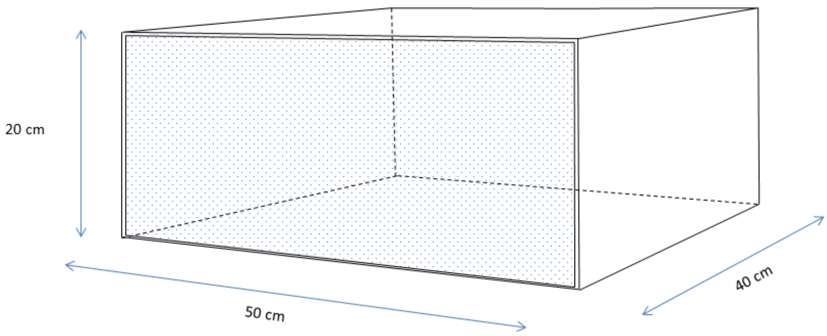


Figure 7.9 Dimensions of the test-box, space is oriented to the south.

The scaled model was oriented towards the south in the middle of the dome. For the measurement of light distribution in the test-box, five calibrated photocell illuminance sensor were used, as a representation of five working plans in the simulation model. The distribution of these sensors inside the box is given in Figure 7.101.

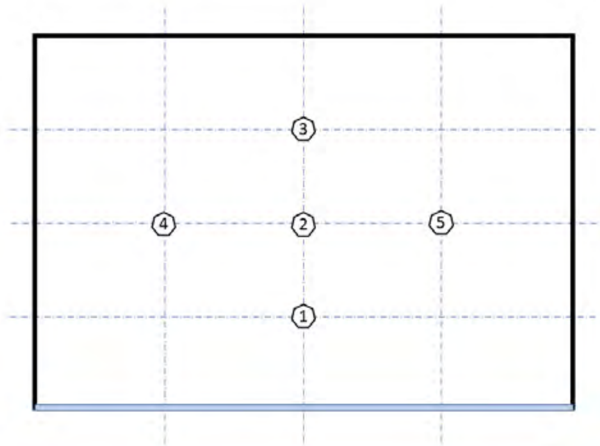


Figure 7.10 Sensors distribution in space

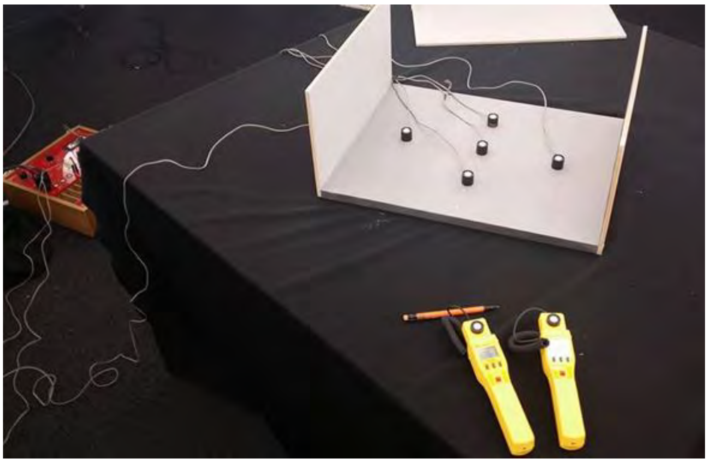


Figure 7.11 The test-box with illuminance sensors.

Figure 7.12 The scaled model is positioned in the middle of the dome and oriented correctly towards the south.

Two optimised screens are utilised for the experimental work as mentioned before as a representation of the optimised design for summer and winter seasons. The two 3D printed screens used are shown in Figure 7.13 (a-b).

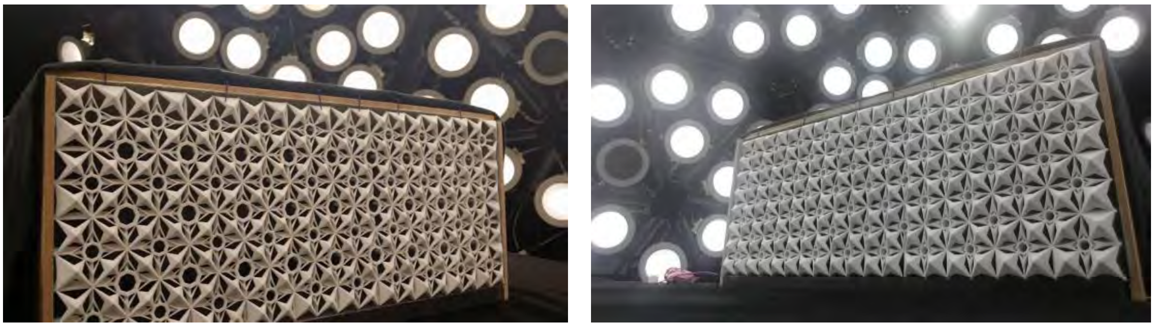


Figure 7.13 Models used in the experimental work: a)The optimised (TABS) design of 21st of June at 12 pm, (b) The optimised (TABS) design of 21st of December at 12 pm

Six measurements were carried out for each screen using two predefined CIE standard skies:

1. Overcast sky.
2. Clear sky.

All data were automatically collected and sorted for each TABS screen at different times and sky types to be compared with the simulation model in the last step based on the validation methodology mentioned above (see Figure 7.14).

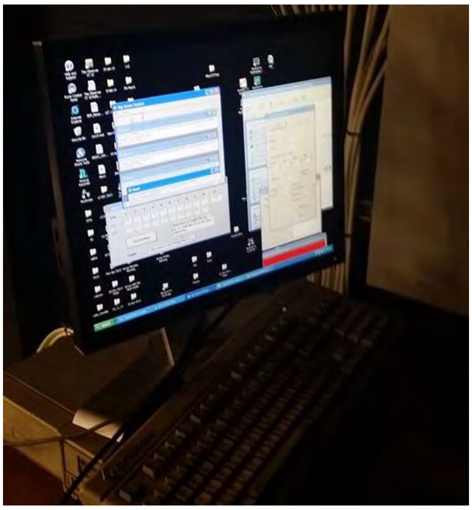


Figure 7.14 Data recording

7.4. Simulations

Building performance simulations were carried out using a scaled simulation model with the same dimensions, material and TABS configurations for the two selected optimised designs representing the summer and winter seasons without external obstructions as used in the empirical experiment (see Figure 7.15).

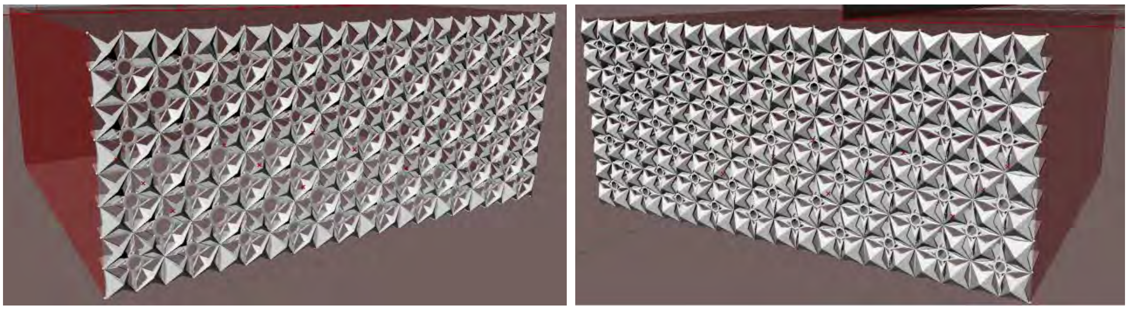


Figure 7.15 Models used in the simulation: a) The simulation model of the optimised TABS designs of 21st of June at 12 pm; (b) The simulation model of the optimised TABS designs of 21st of December at 12 pm

Simulations in DIVA for Grasshopper were carried out for calculating the illuminance values of five nodes distributed exactly as the photocell illuminance sensor has been positioned in the empirical experiment and with the same relative height from the flooring level.

Finally, two measurements were carried out for each time with and without screen using two predefined CIE standard skies:

1) Overcast sky.
2) Clear sky.

All simulations model's results are collected and sorted to be compared to the measurements of the empirical experiment as a last step of the validation process.

7.5. Comparing Results

The optimum validation standard would be by comparing the model simulation results and the measurements of an adequately performed empirical experiment, even though this ideal condition does not easily exist in practice due to the potential of errors. However, the deliberate intention while carrying out both empirical experiment and the simulation process will improve the accuracy of the validation process (Neymark, Judkoff et al. 2002).

Evaluation criteria:

The evaluation criteria are based on two main points:

a. Illuminance values.
b. Daylight distribution trend.

The description of the results can be described as follows:

1. Overcast sky:

a. Screen 1 (21st of June at 12 pm):

- Illumination values:

Figure 7.16 shows the comparison between measurements and simulation results of the screen, for the five sensors, the results present illuminance values on 21st of June at 12 pm under an overcast sky.

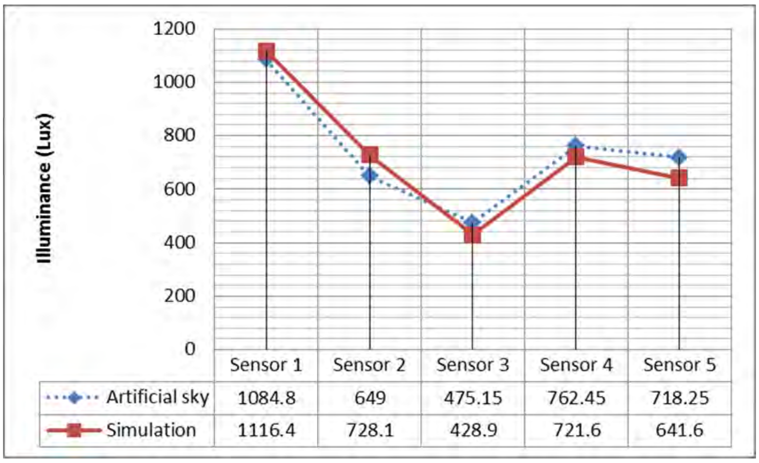


Figure 7.16 Comparison between measurements and simulation results of the screen one on the 21st of June at 12 pm under an overcast sky, with the measured illuminance (dashed lines) and simulated illuminance (solid lines) for five different sensor points.

The comparisons in Figure 7.16 show good agreement between the results of measurements and simulations. The highest agreement was found for points 1, 3, and 4 with a maximum difference approximately between 3-6 %, points 2 and 5 showed lower agreement with a maximum difference approximately between 10-11 %

- Daylight distribution's trend:

The graph shows that the comparison of daylight distribution, behaviour in both simulation and empirical experiment are almost the same and had the same behaviour with a minor slight difference.

b. Screen 1 (21st of December at 12 pm):

- Illumination values:

Figure 7.17 shows the comparison between measurements and simulation results of the screen (2), for the five sensors, the results present illuminance values on 21st of Dec. at 12 pm under an overcast sky.

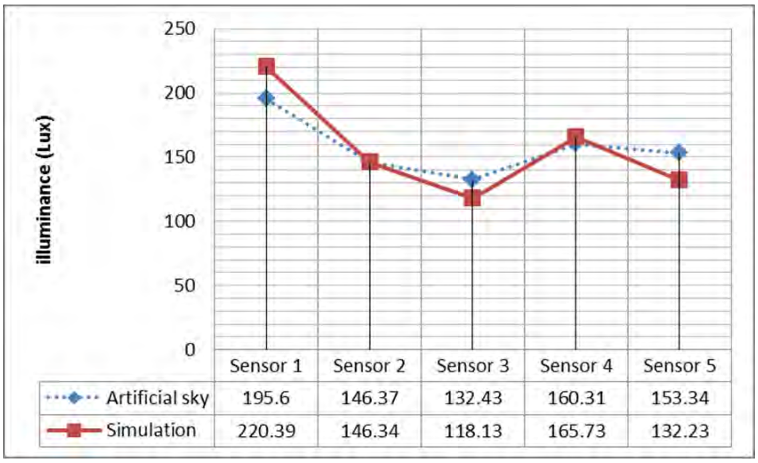


Figure 7.17 Comparison between measurements and simulation results of screen two on 21st of Dec. at 12 pm under an overcast sky, with the measured illuminance (dashed lines) and simulated illuminance (solid lines) for five different sensor points.

The comparisons in Figure 7.17 show good agreement between the results of measurements and simulations. The highest agreement was found for points 2 and 4 with a maximum difference approximately between 1-4 %, and points 1, 3 and 5 showed lower agreement with a maximum difference approximately between 11-14 %

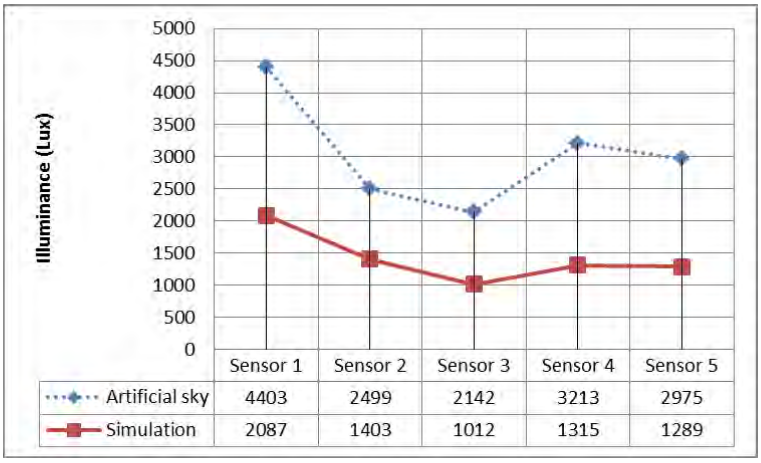
- Daylight distribution’s behaviour:

The graph shows that the comparison of daylight distribution, behaviour in both simulation and empirical experiment are almost the same and had the same behaviour with a minor slight difference.

2. Clear sky:
   a. Screen 1 (21st of June at 12 pm):

- Illumination values:

Figure 7.18 shows the comparison between measurements and simulation results of screen, for the five sensors, the results present illuminance values on 21st of June at 12 pm under a clear sky with sun.



	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
Artificial sky	4403	2499	2142	3213	2975
Simulation	2087	1403	1012	1315	1289

Figure 7.18 Comparison of measurements and simulations of the screen one on the 21st of June at 12 pm under clear sky with the sun, with the measured illuminance (dashed lines) and simulated illuminance (solid lines) for five different sensor points.

The comparisons in Figure 7.18 show that the agreement between the absolute values of measurements and simulations under a clear sky with the sun is lower than the case of the overcast sky. However, still, there is an indication of similarity in term of the daylight distribution trends of both models. Thus, further analysis are essential to be carried out for analysis the daylight distribution’s trend of the five (sensors/nodes) inside the (experimental/simulation) models with and without the screen for each model separately, for comparing the trend of daylight distribution of each model with and without screen and finally extracting the illumination ratio for each model (sensor/node) with and without screen to be compared with the relative ratio of each point in the other model.

- Daylight distribution’s trend:

First stage: a comparison of illuminance values measured with and without a screen was carried out.

Figure 7.19 and Figure 7.20 show that the comparison of daylight distribution trend, with and without a screen in both, Simulation and empirical experiment separately is almost similar with slight minor differences.

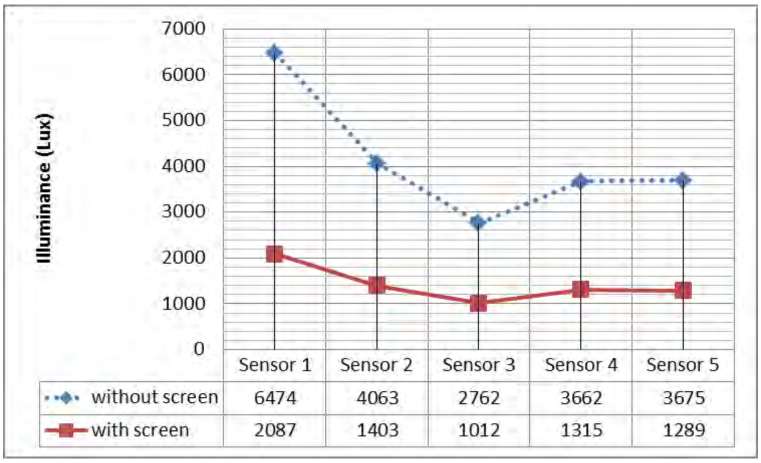


Figure 7.19 The comparison of daylight distribution trend, with and without screen in simulation model (21st of June at 12 pm).

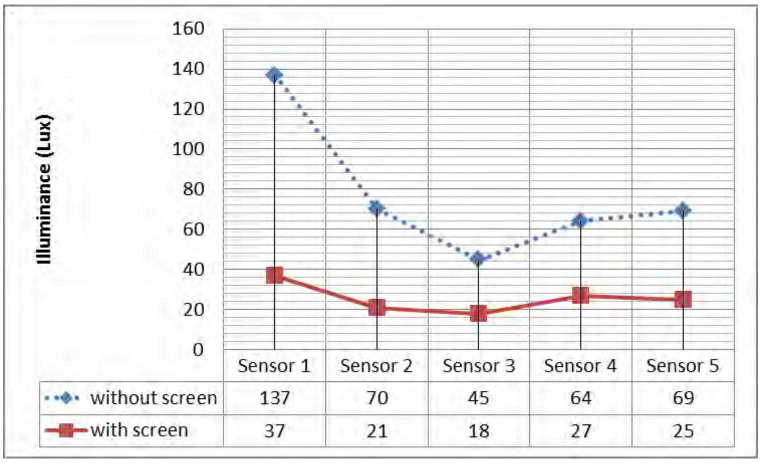


Figure 7.20 The comparison of daylight distribution trend, with and without the screen in the experimental model (21st of June at 12 pm).

Second stage:

Table 7.3 and Figure 7.22 shows a comparison between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model.

Table 7.3 comparisons between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st of June at 12 pm).

No	Model	Illuminance (Lux)		Ratio
		Without screen	With screen	
Node 1	Simulation	6474	2087	0.32
Sensor 1	Experiment	137	37	0.27
Node 2	Simulation	4063	1403	0.34
Sensor 2	Experiment	70	21	0.30
Node 3	Simulation	2762	1012	0.36
Sensor 3	Experiment	45	18	0.40
Node 4	Simulation	3662	1315	0.35
Sensor 4	Experiment	64	27	0.42
Node 5	Simulation	3675	1289	0.35
Sensor 5	Experiment	69	25	0.36

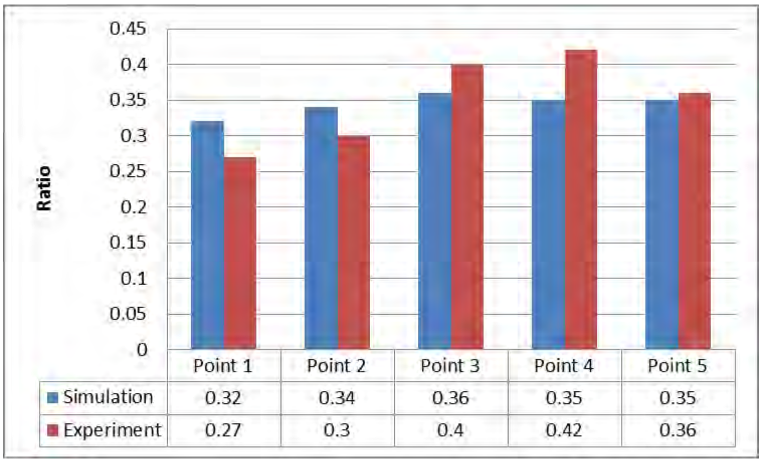


Figure 7.21 comparisons between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st of June at 12 pm).

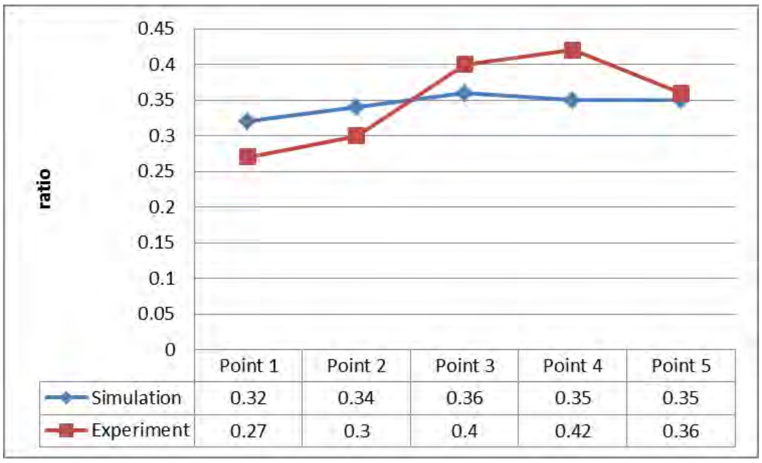


Figure 7.22 comparisons between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st of June at 12 pm).

The results show a minor difference in term of the relative ratios, ranging from 0.04 to 0.07, which is considered acceptable for validating the TABS on 21st of June at 12 pm.

b. Screen 2 (21st of December at 12 pm):

- Illumination values:

Figure 7.23 shows the comparison between measurements and simulation results of the screen (2), for the five sensors. The results present illuminance values on 21st of Dec. at 12 pm under a clear sky with sun.

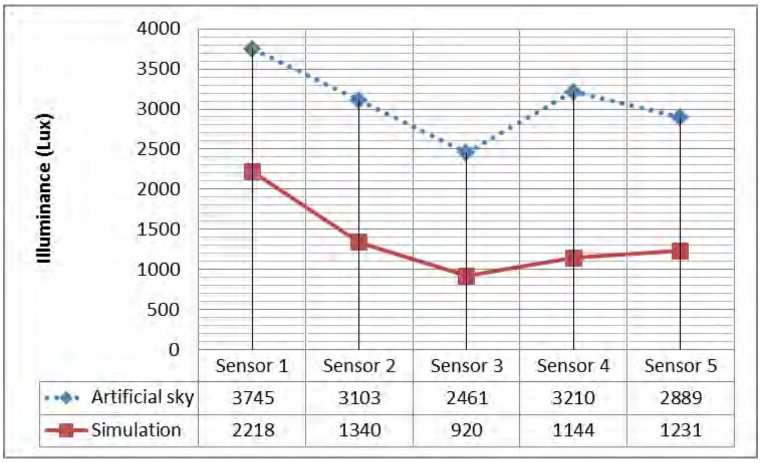


Figure 7.23 Comparison of measurements and simulations of screen two on 21st of Dec. at 12 pm under a clear sky with sun, with the measured illuminance (dashed lines) and simulated illuminance (solid lines) for five different sensor points.

Figure 7.23 show that the agreement between the absolute values of measurements and simulations under a clear sky with the sun is lower than the case of the overcast sky. However, there is an indication of similarity in term of daylight distribution's trend of both models. Thus, further analysis are essential to be carried out for analysis the daylight distribution's trend of the five (sensors/nodes) inside the (experimental/simulation) models with and without the screen for each model separately, for comparing the trend of daylight distribution of each model with and without screen and finally extracting the illumination ratio for each model (sensor/node) with and without screen to be compared with the relative ratio of each point in the other model.

- Daylight distribution's trend:

First stage: a comparison of illuminance values measured with and without the screen was carried out.

Figure 7.24 shows that the comparison of daylight distribution trend, with and without the screen in both simulation and empirical experiment separately, is almost similar with slight minor differences.

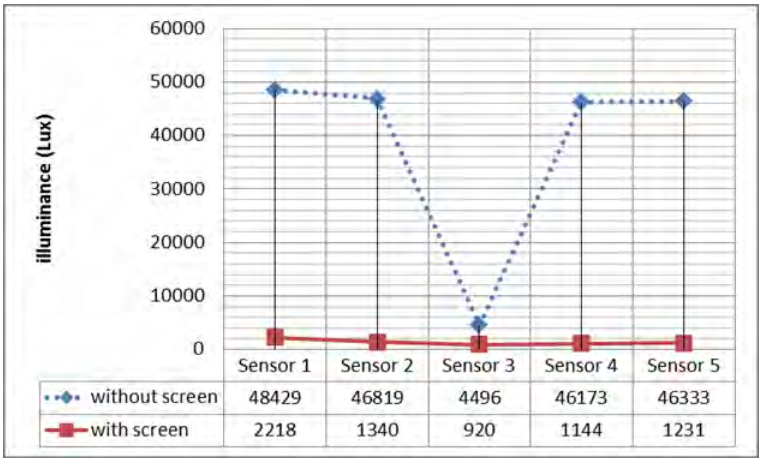


Figure 7.24 The comparison of daylight distribution trend, with and without screen in Simulation model (21st of December at 12 pm).

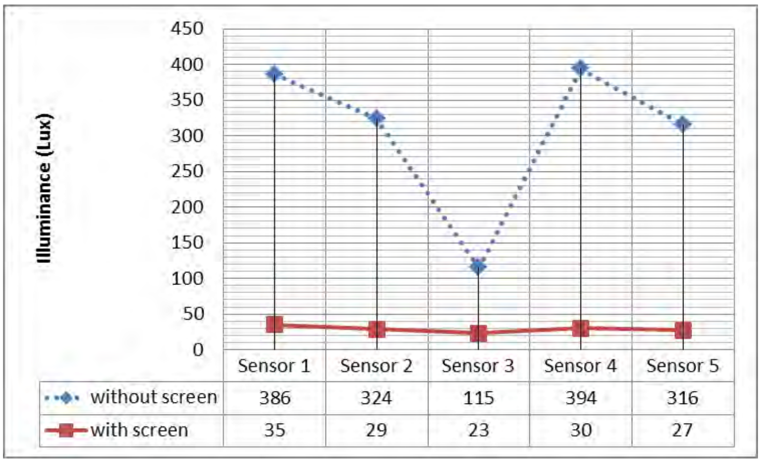


Figure 7.25 The comparison of daylight distribution trend, with and without the screen in the experimental model (21st of December at 12 pm).

Second stage:

Table 7.4 and Figure 7.26 show a comparison between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model.

Table 7.4 comparisons between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st of December at 12 pm).

No	Model	Illuminance (Lux)		Ratio (%)
		Without screen	With screen	
Node 1	Simulation	48429	2218	0.045
Sensor 1	Experiment	386	35	0.09
Node 2	Simulation	46819	1340	0.028
Sensor 2	Experiment	324	29	0.089
Node 3	Simulation	4496	920	0.2
Sensor 3	Experiment	115	23	0.2
Node 4	Simulation	46173	1144	0.024
Sensor 4	Experiment	394	30	0.07
Node 5	Simulation	46333	1231	0.026
Sensor 5	Experiment	316	27	0.085

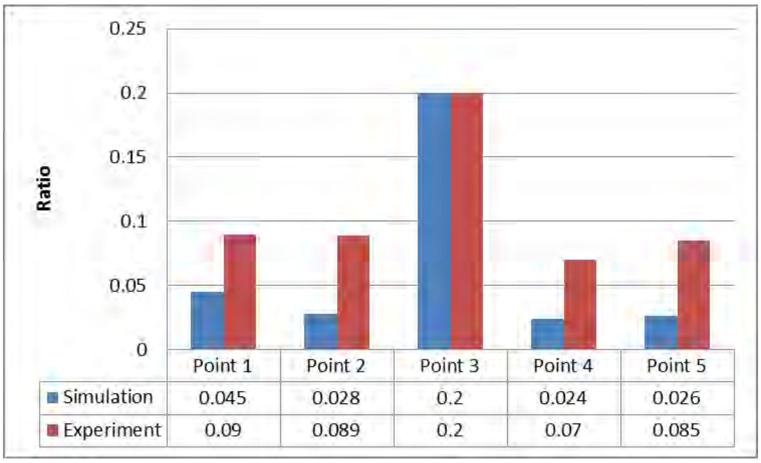


Figure 7.26 comparisons of the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st of December at 12 pm).

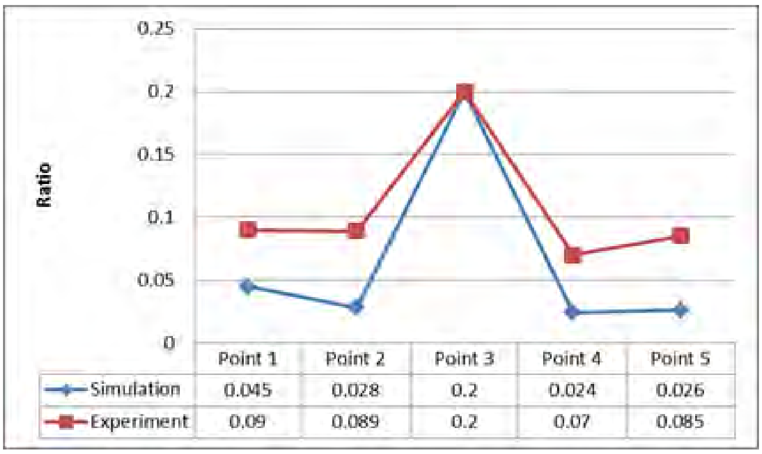


Figure 7.27 Comparisons between the illumination ratio for each model (sensor/node) with and without the screen with the relative ratio of each point in the other model (21st Dec. at 12 pm).

7.6. Conclusion

The findings of the empirical validation study were presented in this chapter to check the validity of the TABS model. A scaled model and two 3D printed screens of optimised TABS for the 21st June at 12 pm, and 21st December at 12 pm, as a representation of summer and winter seasons, were used. An experimental process took place at the Bartlett daylight simulator at University College London. Two types of the sky were selected for the empirical validation study - overcast sky and clear sky with the sun. The results of the overcast sky showed good agreement between the results of the empirical studies and simulation in term of illuminance absolute values and daylight distribution trend. In the case of clear sky with the sun, the results show lower agreement regarding absolute illuminance values and a good agreement in term daylight distribution trend. Thus, further analyses were carried out for each model to find the impact of the screen on the daylight distribution trend by calculating the ratio between illuminance values of each point with and without a screen in both environments (experimental and simulation) and compared together. Finally, this comparison shows acceptable agreement.

This validation exercise gave confidence that the complex modelling and analyses being undertaken by the various software were being performed in a rigorous and appropriate manner. Based on this study, it can be concluded that the results of the TABS model are satisfactory enough to be used for optimising Territorial Adaptive Building Skin TABS for all the twelve selected times and comparisons of alternative design strategies included in this study.

Chapter Eight

8. Results

In this chapter, the results from various simulations and optimisations processes are structured in three main stages and presented along with a short discussion on each simulation.

Stage One:

Presents the results of TABS and its subsystem's performance in three main phases, the can be described as follows:

- Phase one:

  Presents the results of the optimisation processes of Territorial Adaptive Building Skin TABS at all the twelve examined times (TABS configurations (see Table 8.1, and Table 8.2) and design parameters (see Table 8.3). Moreover, presents the performance of the twelve optimised TABS in comparison to the individual performance of the TABS subsystems (Shading subsystem, and redirecting subsystem), at the same examined times, regarding five performance indicators: Task-plans illuminance, illuminance distribution, illuminance contrast ratio, daylight penetration depth, and solar radiation.

- Phase two:

  Presents the results of the Point-in–Time Daylight Glare Probability evaluation of the twelve optimised TABS at all the twelve examined times in comparison to the individual performance of the TABS subsystems (Shading subsystem, and redirecting subsystem), at the same examined times.

- Phase three:

  Presents the results of further analysis carried out to examine the capability of the twelve optimised TABS to achieve a daylight penetration depth 3x (12 m), inside the tested space.

Stage Two:

Presents the results of the optimisation processes of:

- Annually optimised WWR (AOWWR).
- Annually optimised static building envelope (AOSBE).

This research assesses daylight performance using, Dynamic Daylighting Performance Metrics (DDPM) (Daylight autonomy (DA500lux) and Glare Probability. The aim was to find the optimum WWR and static building envelope configuration that achieved adequate annual performance (maintaining 500 Lux for at least 50% of the working hours for 17 points distributed in the space), and to achieve imperceptible glare (DGP less than 35%).

Stage Three:

Presents the results of daylight performance-based comparison of the different systems:

- Base case
- Annually optimised WWR (AOWWR).
- Annually optimised static building envelope (AOSBE).
- (TABS).

The results of this stage were structured in two main phases, can be described as follows:

Phase one:

Presents the results and compared the performance of TABS with other solutions such as fully glazed base case, Annually optimised WWR (AOWWR), and Annually optimised static building envelope (AOSBE), regarding five performance indicators: Task-plans illuminance, illuminance distribution, illuminance contrast ratio, daylight penetration depth, and solar radiation.

For the performance evaluation process, this research assessed daylight performance using the two metrics: Point-in-Time illuminance (for 17 points inside space using DIVA for Grasshopper and further evaluation using the same metrics in Diva for Rhino for a grid spacing (0.425*0.425 m)).

Phase two:

- Presents the results of the Point-in–Time Daylight Glare Probability evaluation of the twelve optimised TABS at all the twelve examined times in comparison to with other solutions such as fully glazed base case, Annually optimised WWR (AOWWR), and Annually optimised static building envelope (AOSBE), at the same examined times.

All cases were evaluated at all the twelve times using the same metrics, and their performance regarding the performance indicators included in the design criteria are discussed.

8.1. Stage One: Results of the Performance of TABS System and Sub-Systems.

All results summarised as follows:

First Phase:

Table 8.1 Optimised TABS configuration (Mar. 21st and Jun. 21st at 9 am, 12 pm, and 3 pm)

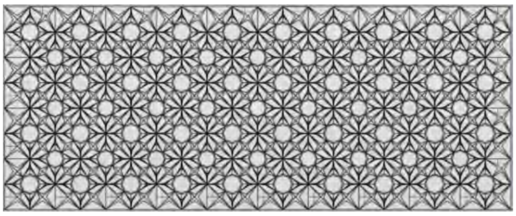
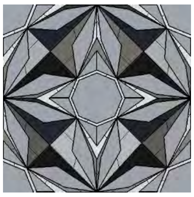
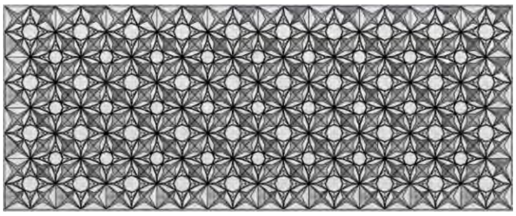
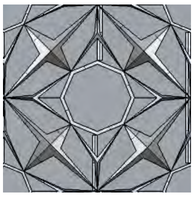
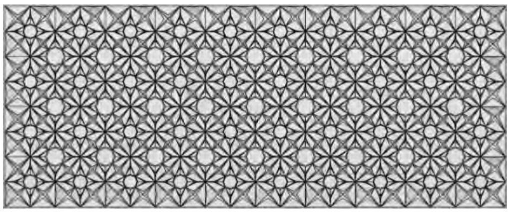
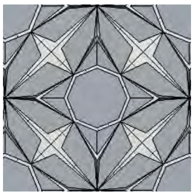
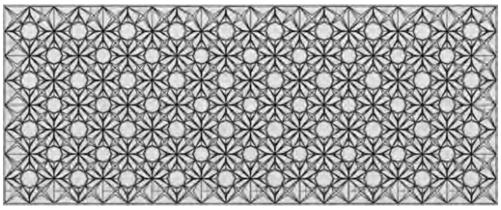
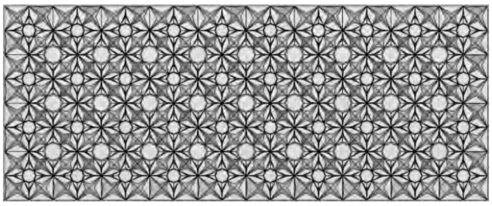
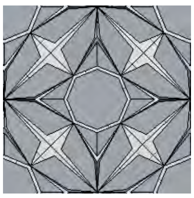
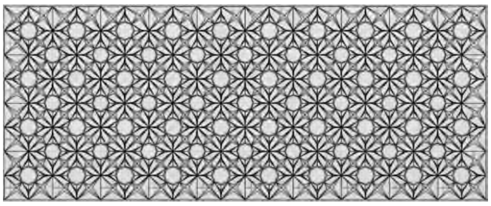
Time	Mar. 21st		
	Pattern	Section	Perspective
9 am			
12 pm			
3 pm			
Time	Jun. 21st		
	Pattern	Section	Perspective
9 am			
12 pm			
3 pm			

Table 8.2 Optimised TABS configuration (Sep. 21st and Dec. 21st at 9 am, 12 pm and 3 pm)

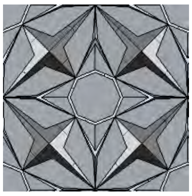
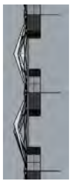
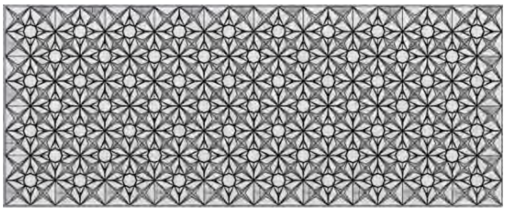
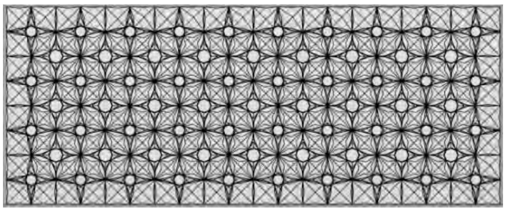
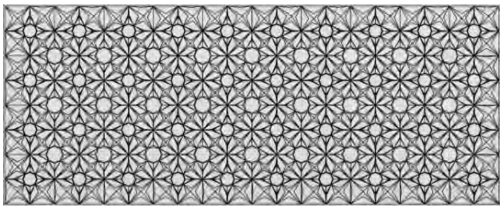
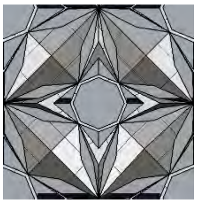
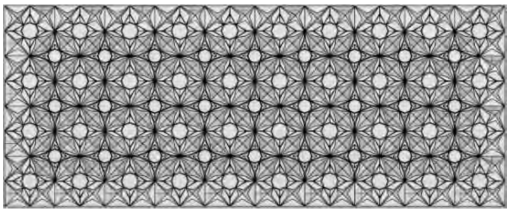
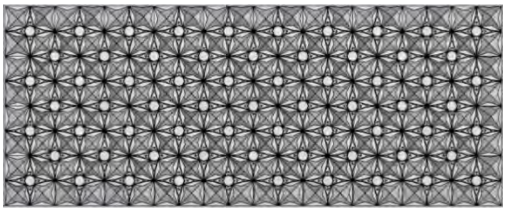
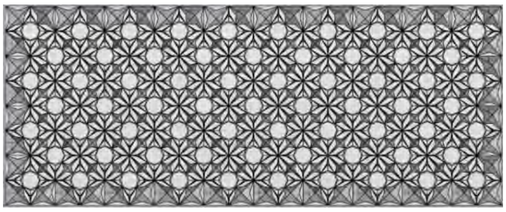
Time	Sep. 21st		
	Pattern	Section	Perspective
9 am			
12 pm			
3 pm			
Time	**Dec. 21st**		
	Pattern	Section	Perspective
9 am			
12 pm			
3 pm			

Table 8.3 Optimum TABS parameters for all the twelve selected times

Time	Parameters														
	ESP (m)	EMP (m)	ORSP1 (%)	MMPOR (%)	ORSP2 (%)	BPOR (%)	UROR (%)	LLOR (%)	OD (m)	MOR (m)	SOR (m)	HLD (m)	HLIA (°)	VLD (m) (Fix.)	VLIA (°) (Fix.)
Mar															
9 am	0.025	0	0.8	0.7	0.8	0.7	0.047	0.086	0.1	0.16	0.18	0.25	15	0.1	0
12 pm	0.025	0.25	0.6	0.4	0.6	0.6	0.1	0.084	0.15	0.16	0.13	0.01	15	0.1	0
15 pm	0.025	0.05	0.8	0.7	0.8	0.7	0.047	0.086	0.01	0.13	0.18	0.2	0	0.1	0
Jun.															
9 am	0.025	0	0.8	0.7	0.8	0.7	0	0	0.1	0.18	0.16	0.01	0	0.1	0
12 pm	0.025	0.15	0.8	0.5	0.8	0.6	0.1	0.084	0.01	0.13	0.18	0.25	15	0.1	0
15 pm	0.025	0	0.8	0.7	0.8	0.7	0	0	0.01	0.18	0.16	0.01	0	0.1	0
Sep.															
9 am	0.025	0.1	0.8	0.6	0.8	0.7	0	0	0.1	0.13	0.13	0.25	0	0.1	0
12 pm	0.025	0	0.2	0.4	0.7	0.1	0.1	0.084	0.4	0.10	0.13	0.35	30	0.1	0
15 pm	0.025	0	0.8	0.7	0.9	0.6	0.1	0.084	0.15	0.13	0.16	0.25	15	0.1	0
Dec.															
9 am	0.025	0.05	0.9	0.2	0.5	0.6	0	0	0.1	0.16	0.13	0.1	15	0.1	0
12 pm	0.025	0.25	0.4	0.4	0.3	0.3	0.1	0.084	0.4	0.10	0.10	0.5	15	0.1	0
15 pm	0.025	0.25	0.8	0.6	0.8	0.3	0.1	0.08	0.4	0.18	0.18	0.1	30	0.1	0

Extrusion of all Small Patterns (ESP)

Extrusion of all Main Patterns (EMP)

Opening Ratio of Small Patterns rows 1,3,5,7 (ORSP1)

Middle Main Pattern Opening Ratio (MMPOR)

Opening Ratio of Small Patterns rows 1,3,5,7 (ORSP2)

Boundaries Patterns Opening Ratio (BPOR)

Upper and Right rows Opening Ratio (UROR)

Lower and Left rows opening Ratio (LLOR)

Octagons Depth (OD)

Main Octagons Radius (MOR)

Secondary Octagons Radius (SOR)

Horizontal Louvers Depth (HLD)

Horizontal Louvers Inclination Angle (HLIA)

Vertical Louvers Depth (VLD)

Vertical Louvers Inclination Angle (VLIA)

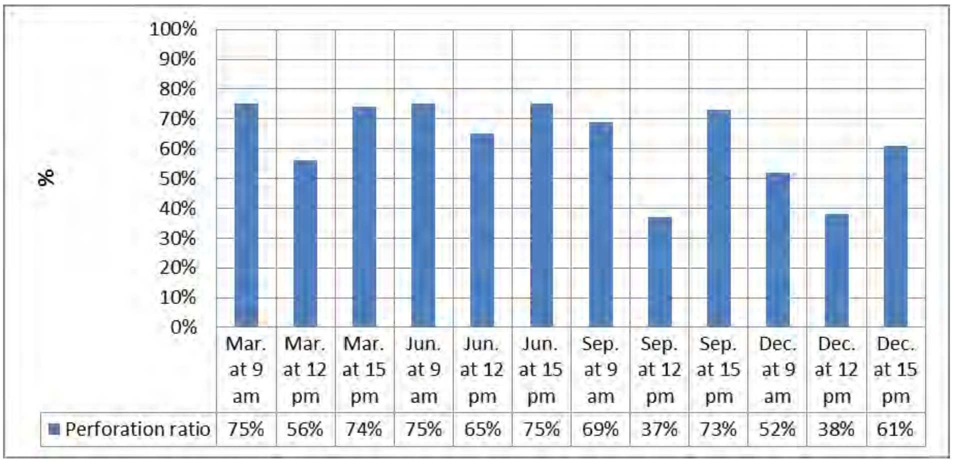


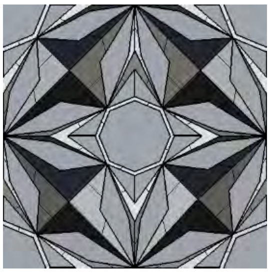
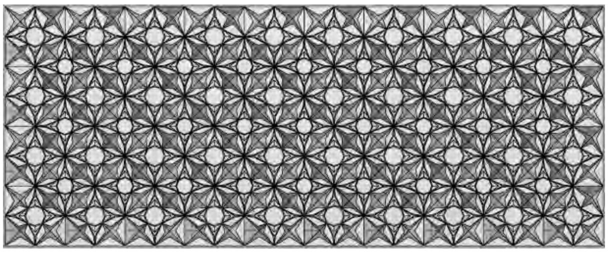
Figure 8.1 Perforation ratios (PR) of the successful TABS at the twelve examined times.

TABS performance at all the twelve times regarding performance indicators: Task point's illuminance, Illuminance distribution, Illuminance contrast ratio, Daylight depth and solar radiation, are presented in the following sections.

TABS performance on 21st of March, June, September and December at 12 pm regarding performance indicators: Task point's illuminance, Illuminance distribution, Illuminance contrast ratio, Daylight depth and solar radiation, are presented in the following sections while TABS performance on 21st of March, June, September and December at 9am and 3 pm are presented in Appendix A.

8.1.1.1.Case Two: *21st March at 12 pm:*

Table 8.4 TABS configuration for 21st of March

	Pattern	Section	Perspective
12 pm			

1. Task points illuminance:

The results of the TABS show that 100% of the task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, 9 points out of 9 measuring nodes received (500 < Illuminance < 2000 Lux), which succeeded in fulfilling the required criteria. In the case of TABS's redirecting subsystem, only 5 points out of 9 measuring nodes received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria (see Figure 8.2).

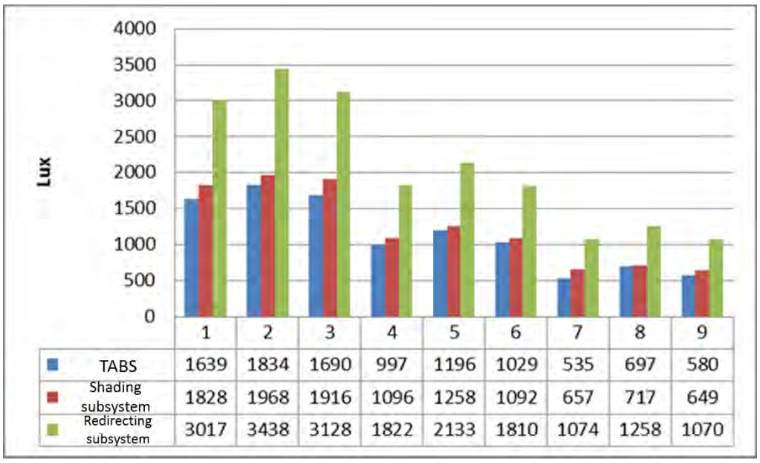


Figure 8.2 Task points Illuminance March 21st at 12 pm

2. Illuminance distribution:

The results of the TABS show that (300 < 89.4 % of area < 3000 Lux) (day lit), (10.6 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, (300 < 87.8 % of area < 3000 Lux) (day lit), (12.2 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of TABS's redirecting subsystem, (300 < 72.6 % of area < 3000 Lux) (day lit), (27.4 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which failed in fulfilling the required criteria (see Figure 8.3 and

Table 8.5).

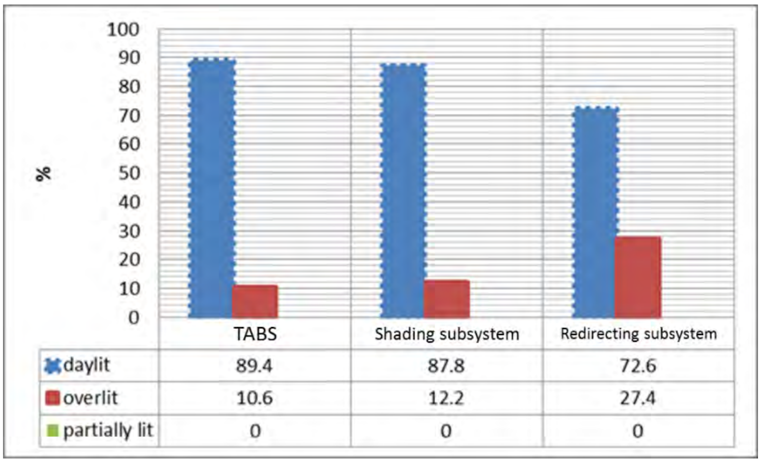
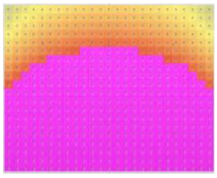
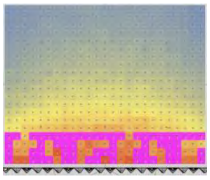
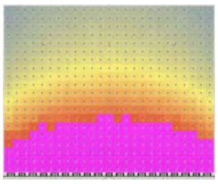
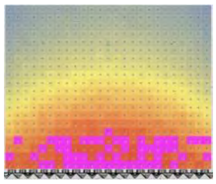


Figure 8.3 Base case daylight distribution (March 21st at 12 pm)

Table 8.5 Daylight distribution in all cases (March 21st at 12 pm).

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the TABS show that the highest illuminance value was 2269 Lux, and the lowest value was 485 Lux, with a contrast ratio of 1:4.7, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, the highest illuminance value was 37735 Lux and the lowest value was 607 Lux, with a contrast ratio of 1:62, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, the highest illuminance value was 39501 Lux and the lowest value was 945 Lux, with a contrast ratio of 1:41, which failed in fulfilling the required criteria.

4. Daylight depth:

The results of the TABS show that 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, only 7 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 1 point received > 3000 Lux, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, 5 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria. (See Figure 8.4)

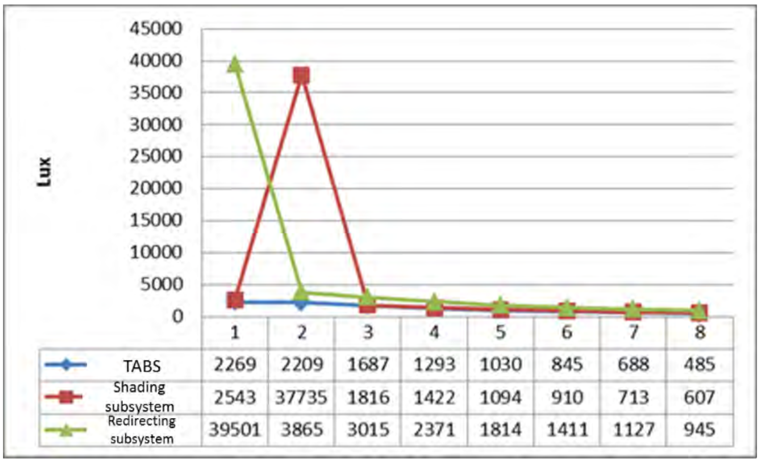


Figure 8.4 Base case daylight depth (21st of March at 12 pm)

5. Solar radiation:

The results of the TABS show that the 40 measuring nodes received 40 KWh/m^2 during 21st March. In the case of the TABS's shading subsystem, 40 KWh/m^2 was received. In regard to TABS's redirecting subsystem, 79 KWh/m^2 was received (see Figure 8.5).

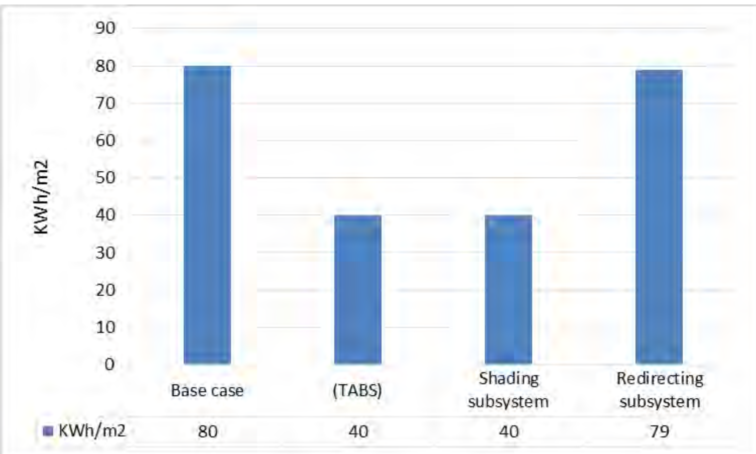


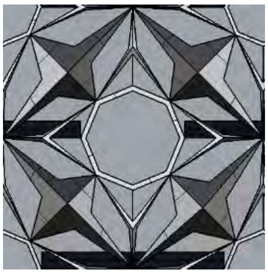
Figure 8.5 solar radiation (21st of March at 12 pm) all cases

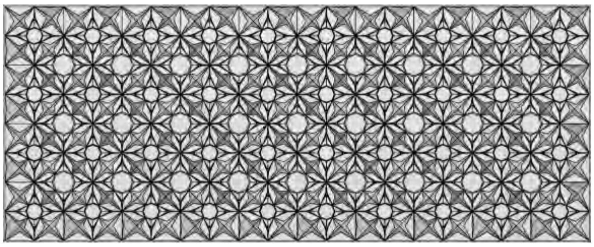
8.1.1.2.Case Five: 21st June at 12 pm:

Table 8.6 TABS configuration for Jun. 21st at 12 pm

Pattern	Section	Perspective

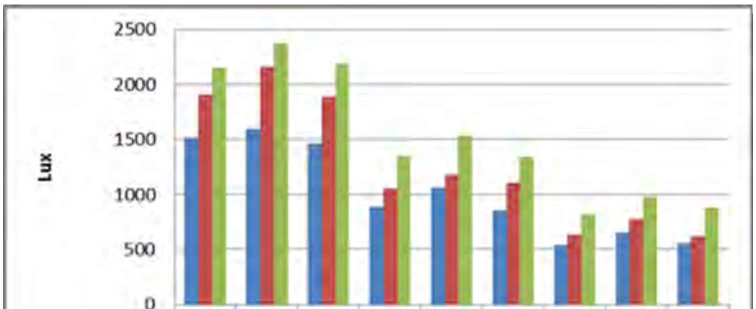
12 pm





1. Task points illuminance:

The results of the TABS show that 100% of the task points (9 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, eight tasks-plans nodes out of 9 measuring nodes, received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, only six tasks-plans nodes out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. (See Figure 8.6)



	1	2	3	4	5	6	7	8	9
TABS	1513	1591	1468	894	1062	859	543	656	562
Shading subsystem	1910	2165	1893	1053	1173	1108	638	775	617
Redirecting subsystem	2153	2368	2189	1353	1533	1341	816	977	878

Figure 8.6 Task points Illuminance June 21st at 12 pm

2. Illuminance distribution:

The results of the TABS show that (300 < 100 % of area < 3000 Lux) (day lit), (0 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, (300 < 95 % of area < 3000 Lux) (day lit), (5 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of TABS's redirecting subsystem, (300 < 100 % of area < 3000 Lux) (day lit), (0 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria

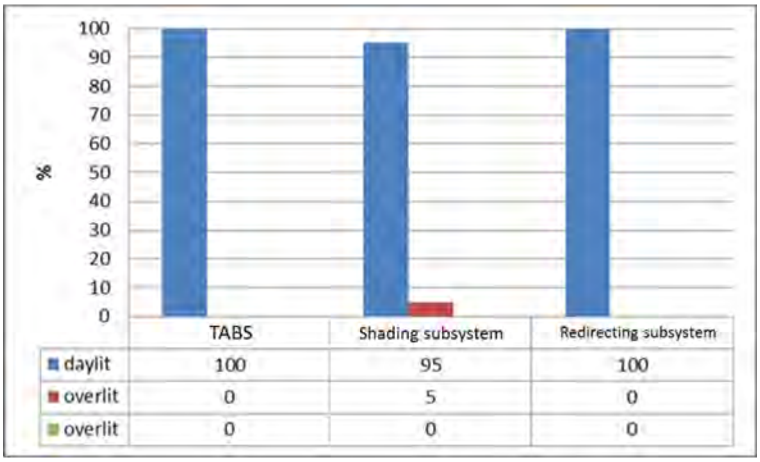
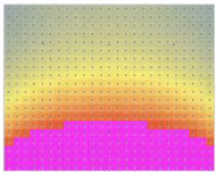
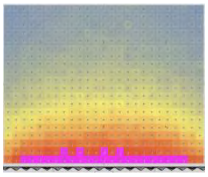
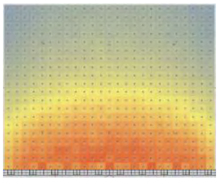
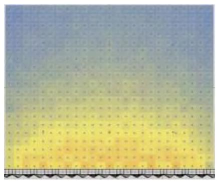
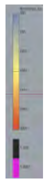


Figure 8.7 Base case daylight distribution (June 21st at 12 pm)

Table 8.7 Daylight distribution in all cases (June 21st at 12 pm).

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the TABS show that the highest illuminance value was 1781 Lux, and the lowest value was 496 Lux, with a contrast ratio of 1:3.5, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, the highest illuminance value was 2970 Lux and the lowest value was 617 Lux, with a contrast ratio of 1:4.8, which succeeded in fulfilling the required criteria. In the case of TABS's redirecting subsystem, the highest illuminance value was 2615 Lux and the lowest value was 793 Lux, with a contrast ratio of 1:3, which succeeded in fulfilling the required criteria.

4. Daylight depth:

The results of the TABS show that 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of TABS's redirecting subsystem, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. (Figure 8.8)

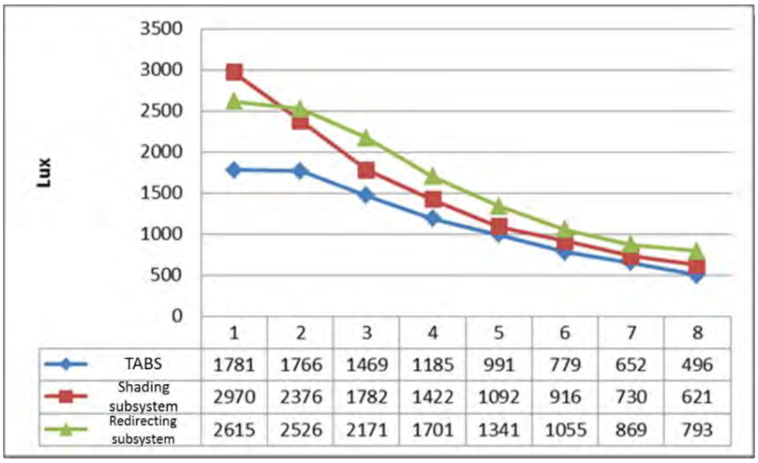


Figure 8.8 Base case daylight depth (21st June at 12 pm)

5. Solar radiation:

The results of the TABS show that the 40 measuring nodes received 20 KWh/m^2 during 21st June. In the case of the TABS's shading subsystem, 40 KWh/m^2 was received. Regarding TABS's redirecting subsystem, 40 KWh/m^2 was received.

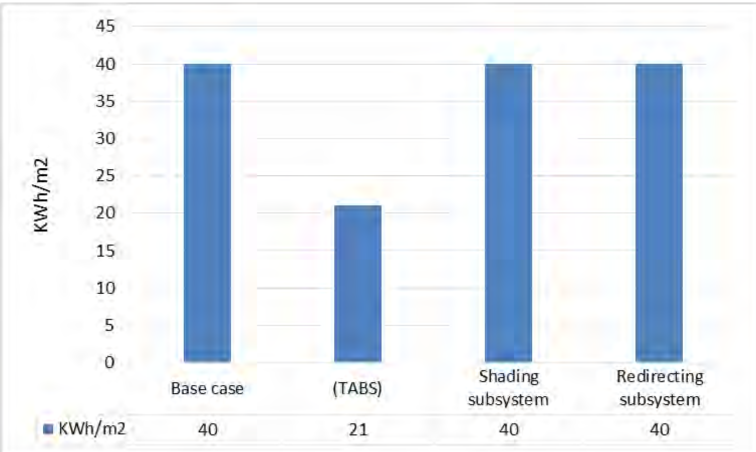
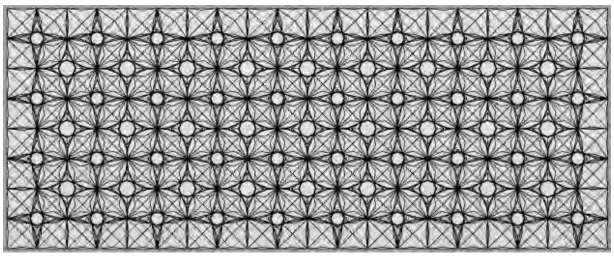


Figure 8.9 Solar radiation (21st June at 12 pm) all cases

8.1.1.3.Case Eight: 21st Sep. at 12 pm:

Table 8.8 TABS configuration for Sep. 21st at 12 pm

	Pattern	Section	Perspective
12 pm			

1. Task points illuminance:

The results of the TABS show that 100% of the task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, only 6 task points nodes out of 9 measuring nodes received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, 7 points out of 9 measuring nodes received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria (see Figure 8.10).

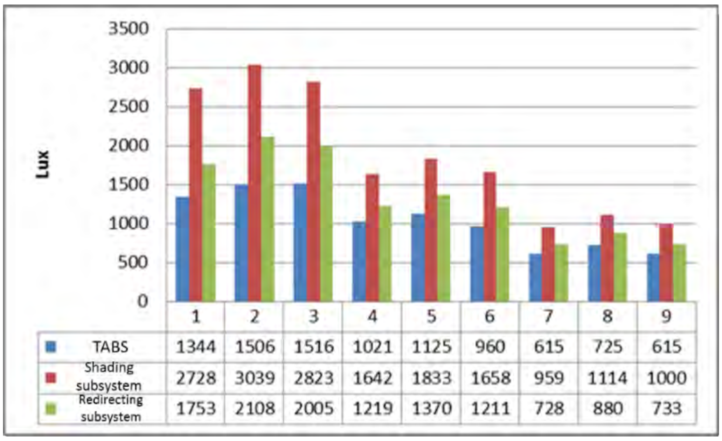


Figure 8.10 Task points Illuminance Sep. 21st at 12 pm

2. Illuminance distribution:

The results of the TABS show that (300 < 98.4 % of area < 3000 Lux) (day lit), (1.6 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, (300 < 78.2 % of area < 3000 Lux) (day lit), (21.8 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, (300 < 97.6 % of area < 3000 Lux) (day lit), (2.4 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria (see Figure 8.11 and Table 8.9).

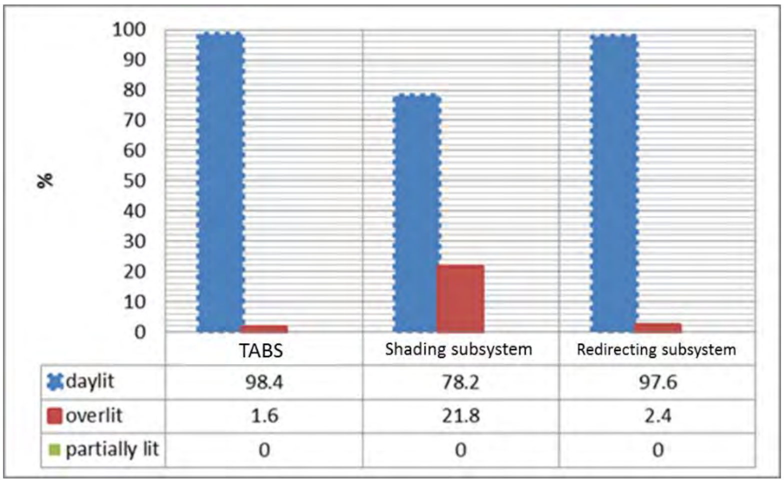
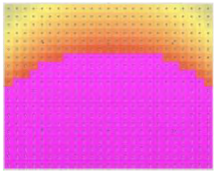
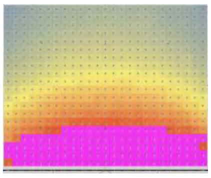
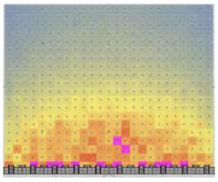
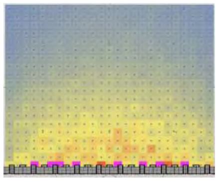


Figure 8.11 Base case daylight distribution (21st Sep at 12 pm)

Table 8.9 Daylight distribution in all cases (Sep. 21st at 12 pm).

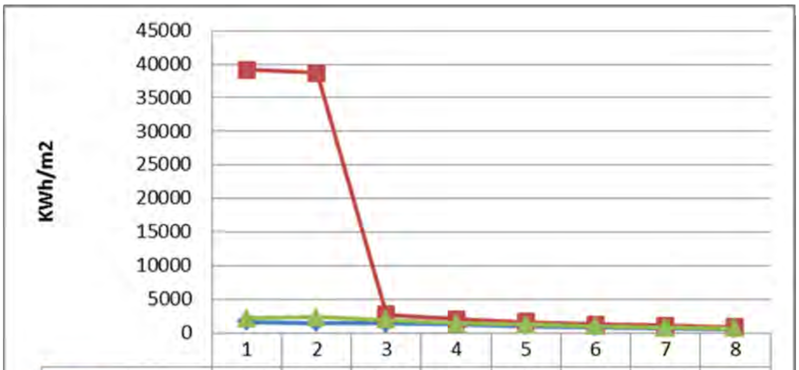
Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the TABS show that the highest illuminance value was 1646 Lux and the lowest value was 534 Lux, with a contrast ratio of 1:3, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, the highest illuminance value was 39219 Lux and the lowest value was 867 Lux, with a contrast ratio of 1:45, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, the highest illuminance value was 2342 Lux and the lowest value was 673 Lux, with a contrast ratio of 1:3.5, which failed in fulfilling the required criteria.

4. Daylight depth:

The results of the TABS show that 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, only 6 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 2 points received > 3000 Lux, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria (see Figure 8.12).



	1	2	3	4	5	6	7	8
TABS	1646	1486	1400	1271	970	837	702	534
Shading subsystem	39219	38741	2732	2060	1658	1261	1055	867
Redirecting subsystem	2148	2342	1952	1425	1219	973	800	673

Figure 8.12 Base case daylight depth (21st Sep at 12 pm)

5. Solar radiation:

The results of the TABS show that the 40 measuring nodes received 0 KWh/m^2 during 21st Sep. In the case of the TABS's shading subsystem, 66 KWh/m^2 received. Regarding TABS's redirecting subsystem, 0 KWh/m^2 received (see figure 8.13).

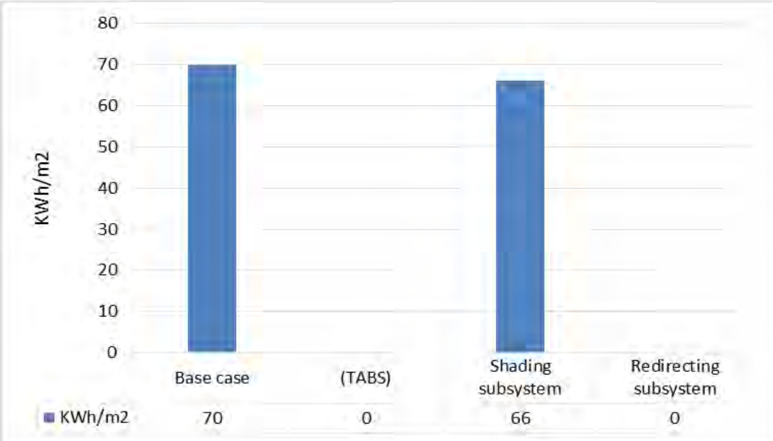
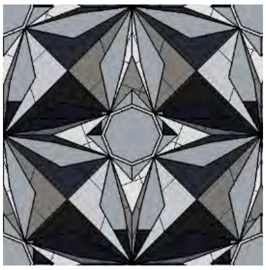
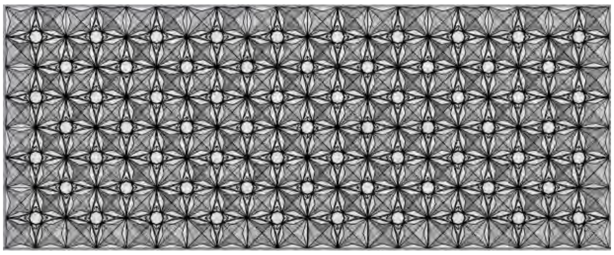


Figure 8.13 Solar radiation (21st Sep. at 12 pm) all cases

8.1.1.4.Case Eleven: 21st Dec. at 12 pm:

Table 8.10 TABS configuration of Dec. 21st at 12 pm

	Pattern	Section	Perspective
12 pm			

1. Task points illuminance:

The results of the TAB show that 100% of the task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, only seven tasks-plans nodes out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, only three tasks-plans nodes out of 9 measuring nodes received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria (see Figure 8.14).

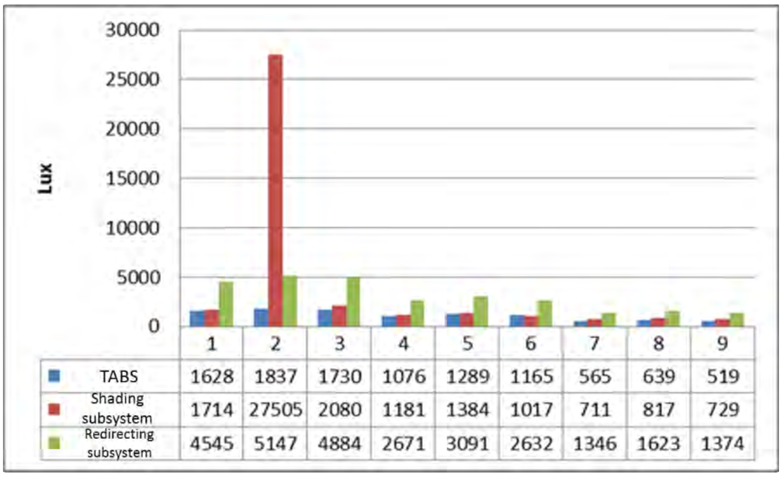


Figure 8.14 Task points Illuminance Dec. 21st at 9 am

2. Illuminance distribution:

The results of the TABS show that (300 < 98.8 % of area < 3000 Lux) (day lit), (1.2 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, (300 < 72.8 % of area < 3000 Lux) (day lit), (27.2 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, (300 < 53.2 % of area < 3000 Lux) (day lit), (46.8 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which failed in fulfilling the required criteria. (See Figure 8.15 and Table 8.11)

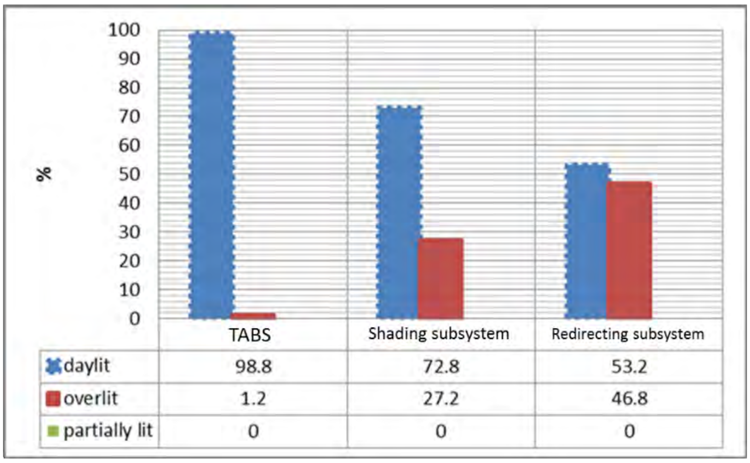
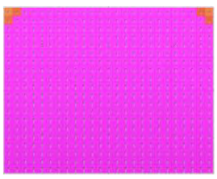
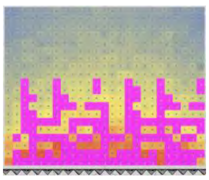
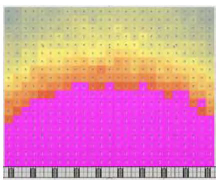
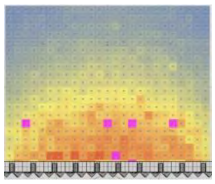


Figure 8.15 Daylight distribution (21st of Dec. at 12 pm)

Table 8.11 Daylight distribution in all cases (Dec. 21st at 12 pm).

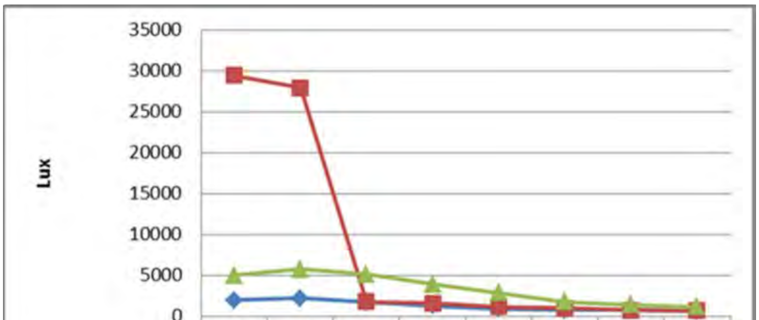
Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the TAB show that the highest illuminance value was 2163 Lux, and the lowest value was 519 Lux, with a contrast ratio of 1:4, which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, the highest illuminance value was 29439 Lux and the lowest value was 656 Lux, with a contrast ratio of 1:44, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, the highest illuminance value was 5727 Lux and the lowest value was 1168 Lux, with a contrast ratio of 1:5, however, it is failed in fulfilling the required criteria because the highest value is more than 3000 Lux.

4. Daylight depth:

The results of the TAB show that 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS's shading subsystem, only 6 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, 3 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria (see Figure 8.16).



	1	2	3	4	5	6	7	8
TABS	1921	2163	1672	1290	922	731	713	620
Shading subsystem	29439	27888	1738	1560	1172	985	727	656
Redirecting subsystem	4978	5727	5087	3916	2826	1764	1369	1168

Figure 8.16 Daylight depth (21st of Dec. at 12 pm)

5. Solar radiation:

The results of the TABS show that the 40 measuring nodes received 38 KWh/m^2 during 21st Dec. In the case of the TABS's shading subsystem, 40 KWh/m^2 received. Regarding TABS's redirecting subsystem, 39 KWh/m^2 was received. (See Figure 8.17).

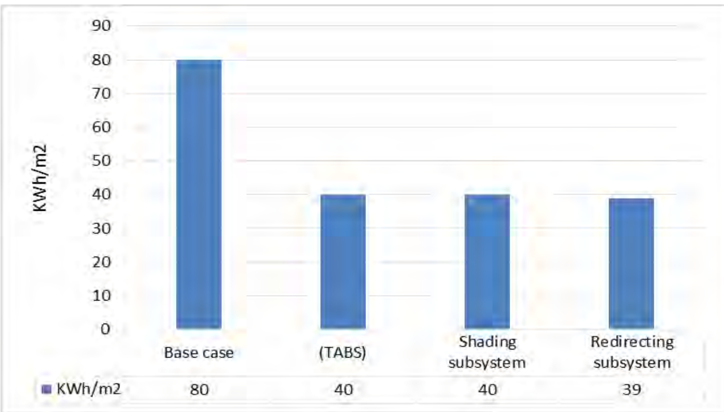


Figure 8.17 Solar radiation (21st of Dec. 12 pm) all cases

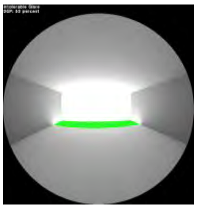
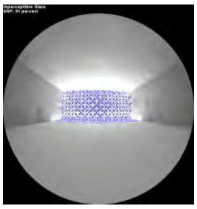
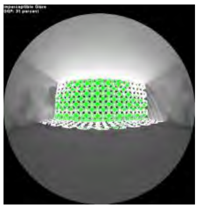
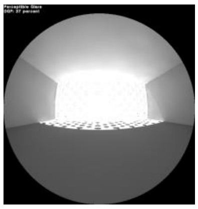
Second phase: Daylight Glare Probability (DGP).

A point-in-time glare simulation in DIVA carried out, and the visual comfort of a person in the centre of space under the simulated conditions at the camera viewpoint was examined. The results can be summarised as follows:

8.1.1.5.Case Two: 21st of March at 12 pm:

The results of the base case show that the examined point received an Intolerable glare 53%, which failed in fulfilling the required criteria. In the case of the TABS's shading subsystem, the tested point received an imperceptible glare 40%, which failed in fulfilling the required criteria. Regarding TABS's redirecting subsystem, the examined point received a perceptible glare 40%, which Failed in fulfilling the required criteria. In the case of the TABS, the measured point received an imperceptible glare 31% which succeeded in fulfilling the required criteria (see Table 8.12).

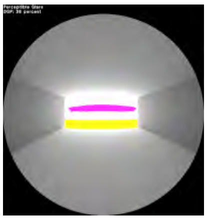
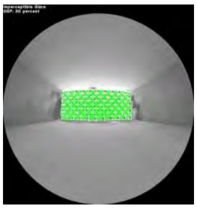
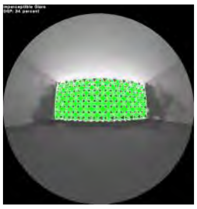
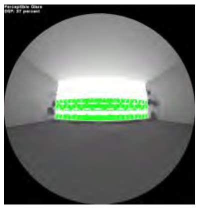
Table 8.12 Daylight Glare Probability (DGP) for each scenario on 21st March

Time	Base case	TABS	Shading subsystem	Redirecting subsystem
12 pm				
Glare Performance	Intolerable: 53%	Imperceptible: 31%	Imperceptible: 31%	Perceptible: 37%

8.1.1.6.Case Five: 21st of June at 12 pm:

The results of the base case show that the examined point received a perceptible glare 38%, which failed in fulfilling the required criteria. In the case of the TABS's shading subsystem, the measured point received a perceptible glare 35%, which failed in fulfilling the required criteria. Regarding TABS's redirecting subsystem, the examined point received an imperceptible glare 31%, which succeeded in fulfilling the required criteria. In the case of the fully optimised TABS system, the examined point received an imperceptible glare 30% which succeeded in fulfilling the required criteria (Table 8.13).

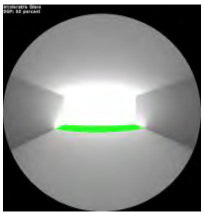
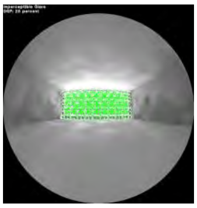
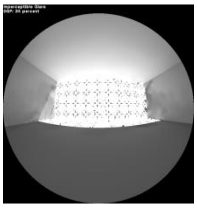
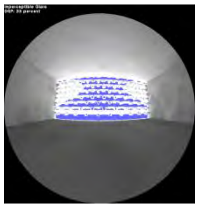
Table 8.13 Daylight Glare Probability (DGP) for each scenario on 21st June

Time	Base case	TABS	Shading subsystem	Redirecting subsystem
12 pm				
Glare Performance	Perceptible: 38%	Imperceptible: 30%	Imperceptible: 34%	Perceptible: 37%

8.1.1.7.Case Eight: 21st Sep at 12 pm:

The results of the base case show that the examined point received an Intolerable glare 52%, which failed in fulfilling the required criteria. In the case of the TABS's shading subsystem, the examined point received a perceptible glare 39%, which failed in fulfilling the required criteria. Regarding TABS's redirecting subsystem, the examined point received a perceptible glare 38%, which failed in fulfilling the required criteria. In the case of the fully optimised TABS system, the examined point received an imperceptible glare 25% which succeeded in fulfilling the required criteria (see Table 8.14).

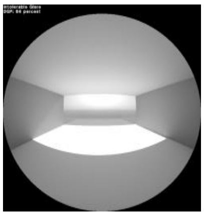
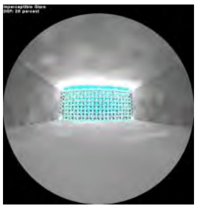
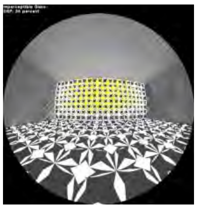
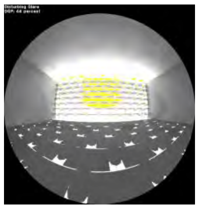
Table 8.14 Daylight Glare Probability (DGP) for each scenario on 21st of Sep.

Time	Base case	TABS	Shading subsystem	Redirecting subsystem
12 pm				
Glare Performance	Intolerable: 52%	Imperceptible: 25%	Imperceptible: 35%	Imperceptible: 33%

8.1.1.8.Case Eleven: 21st December at 12 pm:

The results of the base case show that the examined point received an intolerable glare 84%, which failed in fulfilling the required criteria. In the case of the TABS's shading subsystem, the examined point received an intolerable glare 46%, which failed in fulfilling the required criteria. In the case of TABS's redirecting subsystem, the examined point received an intolerable glare 55%, which failed in fulfilling the required criteria. In the case of the fully optimised TABS system, the examined point received an imperceptible glare 28% which succeeded in fulfilling the required criteria (see Table 8.15).

Table 8.15 Daylight Glare Probability (DGP) for each scenario on 21st Dec.

Time	Base case	TABS	Shading subsystem	Redirecting subsystem
12 pm				
Glare Performance	Intolerable: 84%	Imperceptible: 28%	Imperceptible: 35%	Disturbing: 44%

Third phase: Further analysis (Daylight penetration depth (3X)

The results showed that the TABS achieved daylight penetration depth (2X), with illuminance values ranging from (300 -3000 Lux) at all the examined times, which fulfil the criteria. However, the illuminance values received at the rear point (point no. 8) in all cases indicated that the system could achieve daylight penetration depth more than (2X (8 m)). Therefore, a further analysis was carried out to examine the possibility of achieving daylight penetration depth (3X (12 m)), using DIVA for Rhino (0.425 spacing grid (725 measuring nodes)). The results showed that all the optimised solutions of TABS for each time achieved daylight depth of 3X within the required illuminance range (300-3000 Lux).

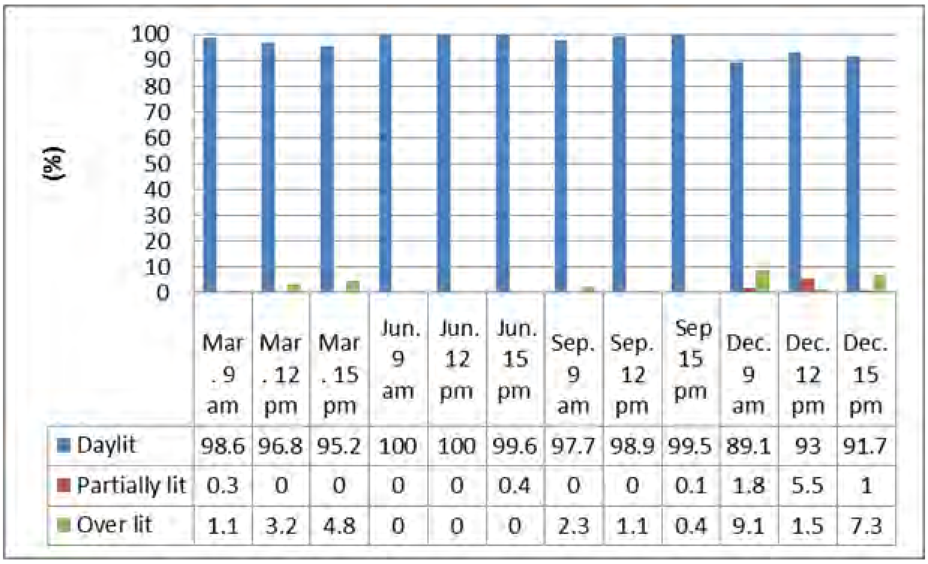
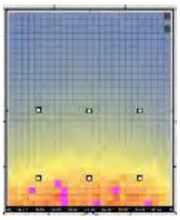
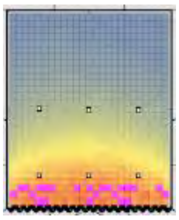
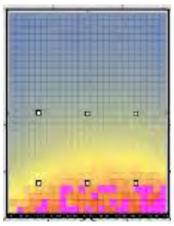
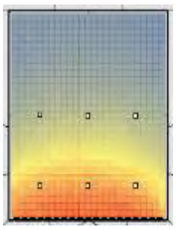
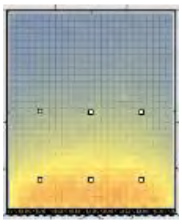
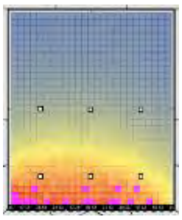
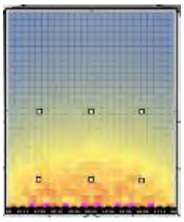
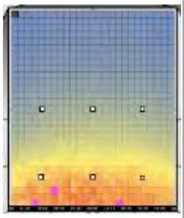
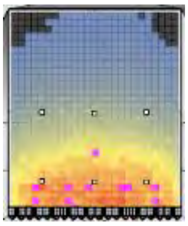
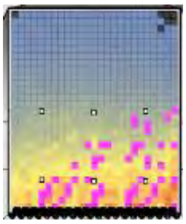


Figure 8.18 Daylight distribution at all tested times

Table 8.16 Daylight distribution at all tested times

March	June

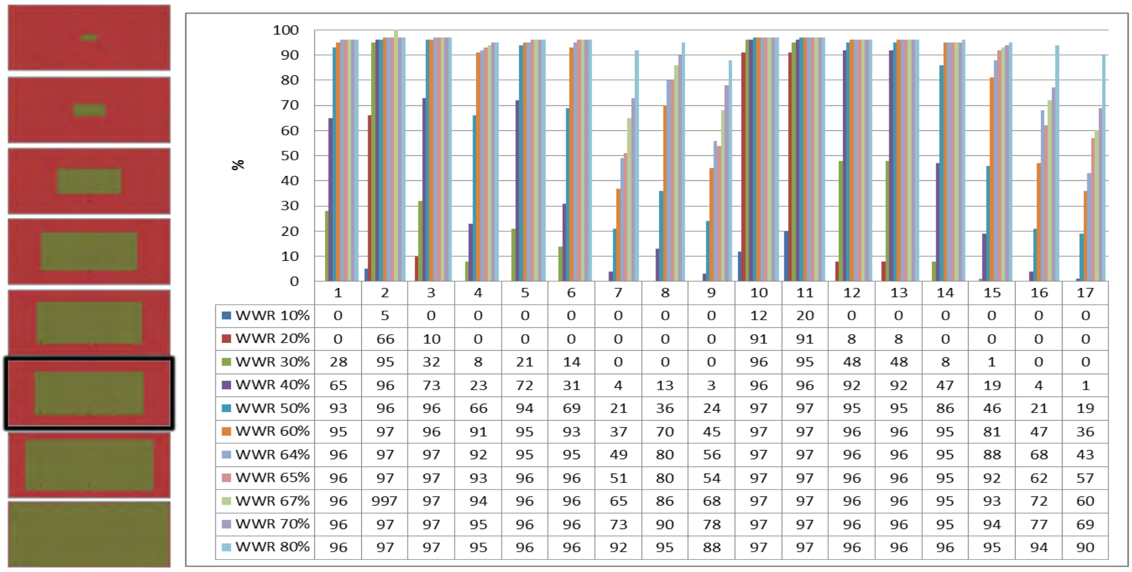
9 am	12 pm	15 pm	9 am	12 pm	15 pm
					
September			**December**		
9 am	**12 pm**	**15 pm**	**9 am**	**12 pm**	**15 pm**
					

8.2. Stage Two: Results of the Optimisation processes of Annually Optimised WWR (AOWWR), and Annually Optimised Static Building Envelope (AOSBE).

Annual optimisation of WWR (AOWWR)

8.2.1.1.Phase one

An optimisation of WWR (window to wall ratio) using the annual daylight autonomy (DA) metric was carried out. The results show that the optimum ratio is 67% for maintaining 500 Lux for at least 50% of the working hours for 17 points distributed inside the space, and minimum solar radiation (see Figure 8.19 and Figure 8.20).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
WWR 10%	0	5	0	0	0	0	0	0	0	12	20	0	0	0	0	0	0
WWR 20%	0	66	10	0	0	0	0	0	0	91	91	8	8	0	0	0	0
WWR 30%	28	95	32	8	21	14	0	0	0	96	95	48	48	8	1	0	0
WWR 40%	65	96	73	23	72	31	4	13	3	96	96	92	92	47	19	4	1
WWR 50%	93	96	96	66	94	69	21	36	24	97	97	95	95	86	46	21	19
WWR 60%	95	97	96	91	95	93	37	70	45	97	97	96	96	95	81	47	36
WWR 64%	96	97	97	92	95	95	49	80	56	97	97	96	96	95	88	68	43
WWR 65%	96	97	97	93	96	96	51	80	54	97	97	96	96	95	92	62	57
WWR 67%	96	997	97	94	96	96	65	86	68	97	97	96	96	95	93	72	60
WWR 70%	96	97	97	95	96	96	73	90	78	97	97	96	96	95	94	77	69
WWR 80%	96	97	97	95	96	96	92	95	88	97	97	96	96	96	95	94	90

Figure 8.19 Annual daylight autonomy (DA) performance of the examined WWR

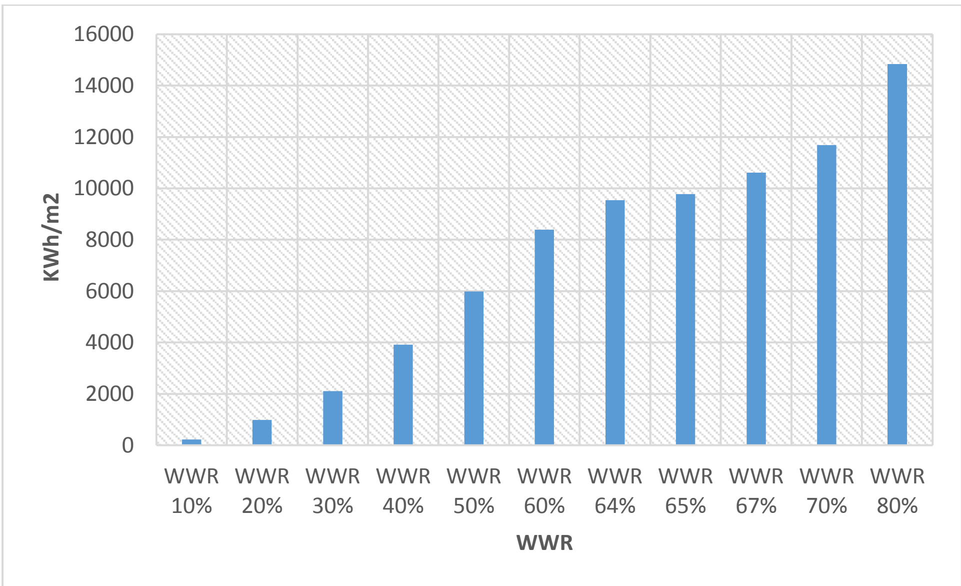


Figure 8.20 Annual solar radiation for all the examined WWR

8.2.1.2.Phase Two

The Daylight Glare Probability (DGP) metric was used in the comfort evaluation. The process can be summarised as follows:

An annual glare simulation was undertaken for the WWR (window to wall ratio) and Base case with hourly calculations of a point in the middle of space at height 1.3m (sitting position and looking towards the window). The results are shown in Figure 8.21 and Figure 8.22.

Figure 8.21 Temporal maps of annual glare throughout the day for the base case without shading

Figure 8.22 Temporal maps of annual glare throughout the day for the (AOWWR)

Annually optimised static building envelope (AOSBE)

8.2.1.3.Phase One

An optimisation of the annual static building envelope (AOSBE) using the daylight autonomy (DA) metric was carried out (DIVA for Grasshopper). Moreover, Spatial daylight autonomy (sDA) and (ASE) with Minimum Threshold 300 Lux 50% of the annual occupancy hours and maximum 10% of the area receiving direct daylight for more than 250 hours per year to examine the capability of the selected solution to fulfil the LEED requirements (using DIVA for Rhino). The results of the optimum design parameters of (AOSBE) for maintaining 500 Lux for at least 50% of the working hours for 17 points distributed in the space, with minimum solar radiation gain are described below (See Table 8.33, Figure 8.55, Figure 8.56, and Figure 8.56). Moreover, the results of the Spatial daylight autonomy (sDA) and (ASE) of the optimised AOSBE showed that 88.8% of space has a sDA 300lux value for more than 50 %of occupied hours and 7% of space has an ASE greater than 250 hours (this space qualifies for 3 LEED points).

Table 8.17 The design parameters of an annually optimised static building envelope (AOSBE)

Parameters														
ESP (m)	EMP (m)	ORSP1 (%)	MMPOR (%)	ORSP2 (%)	BPOR (%)	UROR (%)	LLOR (%)	OD (m)	MOR (m)	SOR (m)	HLD (m)	HLIA (°)	VLD (m) (Fix.)	VLIA (°) (Fix.)
0.025	0.15	0.8	0.5	0.6	0.4	0.047	0.086	0.01	0.15	0.18	0.25	30	0.1	0

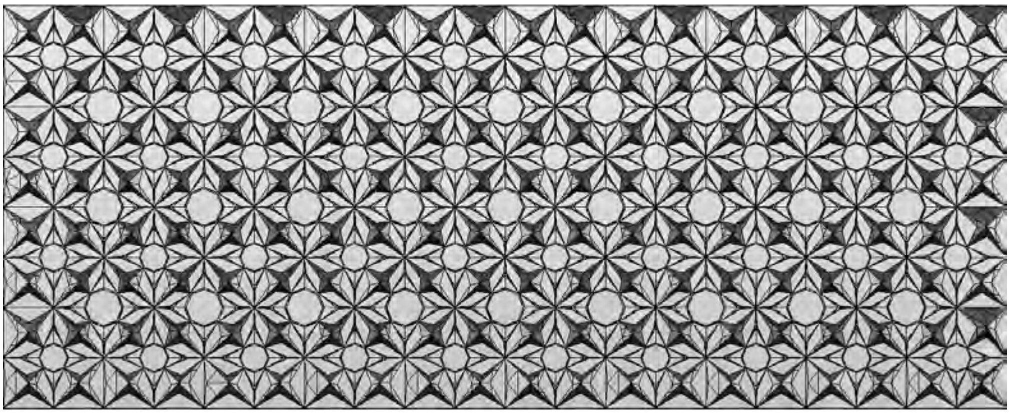


Figure 8.23 The final optimised design of an Annually optimised static building envelope (AOSBE)

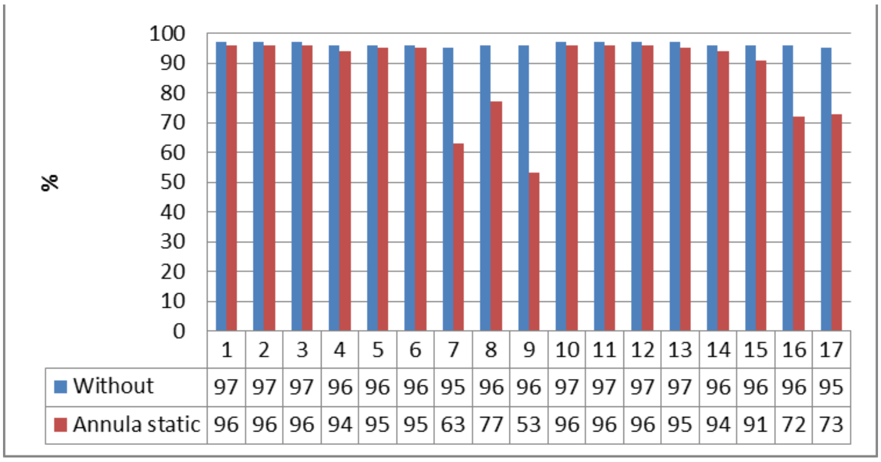


Figure 8.24 Annual daylight autonomy, performance of the Annually optimised static building envelope (AOSBE)

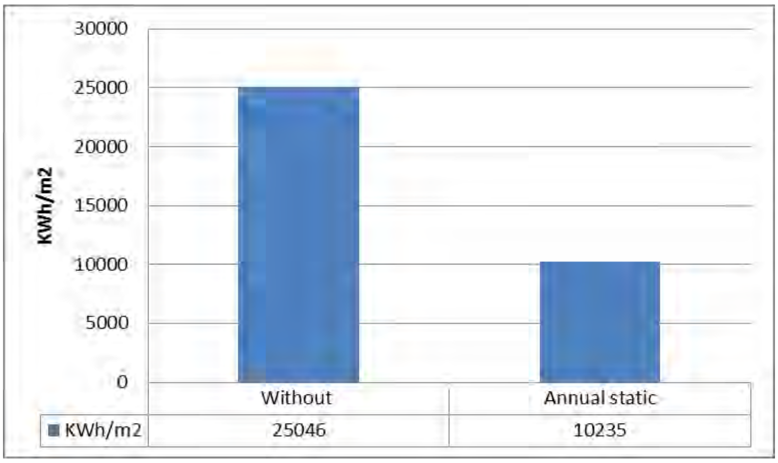


Figure 8.25 Annual solar radiation with and without the Annually optimised static building envelope (AOSBE)

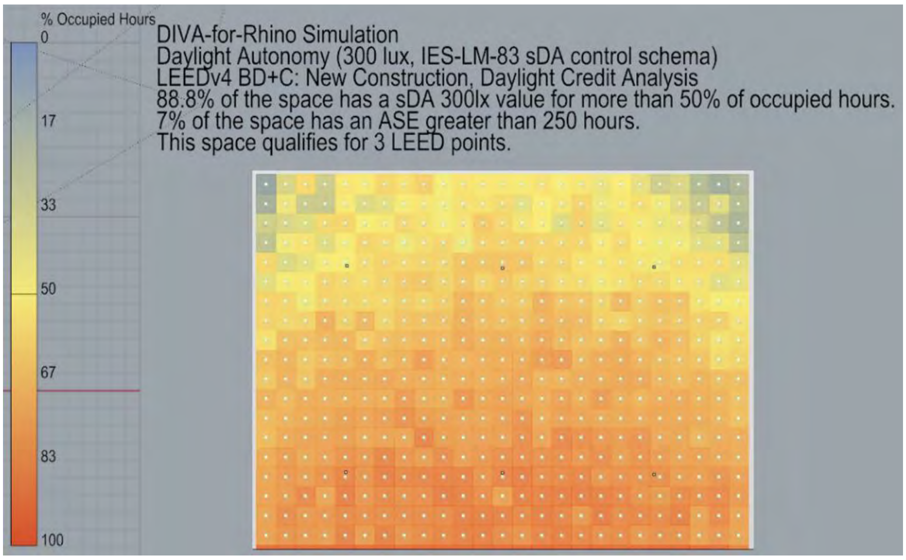


Figure 8.26 Spatial daylight autonomy (sDA) and (ASE) analysis of (AOSBE)

8.2.1.4.Phase Two

The Daylight Glare Probability (DGP) metric is used. The process can be summarised as follows: an annual glare simulation done for the Annually optimised static building envelope (AOSBE), and Base case with the hourly calculation of a point in the middle of space at height 1.3m (sitting position and looking towards the window).

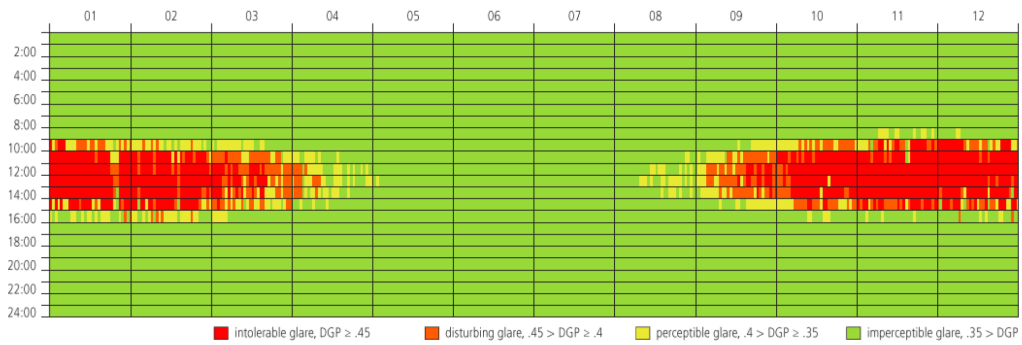


Figure 8.27 Temporal maps of annual glare throughout the day for the base case without shading

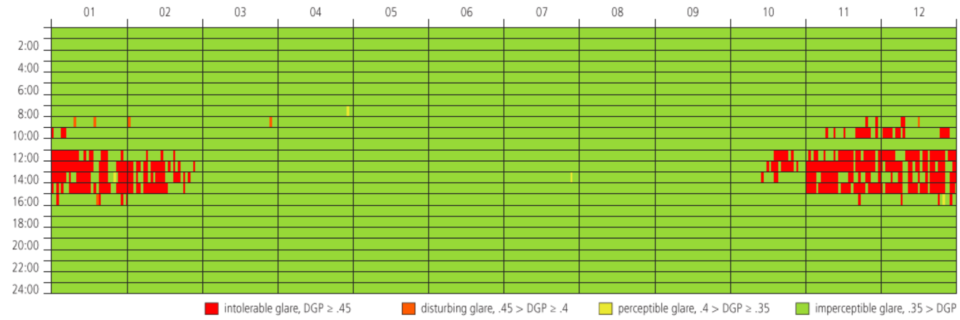


Figure 8.28 Temporal maps of annual glare throughout the day for the Annually optimised static building envelope (AOSBE).

8.3. Stage Three: the results of the performance-based comparison of different systems:

This section represents the simulation results of the base case, AOWWR, AOSBE, and TABS at the twelve examined times during the year. This represents the four seasons (at 9.00 am, 12.00 pm and 3.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice) in two phases:

First phase: discuss Task point's illuminance, Illuminance distribution, Illuminance a contrast ratio of, Daylight depth and solar radiation.

Second phase: discuss Glare Probability (DGP).

All results summarised as follows:

First phase:

8.3.1.1.Case Two: 21st of March at 12 pm:

1. Task points illuminance:

The results of the base case showed that 66.66% of the task points (only six points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 33.33% received > 2000 Lux, which failed in fulfilling the required criteria. In the case of the (AOWWR), 88.88% of the Task points (only eight points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 11.11% received > 2000 Lux, which failed in fulfilling the required criteria. In the case of the (AOSBE), 100 % of the Task points (9 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS, 100% of the Task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria (Figure 8.29).

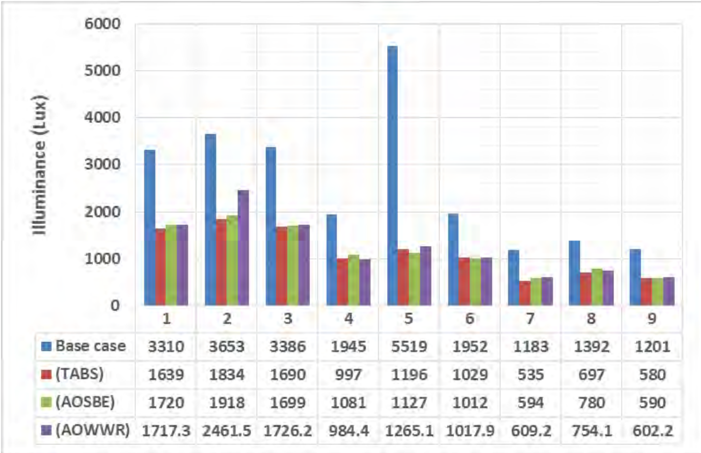


Figure 8.29 Taskplans Illuminance March 21st at 12 pm

2. Illuminance distribution:

The results of all the base case showed that (300 < 33.2 % of area < 3000 Lux) (day lit), (66.8 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of the (AOWWR) (300 < 84.6 % of area < 3000 Lux) (day lit), (15.4 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the (AOSBE) (300 < 90.2 % of area < 3000 Lux) (day lit), (9.8 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS (300 < 89.4 % of area < 3000 Lux) (day lit), (10.6 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria (Figure 8.30 and Table 8.18).

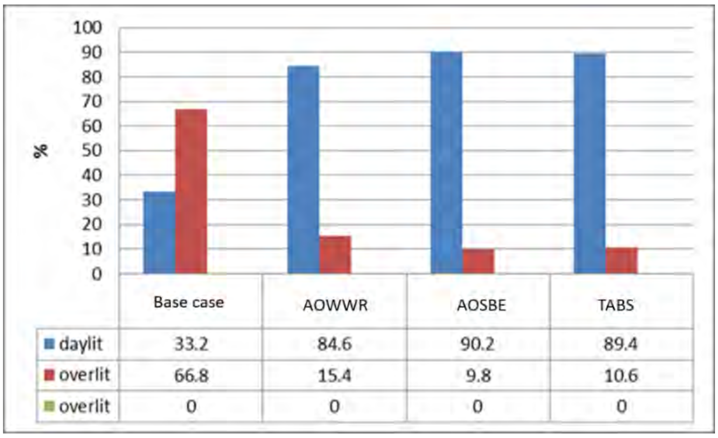
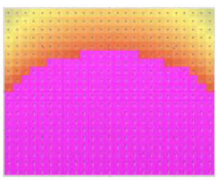
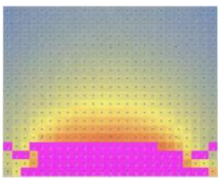
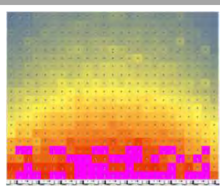
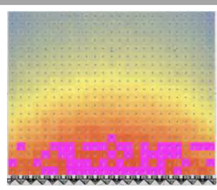
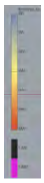


Figure 8.30 Base case daylight distribution (March 21st at 12 pm)

Table 8.18 Daylight distribution in all cases (March 21st at 12 pm).

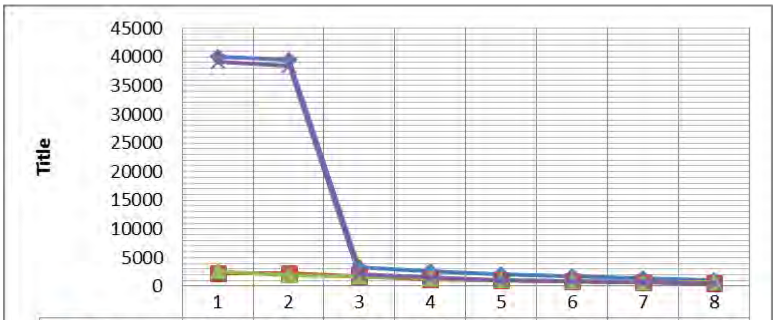
Time	Base case	(AOWWR)	(AOSBE)	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the base case show that the highest illuminance value was 40024 Lux, and the lowest value was 1039 Lux (out of 17 points distributed in the space), with a contrast ratio of 1: 38, which failed in fulfilling the required criteria. In the case of the (AOWWR), the highest illuminance value was 39105.3 Lux and the lowest value was 577.4 Lux, with a contrast ratio of 1:70, which failed in fulfilling the required criteria. In the case of the (AOSBE), the highest illuminance value was 2653 Lux and the lowest value was 590 Lux, with a contrast ratio of 1:4.5, which succeeded in fulfilling the required criteria. In the case of the TABS, the highest illuminance value was 2269 Lux and the lowest value was 485 Lux, with a contrast ratio of 1:4.7, which succeeded in fulfilling the required criteria.

4. Daylight depth:

The results of the base case showed that only five points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 3 points received > 3000 Lux, which failed in fulfilling the required criteria. In the case of the (AOWWR), only six points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 2 points received > 3000 Lux, which failed in fulfilling the required criteria. In the case of the (AOSBE) 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria (Figure 8.31).



	1	2	3	4	5	6	7	8
Base case	40024	39513	3334	2579	2077	1670	1353	1039
(TABS)	2269	2209	1687	1293	1030	845	688	485
(AOSBE)	2653	1962	1741	1367	1051	860	638	679
(AOWWR)	39105.3	38415.3	2057.8	1513.3	1120.4	865.2	664.1	577.4

Figure 8.31 Base case daylight depth (21st of March at 12 pm)

5. Solar radiation:

The results of the fully glazed base case showed that the 40 measuring nodes received 83 KWh/m^2 during 21st March. In the case of the (AOWWR), 43 KWh/m^2 was received. In the case of the (AOSBE), 43 KWh/m^2 was received. In the case of the TABS 40 KWh/m^2 was received (Figure 8.32).

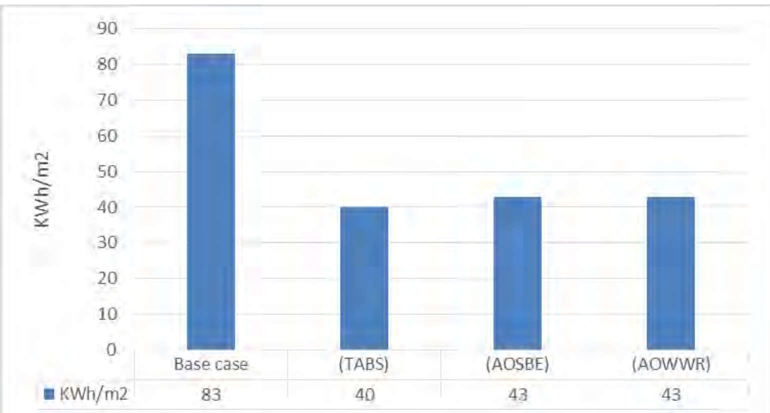


Figure 8.32 solar radiation (21st of March at 12 pm) all cases

8.3.1.2.Case Five: 21st of June at 12 pm:

1. Task points illuminance:

The results of the base case showed that 66.66% of the task points (6 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of the (AOWWR), 88.88 % of the Task points (only 8 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of the (AOSBE), 77.77% of the Task points (only 7 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 22.22% received < 500 Lux, which failed in fulfilling the required criteria. In the case of the TABS, 100% of the Task points (9 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria (see Figure 8.33).

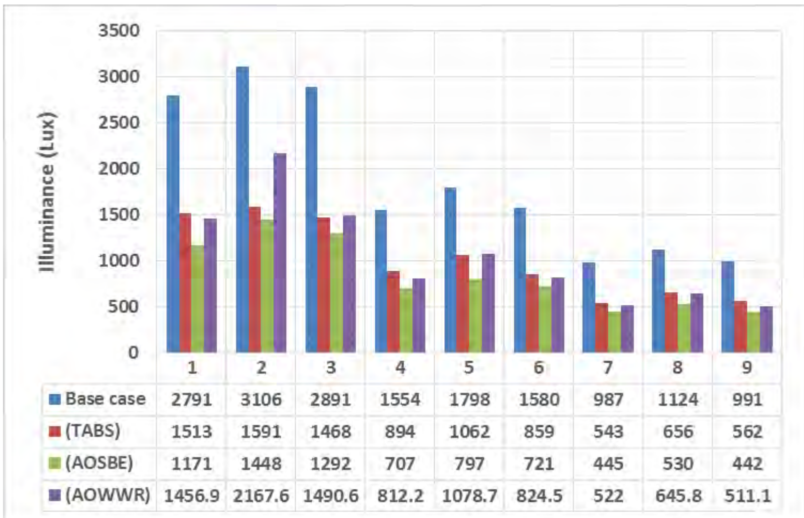


Figure 8.33 Task points Illuminance June 21st at 12 pm

2. Illuminance distribution:

The results of the base case showed that (300 < 74.6 % of area < 3000 Lux) (day lit), (25.4 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of the (AOWWR) (300 < 90.8 % of area < 3000 Lux) (day lit), (9.2 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the (AOSBE) (300 < 99 % of area < 3000 Lux) (day lit), (0 % of area >3000 Lux) (over lit) and (1% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS (300 < 100 % of area < 3000 Lux) (day lit), (0 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria (see Figure 8.34 and Table 8.19).

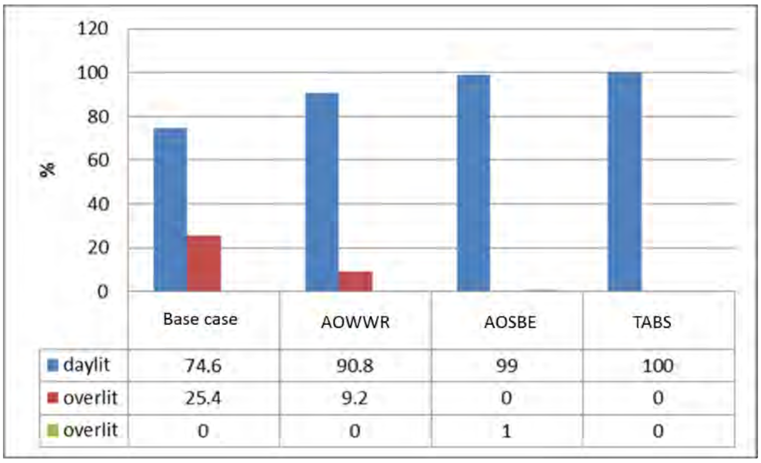
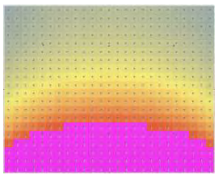
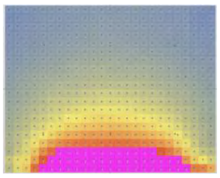
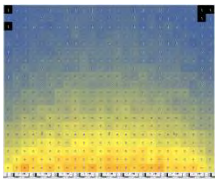
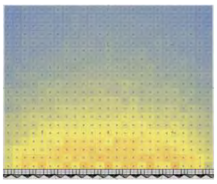


Figure 8.34 Base case daylight distribution (June 21st at 12 pm)

Table 8.19 Daylight distribution in all cases (June 21st at 12 pm).

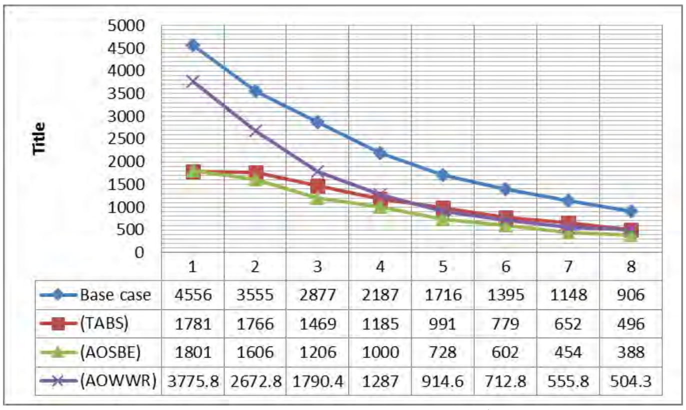
Time	Base case	(AOWWR)	(AOSBE)	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the base case showed that the highest illuminance value was 4556 Lux and the lowest value was 906 Lux, with a contrast ratio of 1: 5, which failed in fulfilling the required criteria because the highest value is higher than the accepted value (3000 Lux). In the case of the (AOWWR), the highest illuminance value was 3775.8 Lux and the lowest value was 504.3 Lux, with a contrast ratio of 1:7, which failed in fulfilling the required criteria. In the case of the (AOSBE), the highest illuminance value was 1801 Lux and the lowest value was 388 Lux, with a contrast ratio of 1:4.6, which succeeded in fulfilling the required criteria. In the case of the TABS, the highest illuminance value was 1781 Lux and the lowest value was 496 Lux, with a contrast ratio of 1:3.5, which succeeded in fulfilling the required criteria.

4. Daylight depth:

The results of the base case showed that 6 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) which failed in fulfilling the required criteria. In the case of the (AOWWR) only 7 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria. In the case of the (AOSBE) 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria (see Figure 8.35).



	1	2	3	4	5	6	7	8
Base case	4556	3555	2877	2187	1716	1395	1148	906
(TABS)	1781	1766	1469	1185	991	779	652	496
(AOSBE)	1801	1606	1206	1000	728	602	454	388
(AOWWR)	3775.8	2672.8	1790.4	1287	914.6	712.8	555.8	504.3

Figure 8.35 Base case daylight depth (21st of June at 12 pm)

5. Solar radiation:

The results of the base case showed that the 40 measuring nodes received 40 KWh/m^2 during 21st June. In the case of the (AOWWR), 12 KWh/m^2 was received. In the case of the (AOSBE), 20 KWh/m^2 was received. In the case of the TABS 20 KWh/m^2 was received (see Figure 8.36).

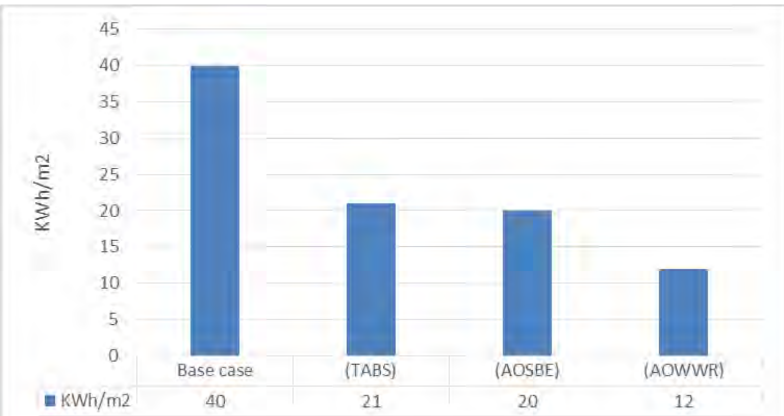
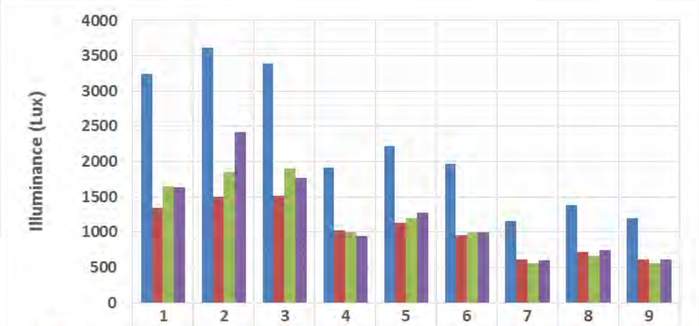


Figure 8.36 solar radiation (21st of June at 12 pm) all cases

8.3.1.3.Case Eight: 21st of Sep. at 12 pm:

1. Task points illuminance:

The results of the base case showed that 55.55 % of the task points (5 points out of 9 measuring nodes) received (500 < Illuminance < 2000 lux), which failed in fulfilling the required criteria. In the case of the (AOWWR), 88.88% of the task points (only 8 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of the (AOSBE), 100 % of the task points (9 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which succeeded in fulfilling the required criteria. In the case of the TABS, 100% of the task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria (see Figure 8.37).



	1	2	3	4	5	6	7	8	9
Base case	3243	3619	3394	1920	2225	1973	1163	1380	1193
(TABS)	1344	1506	1516	1021	1125	960	615	725	615
(AOSBE)	1649	1853	1896	998	1194	1003	555	660	555
(AOWWR)	1632.7	2417.7	1768.4	951	1277.3	996.8	593.4	739.9	612.1

Figure 8.37 Task points Illuminance Sep. 21st at 12 pm

2. Illuminance distribution:

The results of the base case showed that (300 < 35.6 % of area < 3000 Lux) (day lit), (64.4 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of the (AOWWR) (300 < 98.8 % of area < 3000 Lux) (day lit), (1 % of area >3000 Lux) (over lit) and (0.2% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the (AOSBE) (300 < 89.4 % of area < 3000 Lux) (day lit), (10.6 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS (300 < 98.4 % of area < 3000 Lux) (day lit), (1.6 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria (see Figure 8.38 and Table 8.20).

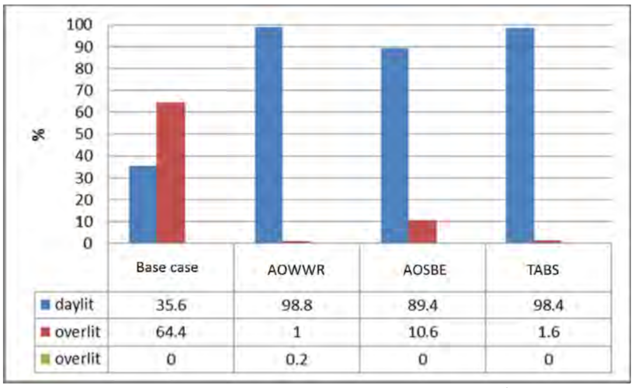
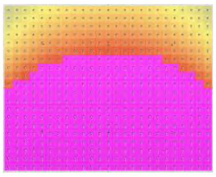
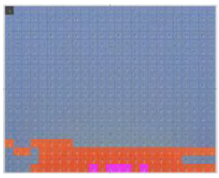
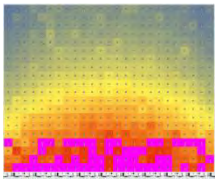
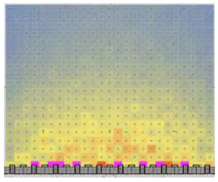
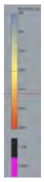


Figure 8.38 Base case daylight distribution (21st of Sep at 12 pm)

Table 8.20 Daylight distribution in all cases (Sep. 21st at 12 pm).

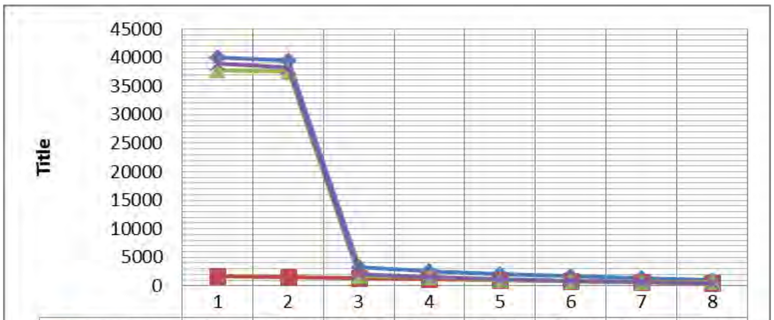
Time	Base case	(AOWWR)	(AOSBE)	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the fully glazed base case showed that the highest illuminance value was 39965 Lux, and the lowest value was 1034 Lux (out of 17 points distributed in the space), with a contrast ratio of 1: 38, which succeeded in fulfilling the required criteria. In the case of the (AOWWR), the highest illuminance value was 39035.7 Lux and the lowest value was 561.5 Lux, with a contrast ratio of 1:69, which failed in fulfilling the required criteria. In the case of the (AOSBE), the highest illuminance value was 37816 Lux and the lowest value was 555 Lux, with a contrast ratio of 1:68, which failed in fulfilling the required criteria. In the case of the TABS, the highest illuminance value was 1646 Lux and the lowest value was 534 Lux, with a contrast ratio of 1:3, which succeeded in fulfilling the required criteria.

4. Daylight depth:

The results of the fully glazed base case show that 5 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) which failed in fulfilling the required criteria. In the case of the (AOWWR), only six points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 2 points received > 3000 Lux, which failed in fulfilling the required criteria. In the case of the (AOSBE) 6 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria. In the case of the TABS, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria (see Figure 8.39).



	1	2	3	4	5	6	7	8
Base case	39965	39451	3301	2588	2052	1658	1334	1034
(TABS)	1646	1536	1400	1271	970	837	702	534
(AOSBE)	37816	37565	1761	1475	1002	774	663	594
(AOWWR)	39035.7	38316.4	2033.3	1485.6	1106.3	836.5	655.3	561.5

Figure 8.39 Base case daylight depth (21st Sep at 12 pm)

5. Solar radiation:

The results of the fully glazed base case showed that the 40 measuring nodes received 70 KWh/m^2 during 21st Sep. In the case of the (AOWWR), 40 KWh/m^2 was received. In the case of the (AOSBE), 40 KWh/m^2 was received. In the case of the TABS 0 KWh/m^2 was received (see Figure 8.40).

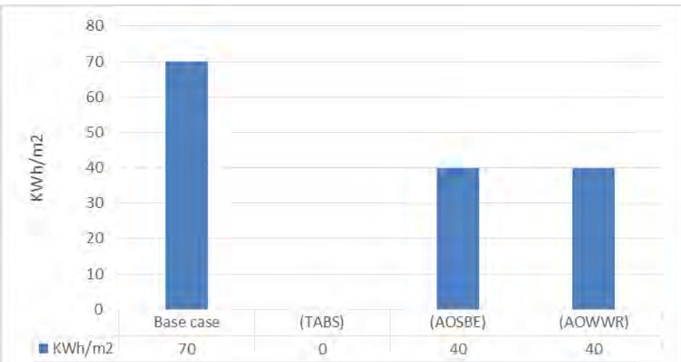


Figure 8.40 solar radiation (21st Sep. at 12 pm) all cases

8.3.1.4.Case Eleven: 21st of Dec. at 12 pm:

1. Task-Plan illuminance:

The results of the base case showed that 22.22 % of the task points (2 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux), which failed in fulfilling the required criteria. In the case of the (AOWWR), 66.66% of the Task points (only 6 points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 33.33 % received > 2000 Lux, which failed in fulfilling the required criteria. In the case of the (AOSBE), 66.66% of the Task points (only six points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 33.33% received > 2000 Lux, which failed in fulfilling the required criteria. In the case of the TABS, 100% of the Task points (nine points out of 9 measuring nodes) received (500 < Illuminance < 2000 Lux) and 0 % received > 2000 Lux, which succeeded in fulfilling the required criteria (see Figure 8.41).

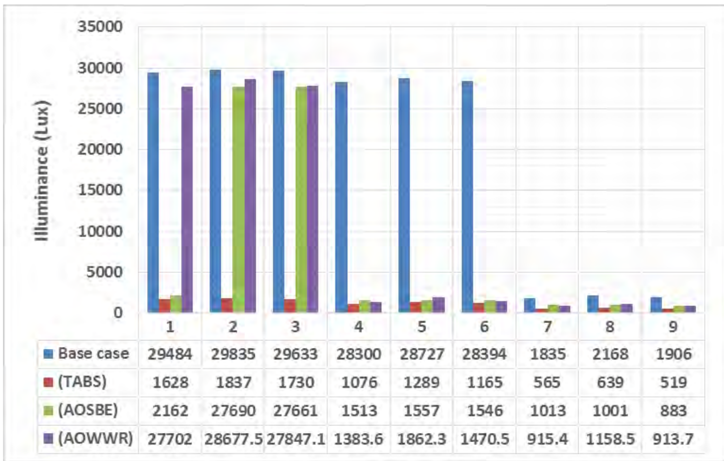


Figure 8.41 Task points Illuminance Dec. 21st at 12 am

2. Illuminance distribution:

The results the base case showed that (300 < 1.2 % of area < 3000 Lux) (day lit), (98.8 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which failed in fulfilling the required criteria. In the case of the (AOWWR) (300 < 67.8 % of area < 3000 Lux) (day lit), (32.2 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the (AOSBE), (300 < 43.6 % of area < 3000 Lux) (day lit), (56.4 % of area >3000 Lux) (over lit) and (0 % < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria. In the case of the TABS, (300 < 98.8 % of area < 3000 Lux) (day lit), (1.2 % of area >3000 Lux) (over lit) and (0% < 300 Lux) (partially lit) which succeeded in fulfilling the required criteria (see Figure 8.42 and Table 8.21).

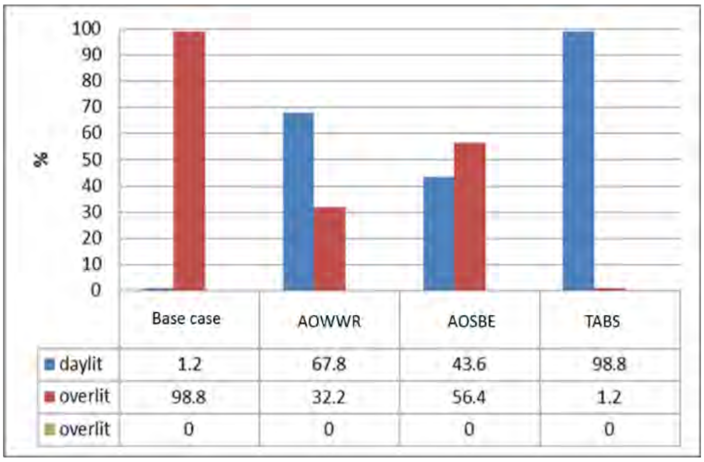
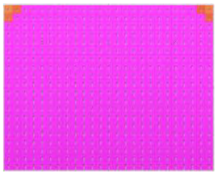
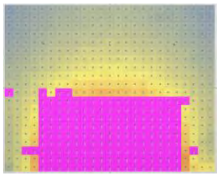
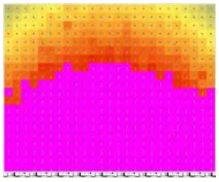
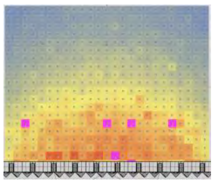
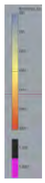


Figure 8.42 Base case daylight distribution (21st Dec. at 12 pm)

Table 8.21 Daylight distribution in all cases (Dec. 21st at 12 pm).

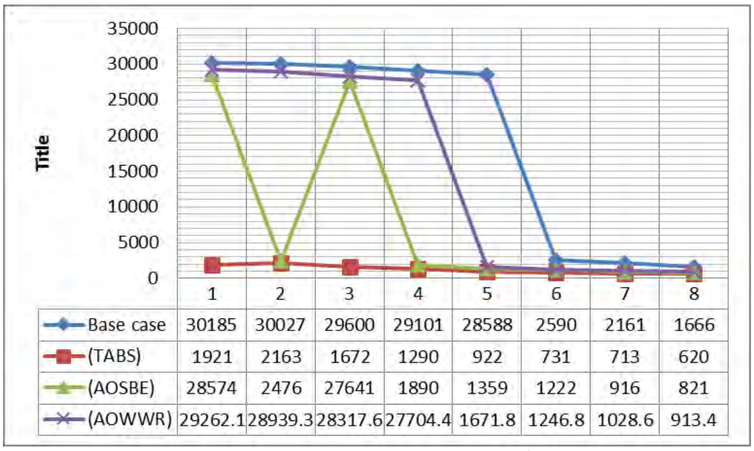
Time	Base case	(AOWWR)	(AOSBE)	TABS	
12 pm					

3. Illuminance contrast ratio:

The results of the base case show that the highest illuminance value was 30185 Lux, and the lowest value was 1666 Lux, with a contrast ratio of 1: 18, which failed in fulfilling the required criteria. In the case of the (AOWWR), the highest illuminance value was 29262.1 Lux and the lowest value was 913.4 Lux, with a contrast ratio of 1:32, which failed in fulfilling the required criteria. In the case of the (AOSBE), the highest illuminance value was 28574 Lux and the lowest value was 821 Lux, with a contrast ratio of 1:34, which failed in fulfilling the required criteria. In the case of the TABS, the highest illuminance value was 2163 Lux and the lowest value was 519 Lux, with a contrast ratio of 1:4, which succeeded in fulfilling the required criteria.

4. Daylight depth:

The results of the base case showed that 3 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) which failed in fulfilling the required criteria. In the case of the (AOWWR) only 4 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux) and 4 points received > 3000 Lux, which failed in fulfilling the required criteria. In the case of the (AOSBE) 6 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which failed in fulfilling the required criteria. In the case of the TABS, 8 points out of 8 measuring nodes received acceptable illuminance values (300 < Illuminance < 3000 Lux), which succeeded in fulfilling the required criteria (see Figure 8.43).



	1	2	3	4	5	6	7	8
Base case	30185	30027	29600	29101	28588	2590	2161	1666
(TABS)	1921	2163	1672	1290	922	731	713	620
(AOSBE)	28574	2476	27641	1890	1359	1222	916	821
(AOWWR)	29262.1	28939.3	28317.6	27704.4	1671.8	1246.8	1028.6	913.4

Figure 8.43 Base case daylight depth (21st of Dec. at 12 pm)

5. Solar radiation:

The results of the fully glazed base case showed that the 40 measuring nodes received 80 KWh/m^2 during 21st Dec. In the case of the (AOWWR), 38 KWh/m^2 was received. In the case of the (AOSBE), 40 KWh/m^2 was received. In the case of the TABS, 40 KWh/m^2 was received (see Figure 8.44).

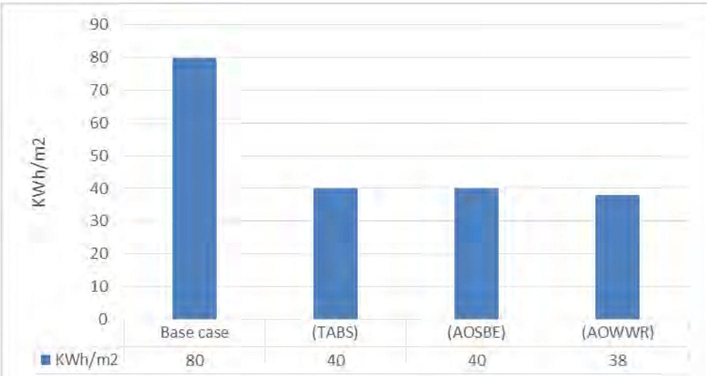


Figure 8.44 Solar radiation (21st Dec. at 12 pm) all cases

Second phase: Glare Probability (DGP).

The Daylight Glare Probability (DGP) metric considers the overall brightness of the view, the position of 'glare' sources and visual contrast.

DIVA for Rhino uses Evalglare to calculate the Daylight Glare Probability (DGP) from a luminance image according to the total vertical eye illuminance and contrast.

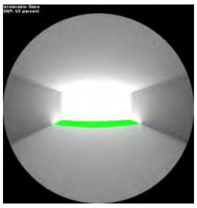
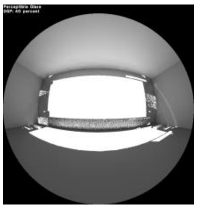
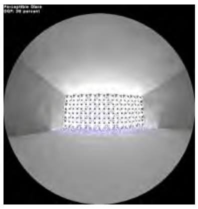
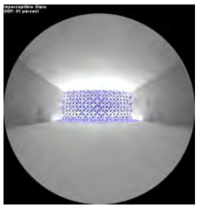
The process can be summarised as follows:

- Point in time Glare probability from a point in the middle of space at height 1.3m (sitting position and looking towards the window) at 12 pm.

8.3.1.5.Case Two: 21st of March at 12 pm:

The results of the base case showed that the examined point received an intolerable glare of 53%, which failed in fulfilling the required criteria. In the case of the (AOWWR), the examined point received an imperceptible glare of 40%, which failed in fulfilling the required criteria. In the case of the (AOSBE), the examined point received a perceptible glare of 40%, which Failed in fulfilling the required criteria. In the case of the TABS, the examined point received an imperceptible glare of 31%, which succeeded in fulfilling the required criteria (see Table 8.22).

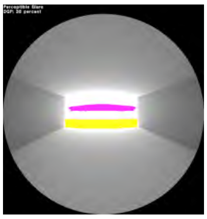
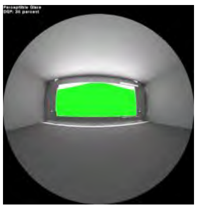
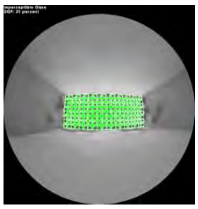
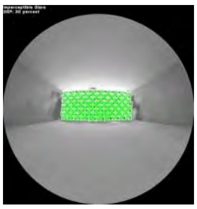
Table 8.22 Daylight Glare Probability (DGP) for each scenario on 21st March

Time	Base case	(AOWWR)	(AOSBE)	TABS
12 pm				
Glare Performance	Intolerable: 53%	Perceptible: 40%	Perceptible: 39%	Imperceptible: 31%

8.3.1.6.Case Five: 21st of June at 12 pm:

The results of the base case showed that the examined point received a perceptible glare of 38%, which failed in fulfilling the required criteria. In the case of the (AOWWR), the examined point received a perceptible glare of 35%, which failed in fulfilling the required criteria. In the case of the (AOSBE), the examined point received an imperceptible glare of 31%, which succeeded in fulfilling the required criteria. In the case of the TABS, the examined point received an imperceptible glare of 30%, which succeeded in fulfilling the required criteria (see Table 8.23).

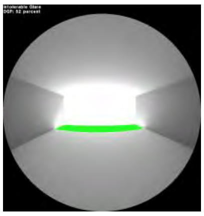
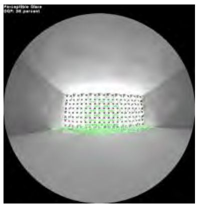
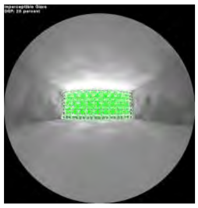
Table 8.23 Daylight Glare Probability (DGP) for each scenario on 21st of June

Time	Base case	(AOWWR)	(AOSBE)	TABS
12 pm				
Glare Performance	Perceptible: 38%	Perceptible: 35%	Imperceptible: 31%	Imperceptible: 30%

8.3.1.7.Case Eight: 21st of Sep at 12 pm:

The results of the base case showed that the examined point received an Intolerable glare of 52%, which failed in fulfilling the required criteria. In the case of the (AOWWR), the examined point received a perceptible glare of 39%, which failed in fulfilling the required criteria. In the case of the (AOSBE), the examined point received a perceptible glare of 38%, which failed in fulfilling the required criteria. In the case of the TABS, the examined point received an imperceptible glare of 25%, which succeeded in fulfilling the required criteria (see Table 8.24).

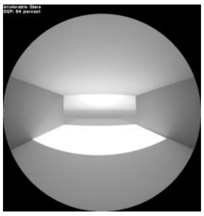
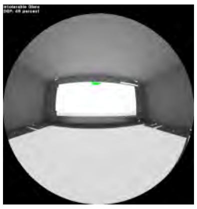
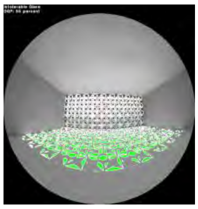
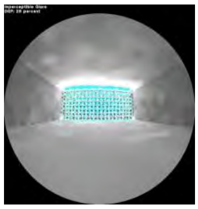
Table 8.24 Daylight Glare Probability (DGP) for each scenario on 21st of Sep.

Time	Base case	(AOWWR)	(AOSBE)	TABS
12 pm				
Glare Performance	**Intolerable: 52%**	**Perceptible: 39%**	**Perceptible: 38%**	**Imperceptible: 25%**

8.3.1.8.Case Eleven: 21st of December at 12 pm:

The results of the base case showed that the examined point received an intolerable glare of 84%, which failed in fulfilling the required criteria. In the case of the (AOWWR), the examined point received an intolerable glare of 46%, which failed in fulfilling the required criteria. In the case of the (AOSBE), the examined point received an intolerable glare of 55%, which failed in fulfilling the required criteria. In the case of the TABS, the examined point received an imperceptible glare of 28%, which succeeded in fulfilling the required criteria (see Table 8.25).

Table 8.25 Daylight Glare Probability (DGP) for each scenario on 21st Dec

Time	Base case	(AOWWR)	(AOSBE)	TABS
12 pm				
Glare Performance	Intolerable: 84%	Intolerable: 46%	Intolerable: 55%	Imperceptible: 28%

Chapter Nine

9. Discussion

9.1. General

The objective of this thesis was to investigate the potential of designing a (TABS) that addressed the forces that are defining the context of the modern office building in Egypt by fulfilling a predefined set of criteria. These criteria were developed to satisfy contextual performance needs and cultural identity. Moreover, by harnessing the parametric, Genetic Algorithm (GA) and building performance simulation (BPS) tools, it was possible to explore the traditional Islamic geometric patterns that can be developed from this approach. This would help create a local identity, a stylistic evolution and significance of the eternal principles of Islamic architecture. It is also a means to integrate and evaluate the ornamental desires of contemporary architecture with the urgent necessity to produce designs that optimise energy and daylight performance. Furthermore, it would be a real test of the designer's ability to combine the beauty and spirit of the traditional architectural patterns, but interpreted in a modern expression harmonious with the current technological advances and building performance demands. However, within the current parametric façade design processes, daylighting devices are not well incorporated with complex patterning facades and building geometries resulted from this new approach. Consequently, integrating these devices with these complex geometries was considered to be a significant challenge regarding both design integration and performance evaluation.

The integration of current Parametric, Genetic Algorithm (GA), and Building Performance Simulation (BPS) tools facilitate the generation of new forms (complex geometries) in architecture and enable the software to automatically generate a broad range of alternative design solutions supporting geometric design explorations and building performance evaluation. In this study, a parametrically developed office building skin was modelled with external intricate ornamental geometries (as a shading system), which was culturally and biomimicry inspired by the local traditional pattern and adaptation strategies. The model integrated an internal dynamic louver system (as a daylight redirecting system) with the aim to incorporate advantages of both shading and daylight redirecting strategies in one integrated system, controlled by parameters that define the geometric configurations and transformations such as depth, width, opening ratio, inclination angles and extrusion, etc.

The aim was to understand and evaluate the effect of the TABS system's configurations on the daylight performance, with the objective of finding adequate solutions that optimised daylighting performance while tackling issues of solar gain and glare in interior spaces to enhance environmental performance through daylighting active design in comparison with the traditional static strategies such as (fully glazed facades, Annually optimised WWR (AOWWR), Annually optimised static building envelope (AOSBE), by implementing computational and building performance simulation tools, for making changes in the spatial quality response of the building, in order to optimise daylighting performance while minimising solar radiation and glare, through daylighting active design. Through this approach, the final form of the architectural artefact is determined by parameters based on performance. The research questions raised at the start of this study can now be considered as part of a discussion of the results given in Chapter Eight.

9.2. Research Questions Revisited

The findings relevant to the primary and secondary research questions regarding the performance and behaviour of a (TABS) will be briefly discussed and summarised in the following section.

Q1. Is the Adaptive Building Skin capable of providing 'satisfactory performance' all year long, in comparison to other traditional static solutions?

The results showed that (TABS) achieved the required performance and succeeded in fulfilling the required criteria at all the twelve examined times, on the other hand, Base case, (AOWWR), and (AOSBE) failed in achieving the targeted performance in most of the examined times. The (TABS) performance recorded 100% success in fulfilling the six Performance indicators (PIs) at the twelve examined times (72/72). In the case of Base case, it is performance recorded 16.6% success in fulfilling the six Performance indicators (PIs) at the twelve examined times (12/72). In the case of (AOWWR), its performance recorded (34.7%) success in fulfilling the six Performance indicators (PIs) at the twelve examined times (25/72). In the case of (AOSBE), its performance recorded (51.3%) success in fulfilling the six Performance indicators (PIs) at the twelve examined times (37/72). In the light of that, the TABS achieved a total performance 48.7% higher than the highest performance of any of the traditional solutions (see Figure 9.1).

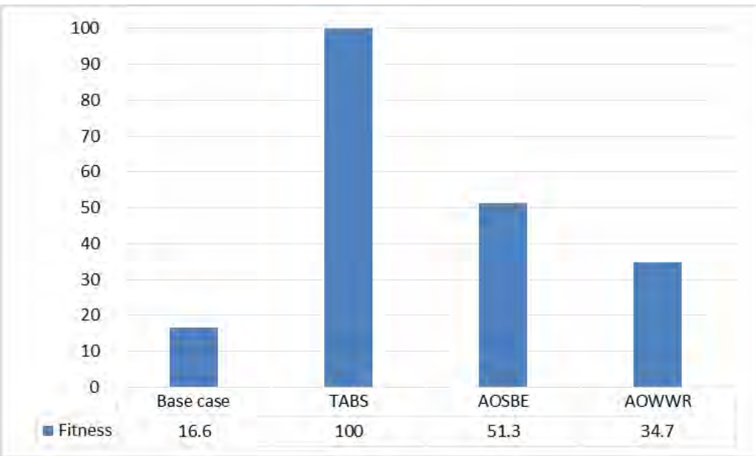


Figure 9.1 Performance comparison of all cases

In terms of the systems' performance regarding each performance indicator, the TABS achieved in fulfilling the PI1 (Task points illuminance) at (12 times out of 12) (100%), PI2 (Illuminance distribution) at (12/12) (100%), PI3 (Illuminance a contrast ratio of) at (12/12) (100%), PI4 (Daylight depth) at (12/12) (100%), PI5 (Solar radiation) at (12/12) (100%) and PI6 (glare) at (12/12) (100%). The Base case achieved in fulfilling the PI1 (Task points illuminance) at (2/12) (16.6%), PI2 (Illuminance distribution) at (2/12) (16.6%), PI3 (Illuminance a contrast ratio of) at (3/12) (25%), PI4 (Daylight depth) at (2/12) (16.6%), PI5 (Solar radiation) at (1/12) (8.3%) and PI6 (glare) at (2/12) (16.6%). The (AOWWR) achieved in fulfilling the PI1 (Task points illuminance) at (0/12) (0%), PI2 (Illuminance distribution) at (9/12) (75%), PI3 (Illuminance a contrast ratio of) at (4/12) (33.3%), PI4 (Daylight depth) at (1/12) (0.08%), PI5 (Solar radiation) at (6/12) (50%) and PI6 (glare) at (6/12) (50%). The (AOSBE) achieved in fulfilling the PI1 (Task points illuminance) at (2/12) (16.6%), PI2 (Illuminance distribution) at (7/12) (58.3%), PI3 (Illuminance a contrast ratio of) at (5/12) (41.6%), PI4 (Daylight depth) at (4/12) (25%), PI5 (Solar radiation) at (12/12) (100%) and PI6 (glare) at (7/12) (58.3%). In the light of that the TABS achieved a performance 83.4% higher than the highest performance of any of the traditional solutions regarding PI1, (25%) PI2, (48.4%) PI3, (75%) PI4, (0%) PI5 and (41.7%) PI6 respectively (see Table 9.1 and Figure 9.2).

Table 9.1 All cases performance regarding each performance indicator

Time	All cases																							
	Base case						(AOWWR)						(AOSBE)						(TABS)					
	PIs						PIs						PIs						PIs					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Mar. 9 am	×	×	×	×	×	×	×	●	×	×	×	●	×	●	×	●	●	●	●	●	●	●	●	●
Mar. 12pm	×	×	×	×	×	×	×	●	×	×	×	×	●	●	●	●	●	×	●	●	●	●	●	●
Mar. 3 pm	×	×	×	×	×	×	×	●	×	×	×	●	×	●	●	●	●	●	●	●	●	●	●	●
Jun. 9 am	●	●	●	●	×	●	×	●	●	●	●	●	×	×	●	×	●	●	●	●	●	●	●	●
Jun. 12pm	×	×	●	×	●	×	×	●	●	×	●	×	×	●	●	●	●	●	●	●	●	●	●	●
Jun. 3 pm	●	●	●	●	×	●	×	●	●	×	●	●	×	×	●	×	●	●	●	●	●	●	●	●
Sep. 9 am	×	×	×	×	×	×	×	●	×	×	×	●	×	●	×	×	●	●	●	●	●	●	●	●
Sep. 12pm	×	×	×	×	×	×	×	●	×	×	×	×	●	●	×	×	●	×	●	●	●	●	●	●
Sep. 3 pm	×	×	×	×	×	×	×	●	×	×	×	●	×	●	×	×	●	●	●	●	●	●	●	●
Dec. 9 am	×	×	×	×	×	×	×	×	×	×	●	×	×	×	×	×	●	×	●	●	●	●	●	●
Dec. 12pm	×	×	×	×	×	×	×	×	×	×	●	×	×	×	×	×	●	×	●	●	●	●	●	●
Dec. 3 pm	×	×	×	×	×	×	×	×	×	×	●	×	×	×	×	×	●	×	●	●	●	●	●	●
Tot.	**12/72 (16.6%)**						**25/72 (34.7%)**						**37/72 (51.3%)**						**72/72 (100%)**					

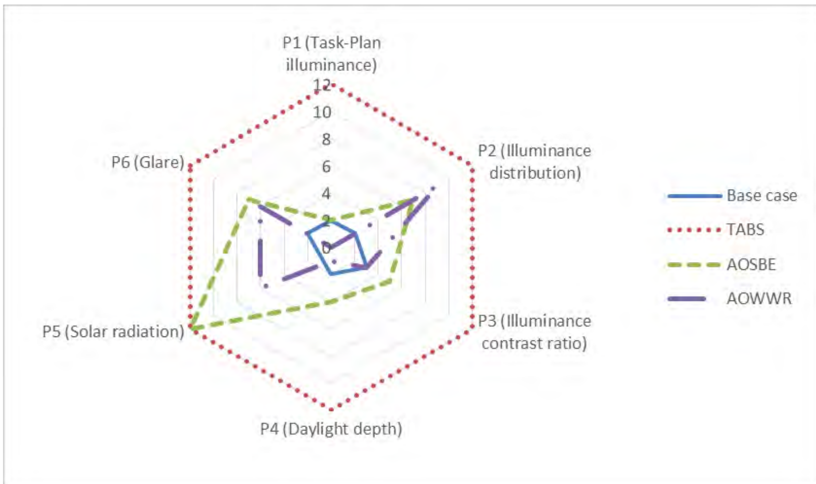


Figure 9.2 All cases performance regarding each performance indicator

The current findings empirically confirm previous theoretical approach of the advantages of Adaptive Building Skin in comparison to other traditional solutions. According to (Wang, Beltrán et al. 2012), traditional static building envelopes suffer because their effectiveness is variable throughout the year due to daily and seasonal climatic changes, resulting in envelope designs that provide less-than-optimal building performance during some periods of the year. On the other hand, adaptive building skins not only offer a high potential to reduce the energy demand for lighting and space conditioning but are also expected to introduce positive contributions to indoor air quality and thermal and visual comfort levels (Loonen, Trčka et al. 2013). Moreover, adaptive opportunities incorporated into the building's skin can offer a range of responses to environmental stimuli, to mitigate undesirable elements and provide the ability to significantly modify indoor comfort without the need of mechanical climate control systems. (Konstantoglou and Tsangrassoulis 2016), As the building skin can provide the ability to accept or reject free energy from the external environment, it can reduce the amount of artificial energy required to achieve comfortable internal conditions (Elghazi, Wagdy et al. 2015).

Furthermore, the findings of this study numerically confirm previous theoretical approaches of the capability of adaptive building skins in handling the variety of different needs and performance indicators. TABS succeeded in handling the different needs throughout the twelve examined times, such as daylight penetration depth (2x) and adequate daylight distribution (80% of the space), along with reducing solar gain to prevent excessive heat gains in the area near to the window and maintain imperceptible glare (≤ 35%). For example, (Turrin, von Buelow et al. 2011), stated that the concept of adaptive architecture is based on the relationship between the different needs/demands and the capability of a building to satisfy them in a changing environment. Moreover, according to (Lee, Selkowitz et al. 2009), the coupling of an automated shading system with moderate to large window areas provides comparable savings in thermal loads to those attained by simply downsizing the window, but with the added benefit of more daylight (see Table 9.1 and Figure 9.2).

Q2. Is the integration of dynamic, complex geometric patterns with a louver system in one (TABS) system effective, regarding their design and performance evaluation, and what are the impacts of this integration on daylighting performance in buildings, and which subsystem (complex geometric pattern or louver system) of the Territorial Adaptive Building Skin contributes more in fulfilling the performance indicators?

The results showed that integrating geometric pattern and louver system in one active system of the (TABS) contributed in improving daylighting performance while reducing solar radiation and the risk of glare. However, both subsystems contributed in fulfilling the daylighting performance indicators with different ratios, as the individual performance of each subsystem varies from season to season.

The whole (TABS) system achieved a successful performance and succeeded in fulfilling the required criteria at all the twelve examined times, on the other hand, TABS's shading subsystem and TABS's redirecting subsystem failed in achieving the targeted performance in several examined times. The (TABS) performance recorded 100% success in fulfilling the six Performance indicators (PIs) at the twelve examined times (72/72). In the case of the TABS's shading subsystem, it is performance recorded 54.1% success in fulfilling the six Performance indicators (PIs) at the twelve examined times (39/72). In the case of TABS's redirecting subsystem, its performance recorded (62.5%) success in fulfilling the six Performance indicators (PIs) at the twelve examined times (45/72). In the light of that the TABS achieved a total performance 37.5% higher than the highest individual performance of any of its subsystems (see Figure 9.3).

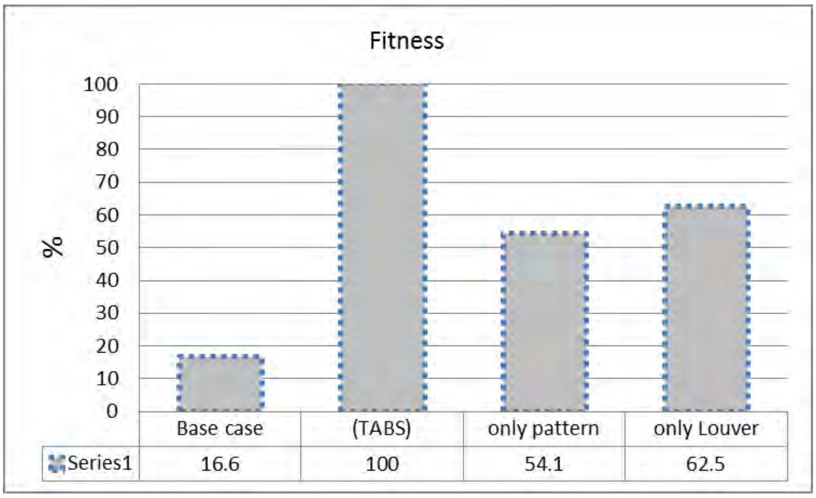


Figure 9.3 Performance comparison of the whole system and its subsystems (TABS's shading and redirecting subsystem)

In terms of the whole TABS system and subsystem's performance regarding each performance indicator, the TABS succeeded in fulfilling all the six PIs (Task points illuminance, Illuminance distribution, Illuminance a contrast ratio of, Daylight depth, Solar radiation, and glare) at (12 times out of 12) (100%). The TABS's shading subsystem achieved in fulfilling the PI1 (Task points illuminance) at (3/12) (25%), PI2 (Illuminance distribution) at (8/12) (66.6%), PI3 (Illuminance a contrast ratio of) at (6/12) (50%), PI4 (Daylight depth) at (4/12) (33.3%), PI5 (Solar radiation) at (8/12) (66.6%) and PI6 (glare) at (10/12) (83.3%). The TABS's redirecting subsystem achieved in fulfilling the PI1 (Task points illuminance) at (3/12) (25%), PI2 (Illuminance distribution) at (8/12) (66.6%), PI3 (Illuminance a contrast ratio of) at (9/12) (75%), PI4 (Daylight depth) at (7/12) (58.3%), PI5 (Solar radiation) at (11/12) (91.6%) and PI6 (glare) at (7/12) (58.3%). In the light of that the contribution of the subsystems can be described as follows:

The contribution of TABS's shading subsystem regarding the whole system performance was higher than the TABS's redirecting subsystem in terms of PI 6 (glare), and they have equally contributed to the whole system performance in terms of PI1 (Task points illuminance) and PI 2 (Illuminance distribution), on the other hand, the contribution of the TABS's redirecting subsystem outweighed the subsystem TABS's shading subsystem contribution in terms of PI 3 (Illuminance a contrast ratio of), PI4 (Daylight depth), and PI5 (Solar radiation). Nevertheless, it is necessary to mention that the discussion above is concerned with highlighting the contribution of each subsystem (regarding only the twelve optimised TABS solutions) in achieving the adequate performance of the whole system, as the TABS optimised as a combined system, not as a combination of individually optimised subsystems. Moreover, the maximum difference between subsystems' performance regarding each performance indicator was 25% (3 out of twelve examined times). Both systems failed in fulfilling the complete six performance indicators except at (June 9 am) for both subsystems and at (Sep. 3 pm) for the TABS's redirecting subsystem (See Table 9.2 and Figure 9.4)

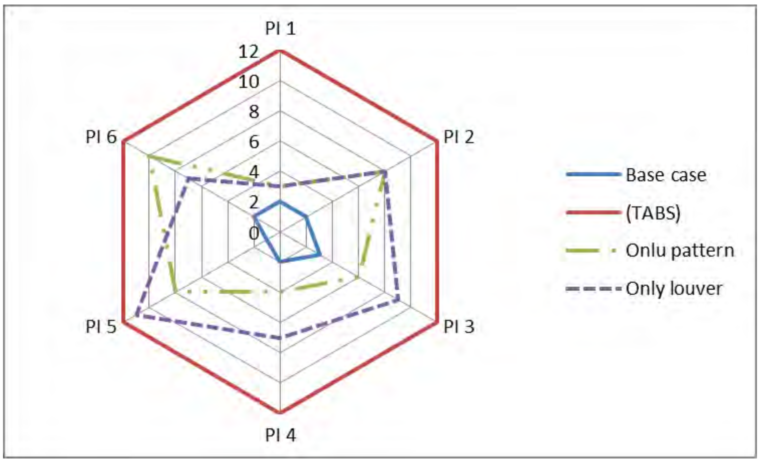


Figure 9.4 The whole system and its subsystems (TABS's shading subsystem and only Louver), performance regarding each performance indicator.

Table 9.2 The whole system and its subsystems (TABS's shading subsystem and only Louver), performance regarding each performance indicator

Time	Models																							
	Base case						(TABS)						(TABS) TABS's shading subsystem						(TABS) only Louver					
	PIs						PIs						PIs						PIs					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Mar. 9 am	×	×	×	×	×	×	●	●	●	●	●	●	×	●	×	×	●	●	×	●	●	●	●	●
Mar. 12pm	×	×	×	×	×	×	●	●	●	●	●	●	●	●	×	×	●	●	×	×	×	×	●	×
Mar. 3 pm	×	×	×	×	×	×	●	●	●	●	●	●	×	●	●	●	●	●	×	●	●	×	●	●
Jun. 9 am	●	●	●	●	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Jun. 12pm	×	×	●	×	●	×	●	●	●	●	●	●	×	●	●	●	×	●	×	●	●	●	●	×
Jun. 3 pm	●	●	●	●	×	●	●	●	●	●	●	●	●	●	●	●	×	●	●	●	●	●	×	●
Sep. 9 am	×	×	×	×	×	×	●	●	●	●	●	●	×	●	●	×	●	●	×	●	●	×	●	●
Sep. 12pm	×	×	×	×	×	×	●	●	●	●	●	●	×	×	●	×	×	●	×	●	●	●	●	●
Sep. 3 pm	×	×	×	×	×	×	●	●	●	●	●	●	×	●	×	×	×	●	●	●	●	●	●	●
Dec. 9 am	×	×	×	×	×	×	●	●	●	●	●	●	×	×	×	×	●	×	×	×	×	×	●	×
Dec. 12pm	×	×	×	×	×	×	●	●	●	●	●	●	×	×	×	×	●	●	×	×	●	×	●	×
Dec. 3 pm	×	×	×	×	×	×	●	●	●	●	●	●	×	×	×	×	●	×	×	×	×	●	●	×
Tot.	**12/72 (16.6%)**						**72/72 (100%)**						**39/72 (54.1%)**						**45/72 (62.5%)**					

The current findings numerically confirm previous theoretical approaches of the positive impact of shading and daylight redirecting systems on daylighting performance in office spaces. For example,

(Vine, Lee et al. 1998), argued that it is important to design a facade system to control daylight appropriately, maximise the benefits of avoiding the potential adverse outcomes. Moreover, (Ruck, Aschehoug et al. 2000), stated that a good selection of systems means a good mixture of systems. Therefore, the combination of both subsystems has a significant impact on the daylight performance in space, regarding handling different performance indicators. Regarding Solar shading systems, they are more efficient in facades that are exposed to direct sunlight as they are capable of preventing direct sun under clear sky conditions (Ruck, Aschehoug et al. 2000). On the other hand, Light redirecting systems don't fundamentally provide shade; it is efficient in the utilization of natural sunlight to decrease the need for artificial lighting in buildings, they control the diffused and direct sunlight to improve the daylight penetration depth and uniform daylight distributions, on sunny and overcast conditions, respectively without the secondary effects of glare and overheating (Ruck, Aschehoug et al. 2000).

Q3. What advantages can parametric, generative design, genetic algorithm (GA) and building performance simulation (BPS) offer in designing (TABS) in early design stages?

General

In general the results of the successful TABS performance at all the examined times showed that integrating parametric design, genetic algorithm (GA) and building performance simulation (BPS) played an effective role in achieving an efficient performance-driven parametric model for designing, evaluating and optimising the TABS system during the three main stages of the TABS development (Conceptual stage, form generation and evaluation stage, and optimisation stage), to fulfil a predetermined criteria and maintain an adequate performance at all the examined times (Figure 9.5).

The TABS performance confirmed previous theoretical approaches of the advantages of the performance-driven parametric model that integrates computational modelling, simulation, and genetic algorithms (GA) tools in architectural design. According to (Huang and Niu 2016), the performance-driven parametric model allows designers to integrate parametric modelling, genetic algorithms (GA), simulation tools into one integrated process governed by design objective, and supports their design decision by being in direct associate with the site and its surrounding environment.

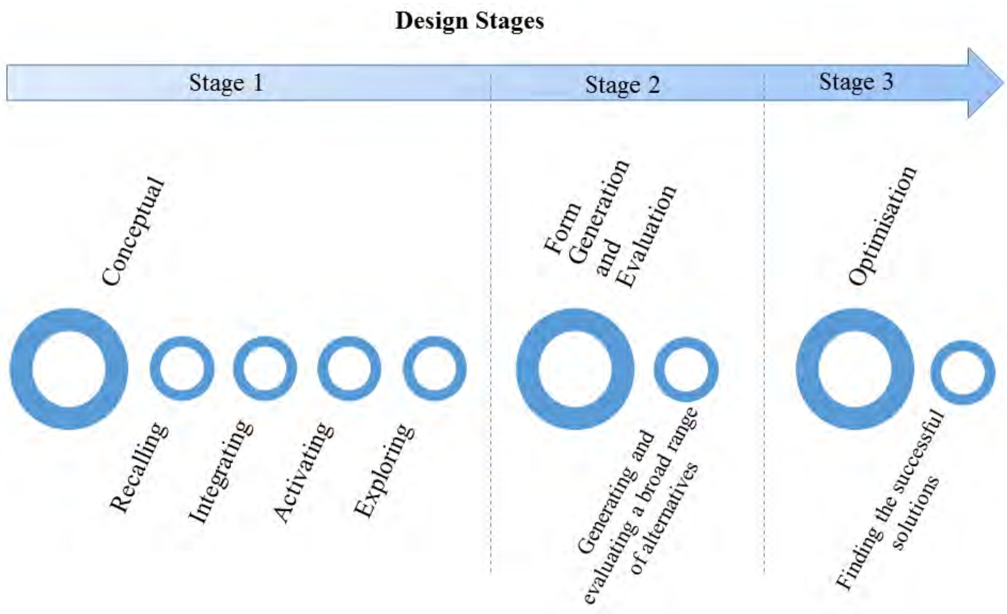


Figure 9.5 TABS development stages

The advantages of utilising these tools are discussed in the following sections.

Stage One: Conceptual stage

The parametric modelling tool "Grasshopper" was efficient during the conceptual design stage, as it effectively facilitates modelling and "recalling" the complex geometry of the local traditional solar screen "Mashrabiya". In addition to control the motion of it is parts, subsequently, facilitating mimicking the mechanisms of the "stomata" adaptations to different scenarios and interpreting these adaptive motions in a 3D geometric configuration. Moreover, testing different potential scenarios of "integrating" the internal daylight redirecting system with the external 3D geometric shading system in a way that aesthetically not negatively affecting the appearance of the whole system and functionally contributes positively to the system performance, through visualising different integration scenarios. Furthermore, effectively afforded the possibility of "activating" the whole system as a mean to embed the capability of the TABS to adapt to different scenarios, through affording the capability to control the whole system via a group of parameters with a wide range of variables, which resulted in creating different options and variables that assisted making effective decisions at the early design stage, as each type of motion has its morphology, aesthetics and effect.

Finally, it was efficient in exploring and understanding the behaviour of daylight at all the examined times without TABS and its interaction with the TABS using interactive visualisation for the sun rays tracing during the four seasons of the entire year. Ladybug plug-in was used to create an environmentally-conscious architectural design. A standard EnergyPlus Weather file (.EPW) for Cairo was imported to Ladybug to visualize the sun's rays on 21st March at 9.00am, 12.00pm and 3.00pm (vernal equinox); 21st June at 9.00am, 12.00pm and 3.00pm (summer solstice); 21st September at 9.00am, 12.00pm and 3.00pm (autumnal equinox) and 21st December at 9.00am, 12.00pm and 3.00pm (winter solstice). Resulted in understanding the impact of the different perforation ratios and extrusion depths of shading system, and the inclination angles and depths of the daylight redirecting system on the daylight performance in the near, middle, and rear area of space at different examined times. Consequently, supported deciding the final group of parameters with a certain range of variables to assist the TABS system to achieve a successful performance at all the examined times, out of the wide range of solutions available in the designed pool of solutions (see section 5.6.3).

The current findings confirmed previous theoretical approaches to the positive impact of utilising parametric tools such as Grasshopper in the architectural design. According to (Jin, Zhang et al. 2013), parametric design is a set of relations and variables parameters to develop a form. Therefore, by changing the parameters, different shapes can be defined. Moreover, the entire building form can be manipulated by modifying certain parameters, which are automatically able to adapt construction data, such as the total number of floors, building aspect ratio and its height (Jin, Zhang et al. 2013). Moreover, Oxman states that Associative geometry possibly can provision a design methodology in which a geometrically defined chain of reliance interactions is the origin for a generative, evolutionary design process. Also, it is possible to control an individual shape or form and explore many options by varying the parameters (Oxman and Oxman 2010).

Also, the study confirmed previous theoretical approaches of the importance of using interactive visualisation for sun rays tracing to create an environmentally-conscious architectural design (Roudsari, Pak et al. 2013).

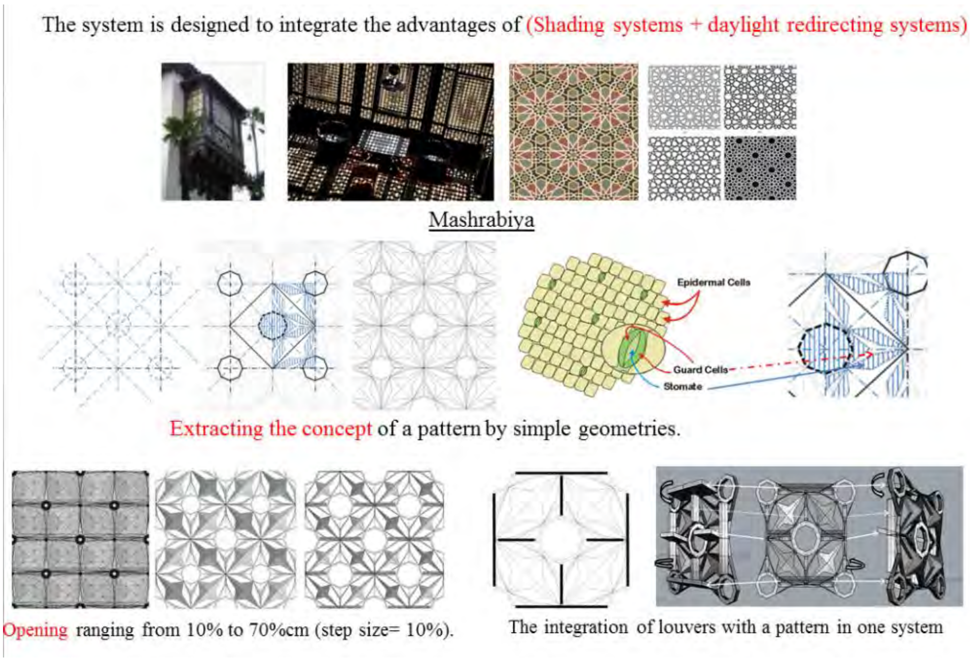


Figure 9.6 Conceptual stage

Stage Two: Form generation and evaluation

The DIVA plug-in for the software RHINO and Grasshopper environments supports a range of performance evaluations, using validated tools incorporating Radiance, Daysim, and Evalglare software. All variables were controlled automatically through the algorithms to start generating the TABS alterations based on the results of the simulations of daylight and solar radiation levels in the office. This framework permits the quick visualisation of daylight results from a parametric design model where numerous design alternatives for daylight performance were examined.

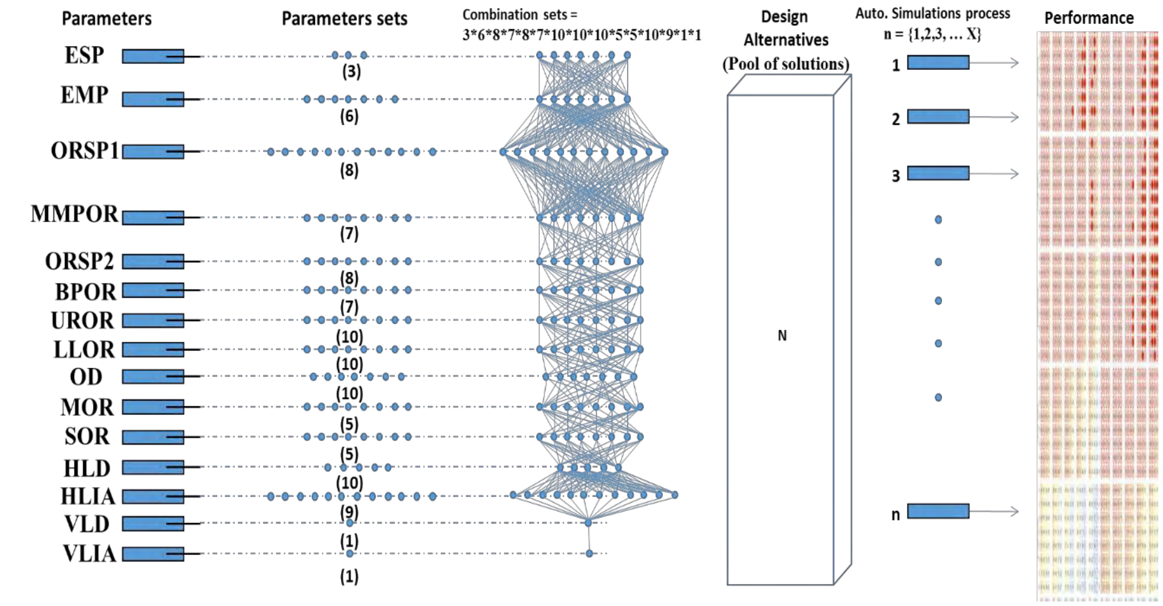


Figure 9.7 Form generation and evaluation

The results proved that the current advancements in computational tools enable designers to envision novel complex geometries, along with climatic performance measures as a means to integrate the contemporary design processes of highly articulated patterned building skin with building performance simulation fundamentally. As proved here, a building's skin (shading and daylight redirecting system), can be both a complex geometry that satisfies the aesthetic desires for ornament, and while also substantially addressing building performance and interior user comfort.

Moreover, the ability to accurately evaluate the performance of a wide range of alternatives for each of the twelve times by the DIVA simulation tools proved its ability to speed up and simplify the process used by the tool for such dynamic design evaluation. However, it is important to note that, in the case of using a broad range of design variables (that resulted in infinite options of skin configurations), it is worthwhile to consider these tools as a means to explore a wide variety of successful alternatives rather than finding an optimal solution, as reaching an optimum solution out of these infinite possible options is very time consuming and required a particular computation capability. The findings confirmed previous theoretical approaches to the positive impact of integrating simulation tools with the parametric model for performance assessments. According to (Turrin, von Buelow et al. 2011), Concentrating on performance criteria, the analysis of available geometric instances based on simulation software and other performance evaluation processes allows exploring and comparing the instances contained in the solution space of the parametric model with respect to a given set of more sharply defined and measurable design criteria.

Stage Three: Optimisation

The results achieved from Galapagos showed its capability in identifying the best performing group of solutions (near to optimum) that fulfil the required performance at all of the twelve times studied out of a broad range of alternatives that has been evaluated and compared based on their fitness or performance to achieve the best performing alternatives. Galapagos helped fitness function by “Maximising” or “Minimising” the fitness value to define the highest or the lowest possible value.

However, it is important to note that due to a limitation of Galapagos in being a single generative solver, it is only able to solve one defined fitness function for the problem. That is why within this study the task point’s illuminance levels were considered to be the main objective to be utilised to define the fitness function.

In the light of that, the fitness function value was set to achieve”9” illuminance values representing the 9 task points inside space to be between 500-2000 Lux. Other performance indicator evaluations was analysed using Grasshopper components included “List items” to extract the values measured for each point, “dispatch component” utilised to identify the successful points that received an accepted range of illuminance values, and then the ‘mass addition’ component was used to count the approved nodes’ numbers to make sure that all the 17 points (9 task points and 8 points represents the daylight depth to be between 500-2000 Lux and between 300-3000 Lux respectively).

For the performance indicator (illuminance contrast ratio), all the illuminance values have been organised in a descending order using the “list item” component, the first point having an index of ‘0’ and the last value having an index of ‘16’; the lowest values are divided by the highest value, if the result is within 1:8 ratios, the solution, is considered acceptable and sent for solar radiation calculation (40 measuring nodes), else, it considered rejected. The same is correct for solar radiation by dividing the received solar radiation with TABS by the solar radiation received in the base case to evaluate the solar radiation reduction that the successful solution achieved (see Figure 6.11).

The utilisation of Galapagos significantly improved the design process, by allowing the exploration of a wide range of design alternatives associated with their performance regarding a certain design problem, which proved the previous theoretical approach of using genetic algorithms as a design aid, to assist the architects in the design process. Moreover, it is noticed that the harsher conditions the Base case examined then, the longer Galapagos needed to reach satisfactory solutions, and vice-versa.

Furthermore, these algorithms do not guarantee a solution unless a well-defined setup for the problem and efficient system's parameters has been defined. For example, Galapagos failed to identify any satisfactory solution for 21st Dec. at 12 pm, which required editing the domain of horizontal louver depth (HLD) to be up to 0.5 m instead of the previous maximum of 0.40 m. Consequently, Galapagos then succeeded in identifying the TABS configurations that fulfilled the required fitness value.

On the other hand, many successful solutions were identified by Galapagos for 21st Jun. at 9 am and 3 pm, as the base case achieved a satisfactory performance without TABS. The findings confirmed previous theoretical approaches to the positive impact of utilising Genetic Algorithms (GAs) in solving problems. For example (Khabazi 2010), stated that the design outcomes would be optimised or a defined problem will be solved by using a numeric based fitness function in its highest/lowest achievable values.

Moreover, (Goldberg 1989) argues that, the optimal design solution will be the achievable combination of parameters' values, which minimises or maximises the objective function. However, the design problem may have a group of solutions based on the available, accepted solutions within the search space "pool of solutions".

Q4. Can a (TABS) be efficiently capable of negotiating with its surrounding environment to optimise daylighting performance, while addressing its cultural identity?

This finding suggests that the demonstrated TABS system **"Theoretically"** can be both a complex geometry that satisfies the aesthetic desires of designing contemporary facades inspired by ornament and renovated traditional patterns as mean to express the building cultural identity by a variety of optimised TABS designs, as the physical appearance of each optimised facade was an authentic representation of the Mashrabiya form, while also addressing concerns over building performance and user comfort by achieving acceptable internal environmental conditions. However, it's important to note that the current research is a step towards achieving a (TABS) system that can efficiently capable of negotiating with its surrounding environment in **"real world"**.

Q5. Do the geometrical characteristics of TABS with complex geometries affect daylighting performance in buildings and do these adaptive response change due to climate, season, hour or orientation?

The results indicate a significant influence of the (TABS) geometric configuration on the daylighting performance at all examined times. The different types and directions of motion embedded in the system affects the daylighting performance inside the space, due to several reasons:

- The regular distribution of the patterns' units (40 unit with dimensions 1mx1m)), which were controlled by a group of parameters that control the system's form and perforation ratio (PR), improved the uniformity level of daylight to the recommended level in the space.
- The three-dimensional qualities of the external ornamental screen (pattern extrusion), provide shading and self-shading at several times, and consequently reduces direct sunlight and solar gain, and protected the working plane from direct sun and eliminated sources of glare.
- The type and direction of motion (Depth, and inclination angles) of the internal louver system and Octagons (8 Sides) improved the daylight distribution and penetration depth by redirecting the daylight into the deep plan in addition to controlling the sun rays that passing through the external ornamental screen and protected the working plane from direct sun and eliminated sources of glare.

The integration of both systems contributed to achieving an adequate performance in terms of all the six PIs at all the examined times, due to the arrangements of the louver system on the axis of the pattern units in a way that redirecting the sun rays that passing throughout the pattern units towards the reflective ceiling and subsequently minimise the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space.

Therefore, it is important to note that the selection of the twelve successful solutions wasn't based on selecting the solution that achieved the highest performance at each time. But based on selecting one of the successful group of solutions for each time with the intention of presenting the diversity and the variety of configurations and solutions that the TABS system able to produce to achieve the required performance throughout all the selected twelve times that represents the four seasons of the entire year.

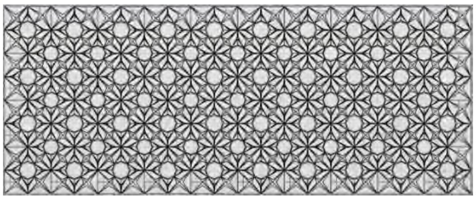
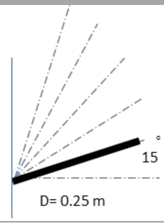
The current findings empirically confirm previous theoretical approaches of the advantages of kinetically adaptive facades. According to (Fox 2003), the motion and changing the position of the surface defined the positioning and pattern about the external environment and resulted in higher or lower levels of solar radiation in the space.

In the light of that, the influence of the TABS geometrical characteristics is discussed in the following sections based on the optimised system configurations for each examined times:

21st of March at 9 am

The results showed that TABS consisted of an external shading system (geometrical patterns) with 75% PR and 0.025m extrusion, and the internal daylight redirecting system consisted of seven horizontal rows of louvers with 0.5 m spacing, and 0.25m depth, and 15° inclination angle, and Octagons with radius 0.16 and 0.18 m and 0.1 m depth fulfilled the required performance inside the office space (Table 9.3).

Table 9.3 The TABS system (external shading pattern and internal louvers), 21st of March at 9 am

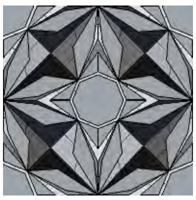
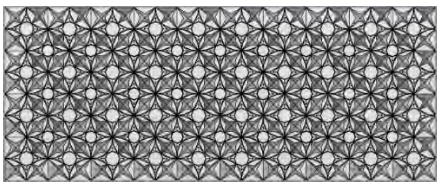
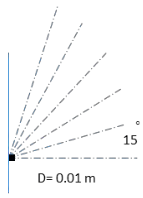
Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case received 66.2% daylit and 33.8% overlit, concentrated in the area near to the window resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 3015.5, 2679, and 2005 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, and 2 as they received 22899, and 22488 Lux respectively. Moreover, it received a perceptible glare 39%. On the other hand, the TABS subsystem's performance, the results showed that the configurations and the associated PR (75%) of the shading subsystem facilitate getting maximum benefit from the available daylight, and prevented glare, as the results showed imperceptible glare 33%. However, due to its shallow depth (0.025m), it partially succeeded in providing shade in the area near the window and improve the daylight distribution in the space, as the results showed that this subsystem alone increased the daylit area from 66.2% in the base case to 81%. However, it resulted in 19% overlit area concentrated in the area near to the window, and consequently in an inadequate illuminance levels for task plan 1, and 2 as they received 2779 and 2559 Lux, respectively, and subsequently, resulted in an inadequate daylight depth for points 1, and 2 as they received 22707 and 22296 Lux, respectively, and subsequently these high illuminance values, resulted in an illuminance contrast ratio out of the acceptable range. On the other hand, the internal daylight redirecting system succeeded in preventing direct sunlight from reaching the area near to the window, as the results showed only 4.8 % overlit distributed in the area near to the window; however, it resulted in an inadequate illuminance levels for task points 2, and 3 as they received 2056 and 2044 Lux, respectively. Moreover, it is succeeded in preventing glare, as the results showed imperceptible glare 30%.The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The high PR (75%) of the external shading system with a shallow extrusion (0.025m) facilitates getting maximum benefit from the naturally available daylight by permitting sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.25m), and 15° inclination angle of the louvers and Octagons with wide radiuses 0.16 and 0.18 m and 0.1 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 31% instead of Intolerable glare 53% in the Base case, also, the daylit area increased from 66.2% in the base case to 97.4% in TABS and the solar radiation reduced from 87 to 55 KWh/m2. In the light of that, it can be concluded that the high PR of the TABS external subsystem, in addition to the depth (0.25m), and 15° inclination angle of the louvers has the most contribution regarding the whole system performance at that time.

21st of March at 12 pm

The results showed that TABS consisted of an external shading system (geometrical patterns) with 56% PR and 0.25m extrusion, and the internal daylight redirecting system consisted of seven horizontal rows of louvers with 0.5m spacing, and 0.01m depth, and 15° inclination angle, and Octagons with radius 0.14 and 0.16 m and 0.15 m depth fulfilled the required performance inside the office space Table 9.4).

Table 9.4 The TABS system (external shading pattern and internal louvers), 21st of March at 12 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 33.2% daylit and 66.8% overlit, concentrated in the area near to the window and the middle area of space and resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 3310, 3653, and 3386 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, 2, and 3 as they received 40024, 39513 and 3334 Lux respectively. Moreover, Intolerable glare 53%. On the other hand, the results showed that the configurations and the associated PR (56%) of TABS allowed the shading subsystem to get maximum benefit and control the available daylight, and prevented glare, as the results showed imperceptible glare 31%. Moreover, the 0.25m extrusion provided adequate shade and contributed in reducing the overlit area in the near area to the window, as the results showed 12.2% overlit concentrated in the area near to the window instead of 66.8% overlit in the base case, However, it led to an inadequate daylight depth for point 2 as it received 37735 Lux, and subsequently these high illuminance values, resulted in an illuminance a contrast ratio of out of the acceptable range. On the other hand, the internal daylight redirecting system, with dependent only on the Octagons as the impact of the 0.01m depth of louvers can be neglected, therefore, failed to prevent direct sunlight reaching the area near to the window, as the results showed 27.4% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 1, 2, and 3 as they received 3017, 3438 and 3128 Lux, respectively. Subsequently, it is failed in preventing glare, as the results showed perceptible glare 37%.

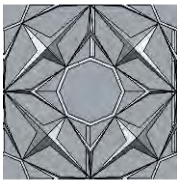
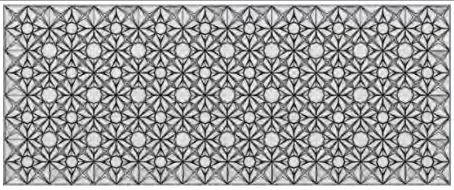
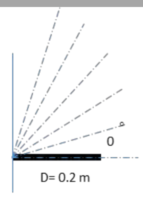
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The low PR (56%) of the external shading system with a deep extrusion (0.25m) facilitates getting maximum benefit from the naturally available daylight by controlling the excessive amount of the daylight entering space and permitting a sufficient amount of daylight to enter the space, in addition, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.01m), and 15° inclination angle of the louvers have no impact on the daylight performance, However, the Octagons with wide radiuses 0.16 and 0.18 m and 0.1 m depth of the daylight redirecting system, partially contributed in redistributing the daylight that passing throughout the shading system. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 31% instead of Intolerable glare 53% in the Base case, also, the daylit area increased from 33.2% in the base case to 89.4% in TABS and the solar radiation reduced from 83 to 40 KWh/m2.

In the light of that, it can be concluded that the system low PR and extrusion of the shading system has the most contribution regarding the whole system performance.

21st of March at 3 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 74% PR and 0.05m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.2m depth, and 0° inclination angle, and Octagons with radius 0.13 and 0.18 m and 0.01 m depth fulfilled the required performance inside the office space (Table 9.5).

Table 9.5 The TABS system (external shading pattern and internal louvers), 21st of March at 3 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 64% daylit and 36% overlit, concentrated in the area near to the window and resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 2007, 2743, and 3079 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, and 2 as they received 23542, and 23096 Lux respectively. Moreover, Disturbing glare 40%. On the other hand, the results showed that the configurations and the associated PR (74%) of TABS allowed the shading system to get maximum benefit from the available daylight, and prevented glare, as the results showed imperceptible glare 33%, however, the high perforation ratio of the external subsystem, caused overlit in the near area to the window, as the results showed 15.6% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 2, and 3 as they received 2119 and 2411 Lux, respectively. However, it succeeded in fulfilling other PIs, such as daylight depth illuminance, illuminance a contrast ratio of, and contribute in reducing solar radiation from 83 in the base case to 69 KWh/m^2

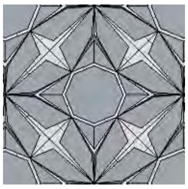
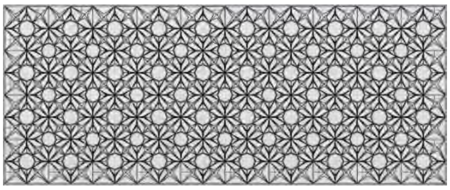
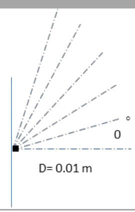
On the other hand, the internal daylight redirecting system failed to prevent direct sunlight from reaching the area near to the window, consequently, caused overheating in the near area to the window, as the results showed 14.2% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 2, and 3 as they received 2420 and 2409 Lux, respectively. However, it is succeeded in preventing glare, as the results showed imperceptible glare 33%.

The integration of both subsystems contributed in achieving an adequate performance in terms of all the six PIs. The high PR (74%) of the external shading system with a shallow extrusion (0.05m) facilitates getting maximum benefit and controlling the naturally available daylight by permitting sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.20m), and 0° inclination angle of the louvers and Octagons with wide radiuses 0.13 and 0.18 m and 0.1 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 30% instead of Disturbing glare 40% in the Base case, in addition, the daylit area increased from 64% in the base case to 90.4% in TABS and the solar radiation reduced from 83 to 50 KWh/m^2. In the light of that, it can be concluded that the high PR of the external subsystem, in addition to the depth (0.20m), and 0° inclination angle of the louvers has the most contribution regarding the whole system performance.

21st of June at 9 am

The results showed that TABS consists of an external shading system (geometrical patterns) with 75% PR and 0.025m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.01m depth, and 0° inclination angle and Octagons with radius 0.18 and 0.16 m and 0.1 m depth fulfilled the required performance inside the office space (Table 9.6).

Table 9.6 The TABS system (external shading pattern and internal louvers), 21st of June at 9 am

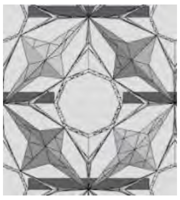
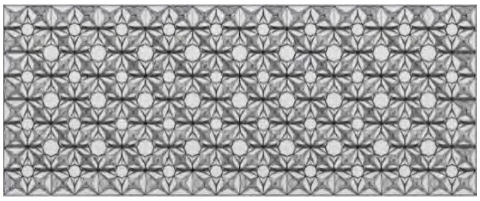
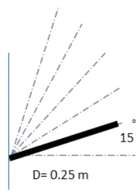
Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 100% daylit resulted in an adequate performance. On the other hand, the results showed that the configurations and the associated PR (80%) of TABS allowed the system to maintain the adequate performance inside space as the base case without shading achieved (300 < 100 % of area < 3000 Lux) (day lit), which succeeded in fulfilling the required criteria. The TABS system with a high perforation ratio (75% PR), and wide openings of Octagons with radius 0.18 and 0.16m achieved 98.6 %

daylit area, and 1.4% partially lit. On the other hand, (AOWWR) and (AOSBE) configurations have a negative impact on the daylight performance inside space as they increased the partially lit area from 0% in the Base case to 11.4% and 30.2% respectively, while minimising the daylit area from 100% in the Base case to 88.6% and 69.8% respectively (see Figure 2.73 and Table 2.38).

The difference in the configurations of the TABS and (AOSBE) highlighted the impact of the geometric characteristics of shading and daylight redirecting systems on the performance of daylight inside space, for example, the 75% PR ratio and the minimum extrusion (0.025m) of the external shading system facilitate getting maximum benefit from the naturally available daylight by permitting sufficient amount of daylight to enter the space, moreover, the redirecting system that consists of louvers with minimum depth (0.01m), and Octagons with wide openings (radius 0.18 and 0.16 m) with a shallow depth (0.1 m) contributed in achieving the required performance by permitting the maximum amount of daylight to enter the space. On the other hand, the lower PR (65.5%) of (AOSBE) with extrusion (0.25m) of the external shading system has a negative impact on the daylight performance due to the low perforation ratio in addition to the 0.25 extrusion as it caused a self-shading and limited the amount of daylight that entering the space, therefore, even though the louver configurations with 0.25m and 15° inclination angle was suitable to improve the daylight depth, the system failed to improve the daylight depth due to the insufficient amount of daylight that entered space and reached the daylight redirecting system as the results showed that the Partially lit area increased from 0% in the base case to 30.2%. In the light of that, it can be concluded that the high PR of the TABS external subsystem, in addition to Octagons with a wide radius 0.18 and 0.16 m and 0.1 m depth has the most contribution regarding the whole system performance.

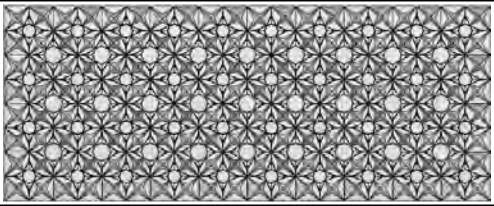
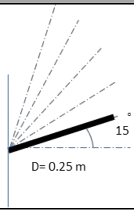
Table 9.7 The configurations of (AOSBE) (21st of June at 9 am)

Pattern	Section	Perspective	Louver inclination angle
			

21st of June at 12 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 65% PR and 0.15m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.25m depth, and 15° inclination angle and Octagons with radius 0.13 and 0.18 m and 0.01 m depth fulfilled the required performance inside the office space.

Table 9.8 The TABS system (external shading pattern and internal louvers), 21st of June at 12 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case received 74% daylit and 25.4% overlit, concentrated in the area near to the window resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 2791, 3106, and 2891 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, and 2 as they received 4556, and 3555 Lux respectively. On the other hand, the results showed that the configurations and the associated PR allowed the TABS to improve the daylight performance inside space as it achieved 100 % (day lit), which succeeded in fulfilling the required criteria. The shading system with intermediate PR (65%) maintained a sufficient supply of daylight to space while the 0.15m extrusion provided efficient shading in the area near of the window, as the results showed that this subsystem alone reduced the overlit area from 25.4% in the base case to 5%. In addition to preventing glare as it achieved Imperceptible glare 34% instead of perceptible glare in the base case. However, it failed in providing a sufficient illuminance level for Task plan two as it received 2165 Lux.

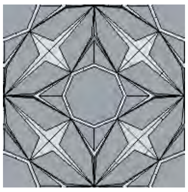
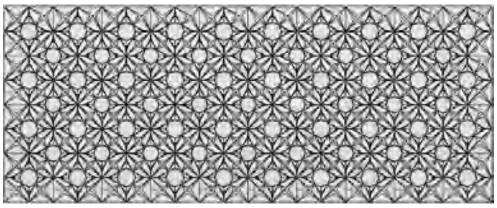
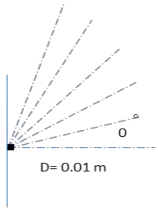
Regarding the daylight redirecting system the horizontal louvers with 0.25m depth, and 15° inclination angle contributed in improving the daylight distribution inside space as the results showed that this subsystem alone reduced the overlit area from 25.4% in the base case to 0%, by redirecting the daylight that passing throughout the shading system to the deep plan. However, it failed in preventing glare as it achieved perceptible glare 37% instead of perceptible glare 38% in the base case. However, it failed in providing a sufficient illuminance level of Task plan 1, 2, and 3 as they received 2153, 2368, and 2189 Lux.

The integration of both systems contributed in achieving an adequate performance regarding all the six PIs. For example, the results showed the daylit area increased from 74.6% in the base case to 100% in TABS and 50% reduction in solar radiation. In the light of that, it can be concluded that the intermediate system PR, extrusion of the shading system, the depth (0.25m), and 15° inclination angle of the louvers has the most contribution regarding the whole system performance.

21st June at 3 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 75% PR and 0.025m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.01m depth, and 0° inclination angle, and Octagons with radius 0.18 and 0.16 m and 0.01 m depth fulfilled the required performance inside the office space (Figure 9.8).

Table 9.8 The TABS system (external shading pattern and internal louvers), 21st of June at 3 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the configurations and the associated PR allowed the TABS to maintain the adequate performance inside space as the base case without shading achieved 100 % day lit area, which succeeded in fulfilling the required criteria. The TABS system with a high perforation ratio (75% PR), and wide openings of Octagons with radius 0.18 and 0.16m achieved 98.8 % daylit area, and 1.2% partially lit. On the other hand, (AOWWR) and (AOSBE) configurations have a negative impact on the daylight performance inside space as they increased the partially lit area from 0% in the Base case to 12.8% and 33.2% respectively. While minimising the daylit area from 100% in the Base case to 87.2% and 66.8% respectively.

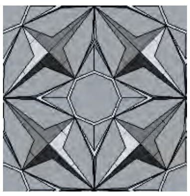
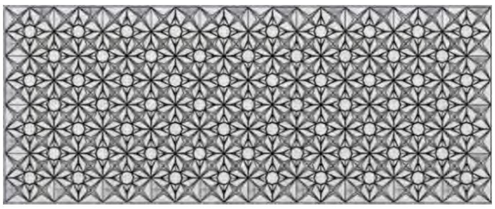
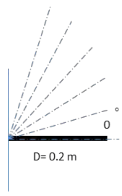
The same as the case of (Jun. 21st at 9 am), the difference in the configurations of the TABS and (AOSBE) highlighted the impact of the geometric characteristics of shading and daylight redirecting systems on the performance of daylight inside space, for example, the high PR (75%) and the minimum extrusion (0.025m) of the external shading system facilitate getting maximum benefit from the naturally available daylight by permitting sufficient amount of daylight to enter the space, moreover, the redirecting system that consists of louvers with minimum depth (0.01m), and Octagons with wide openings (radius 0.18 and 0.16 m) and shallow depth (0.1 m) contributed in achieving the required performance by permitting the maximum amount of daylight to enter the space. On the other hand, the intermediate PR (65.5%) of (AOSBE) with extrusion (0.25m) of the external shading system has a negative impact on the daylight performance due to the low perforation ratio in addition to the 0.25 extrusion as it caused a self-shading and limited the amount of daylight that entering the space, therefore, even though the louver configurations with 0.25m and 15° inclination angle was suitable to improve the daylight depth, the system failed in improving the daylight depth due to the insufficient amount of daylight that entered space and reached the daylight redirecting system as the results showed that the Partially lit area increased from 0% in the base case to 33.2%.

In the light of that, it can be concluded that the high PR of the TABS external subsystem, and Octagons with wide openings (radius 0.18 and 0.16 m) and shallow depth (0.1 m) has the most contribution regarding the whole system performance.

21st of September at 9 am

The results showed that TABS consists of an external shading system (geometrical patterns) with 69% PR and 0.1m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.25m depth, and 0° inclination angle and Octagons with radius 0.13 and 0.13 m and 0.1 m depth fulfilled the required performance inside the office space.

Table 9.9 The TABS system (external shading pattern and internal louvers), 21st of September at 9 am

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 63% daylit and 37% overlit, concentrated in the area near to the window resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 3104, 2822, and 2160 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, 2 and 3 as they received 39965, 39451and 3301 Lux respectively. Moreover, Disturbing glare 41%. On the other hand, the results showed that the configurations and the associated intermediate PR (69%) of TABS the shading system to get maximum benefit from the available daylight, and prevented glare, as the results showed imperceptible glare 30% instead of Disturbing glare 41% in the case of base case, however, the high perforation ratio of the external subsystem, caused overlit in the near area to the window, as the results showed 18.8% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 1, and 2 as they received 2243 and 2001 Lux, respectively. And inadequate daylight depth as point 2 received 23844 Lux, and consequently failed in achieving an adequate daylight contrast ratio. However, it reduced solar radiation from 70 in the base case to 41 KWh/m2.

On the other hand, the internal daylight redirecting system failed to prevent direct sunlight reaching the area near to the window, as the results showed 16.4% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 1, 2, and 3 as they received 2830, 2820 and 2203 Lux, respectively. However, it is succeeded in preventing glare, as the results showed imperceptible glare 32%.

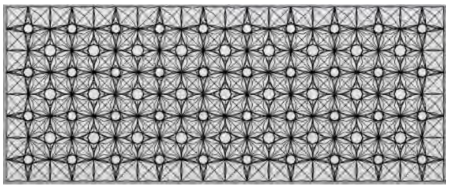
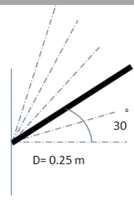
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The intermediate PR (69%) of the external shading system with a deep extrusion (0.25m) facilitates getting maximum benefit from the naturally available daylight by controlling the excessive amount of the daylight entering space and permitting a sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.2m), and 0° inclination angle of the louvers and Octagons with wide radiuses 0.13 and 0.13 m and 0.1 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 29% instead of Disturbing glare 41% in the Base case, also, the daylit area increased from 63% in the base case to 94.8% in TABS and the solar radiation reduced from 70 to 41 KWh/m2.

In the light of that, it can be concluded that the intermediate system PR, extrusion of the shading system, the louvers depth (0.25m), and 0° inclination angle and Octagons with wide radiuses 0.13 and 0.13 m and 0.1 m depth has a balanced contribution regarding the whole system performance.

21st of September at 12 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 37% PR and 0.025m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.35m depth, and 30° inclination angle, and Octagons with radius 0.10 and 0.13 m and 0.4 m depth fulfilled the required performance inside the office space (Table 9.10).

Table 9.10 The TABS system (external shading pattern and internal louvers), 21st of Sep. at 12 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 36.6% daylit and 64.4% overlit, concentrated in the area near to the window and the middle area of space and resulted in an inadequate performance regarding Task points illuminance for points1, 2, and 3 as they received 3243, 3619, and 3394 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, 2 and 3 as they received 39965, 39451and 3301 Lux respectively. Moreover, Intolerable glare 52%. On the other hand, the results showed that the configurations and the associated very low PR (37%) of the shading system contributed in minimising and distributing the excessive amount of daylight entering the space, and reducing the overlit area from 64.4 % in base case to 21.8% and prevented glare, as the results showed imperceptible glare 35%, however, it failed to achieve the required performance (80% daylit), and caused daylight over supplying in the area near to the window, resulted in an inadequate illuminance levels for task plan 1, 2 and 3 as they received 2728, 3039 and 2823 Lux, respectively, and subsequently, resulted in an inadequate daylight depth for points 1, and 2 as they received 39219 and 38471 Lux, respectively, and subsequently these high illuminance values, resulted in an illuminance contrast ratio out of the acceptable range.

On the other hand, the internal daylight redirecting system significantly succeeded in preventing direct sunlight from reaching the area near to the window and improved the daylight distribution inside space due to the louvers with 0.35m depth, and 30° inclination angle, and Octagons with radius 0.10 and 0.13 m and 0.4 m depth, as the results showed that the overlit area reduced from 64.4% in the base case to 2.4%. However, it failed in achieving an inadequate illuminance levels for task plan 2, and 3 as they received 2108 and 2005 Lux, respectively. On the other hand, it is succeeded in preventing glare, as the results showed imperceptible glare 33%.

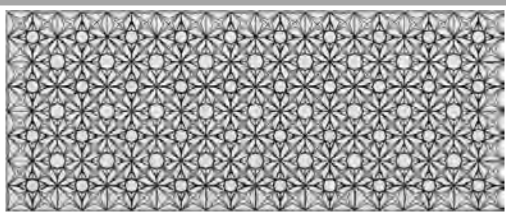
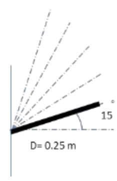
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The very low PR (37%) of the external shading system with a shallow extrusion (0.025m), contributed in efficiently controlling the excessive naturally available daylight by permitting sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.25m), and 30° inclination angle of the louvers and Octagons with minimum radiuses 0.10 and 0.13 m and deeper depth (0.4 m) of the daylight redirecting system, successfully contributed in minimising and redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 25% instead of Intolerable glare 52% in the Base case, also, the daylit area increased from 36.6% in the base case to 98.4% in TABS and the solar radiation significantly reduced.

In the light of that, it can be concluded that the very low PR of the TABS external subsystem, in addition to the depth (0.25m), and 30° inclination angle of the louvers, and the small openings and deep depth of the Octagons have the most contribution regarding the whole system performance.

21st of September at 3 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 73% PR and 0.025m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.25m depth, and 15° inclination angle and Octagons with radius 0.13 and 0.15 m and 0.15 m depth fulfilled the required performance inside the office space (Table 9.11).

Table 9.11 The TABS system (external shading pattern and internal louvers), 21st of Sep. at 3 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 70.8% daylit and 29.2% overlit, concentrated in the area near to the window and the middle area of space and resulted in an inadequate performance regarding Task points illuminance for points 2, and 3 as they received 2504, and 2856 Lux respectively, in addition to inadequate performance regarding daylight depth for points 1, and 2 as they received 20959 and 20502 Lux respectively. Moreover, perceptible glare 37%. In contrary, the results showed that the configurations and the associated high PR (73%) of the shading system maximised the benefit from the available daylight, and prevented glare, as the results showed imperceptible glare 33% instead of Perceptible glare 37% in the case of base case, however, it caused overlit in the near area to the window, as the results showed 15.8% overlit concentrated in the area near to the window, resulted in an inadequate illuminance levels for task plan 2, and 3 as they received 2404 and 2738 Lux, respectively, and inadequate daylight depth as points 1 and 2 received 20807, and 20395 Lux respectively, and consequently failed in achieving an adequate daylight contrast ratio. Moreover, it failed in reducing solar radiation as it received the same as the base case 70 KWh/m2.

On the other hand, the internal daylight redirecting system significantly succeeded in preventing direct sunlight to reach the area near to the window and improved the daylight distribution inside space due to the louvers with 0.25m depth, and 15° inclination angle, and Octagons with radius 0.13 and 0.15 m and 0.15 m depth, as the results showed that the overlit area reduced from 29.2% in the base case to 0.6%. Moreover, it succeeded in fulfilling other PIs, such as daylight depth illuminance, illuminance contrast ratio, and contribute to reducing solar radiation from 70 in the base case to 40 KWh/m2, in addition to in preventing glare, as the results showed imperceptible glare 29%.

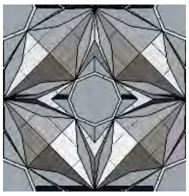
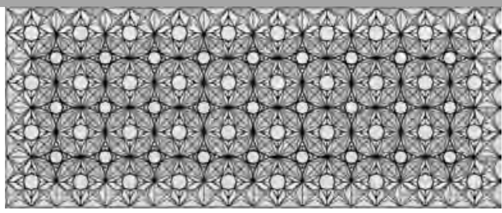
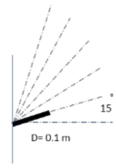
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The high PR (73%) of the external shading system with a shallow extrusion (0.025m) facilitates getting maximum benefit from the naturally available daylight by permitting sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.25m), and 15° inclination angle of the louvers and Octagons with intermediate radiuses of 0.13 and 0.15 m and 0.15 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 27% instead of Perceptible glare 53% in the Base case, in addition, the daylit area increased from 70.8% in the base case to 96.8% in TABS, however, the partially lit area increased from 0% in the base case to 2.6% in the case of TABS. Finally, the solar radiation reduced from 70 to 40 KWh/m2.

In the light of that, it can be concluded that the TABS daylight redirecting subsystem with (0.25m) depth, and 15° inclination angle of the louvers and Octagons with intermediate radiuses of 0.13 and 0.15 m and 0.15 m depth has the most contribution regarding the whole system performance.

21st of December at 9 am

The results showed that TABS consists of an external shading system with 52% PR and 0.05m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.1m depth, and 15° inclination angle and Octagons with radius 0.16 and 0.13 m and 0.1 m depth fulfilled the required performance inside the office space (Table 9.12)

Table 9.12 The TABS system (external shading pattern and internal louvers), 21st of Dec. at 9 am.

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 26.7% daylit and 73.8% overlit, concentrated in the area near to the window and the middle area of space and resulted in an inadequate performance regarding Task points illuminance for points1, 2, 3, 4 and 5 as they received 17909, 16621, 15800, 16516 and 15795 Lux respectively, in addition to inadequate performance regarding daylight depth for points points1, 2, 3, 4 and 5 as they received 16948, 16780, 16567, 16156 and 15721 Lux respectively. Moreover, Intolerable glare 59%. In contrary, the results showed that the configurations and the associated low PR (52%) of the shading system to minimise and distribute the excessive amount of daylight entering the space, and reducing the overlit area from 73.8 % in base case to 29.6 %, however, it failed in preventing glare, as the results showed Intolerable glare, and caused daylight over supplying in the near area to the window and the middle area of space, resulted in an inadequate illuminance levels for task plan 1, and 5 as they received 2447 and 14704 Lux, respectively, and subsequently, resulted in an inadequate daylight depth for points 1, and 2 as they received 15129 and 15092 Lux, respectively, and subsequently these high illuminances values, resulted in an illuminance contrast ratio out of the acceptable range.

On the other hand, the internal daylight redirecting system failed to prevent direct sunlight from reaching the space, consequently, caused overlit area in the near area to the window and the middle area of the space, as the results showed 45.2% overlit, resulted in an inadequate illuminance levels for task plan 1, 2, 3, 4 and 5 as they received 17072, 16784, 16403, 15772 and 2086 Lux, respectively. Subsequently, these high illuminance values resulted in an illuminance contrast ratio out of the acceptable range. Moreover, it is failed in preventing glare, as the results showed Intolerable glare.

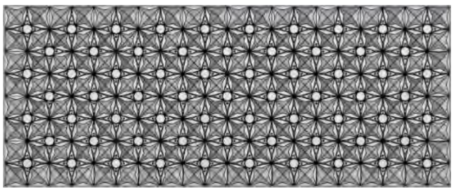
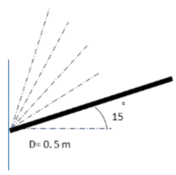
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The low PR (52%) of the external shading system with a shallow extrusion (0.05m) facilitates getting benefit and controlling the naturally excessive available daylight by permitting sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.1m), and 15° inclination angle of the louvers and Octagons with intermediate radiuses of 0.16 and 0.13 m and 0.1 m depth of the daylight redirecting system, did little regarding redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, failed to significantly minimise the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. However, results showed the TABS achieved imperceptible glare 32% instead of Intolerable glare 59% in the Base case. Also, the daylit area increased from 26.2% in the base case to 86.2% in TABS. Also, the solar radiation reduced from 80 to 40 KWh/m2.

In the light of that, it can be concluded that the both subsystems failed individually in achieving an adequate, however the integration of both subsystems contributed in achieving the required performance, due to the combination of low PR of the external subsystem, in addition to the depth (0.1m), and 15° inclination angle of the louvers and Octagons with intermediate radiuses of 0.16 and 0.13 m and 0.1 m depth of the daylight redirecting system.

21st of December at 12 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 38% PR and 0.25m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.5m depth, and 15° inclination angle and Octagons with radius 0.10 and 0.10 m and 0.4 m depth fulfilled the required performance inside the office space (Table 9.13).

Table 9.13 The TABS system (external shading pattern and internal louvers), 21st of Dec. at 12 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 1.2% daylit and 98.8% overlit, concentrated in the area near to the window and the middle area of space and resulted in an inadequate performance regarding Task points illuminance for points1, 2, 3, 4, 5 and 6 as they received 29484, 29835, 29633, 28300, 28727 and 28394 Lux respectively, in addition to inadequate performance regarding daylight depth for points points1, 2, 3, 4 and 5 as they received 30185, 30027, 29600, 29101 and 28588 Lux respectively. Moreover, Intolerable glare 84%. In contrary, the results showed that the configurations and the associated very low PR (38%) of the shading system contributed in minimising and distributing the excessive amount of daylight entering the space, and reducing the overlit area from 98.8 % in base case to 27.2 %, and succeeded in preventing glare, as the results showed imperceptible glare 35%, it caused patches of daylight over supplying in the near area to the window and the middle area of space, resulted in an inadequate illuminance levels for task plan 2, and 3 as they received 27505 and 2080 Lux, respectively, and subsequently, resulted in an inadequate daylight depth for points 1, and 2 as they received 29439 and 27888 Lux, respectively, and subsequently these high illuminance values, resulted in an illuminance contrast ratio out of the acceptable range.

On the other hand, the internal daylight redirecting system failed to prevent direct sunlight from reaching the space, consequently, caused overlit area in the near area to the window and the middle area of the space, as the results showed 46.8% overlit, resulted in an inadequate illuminance levels for task plan 1, 2, 3, 4, 5 and 6 as they received 4545, 5147, 4884, 2671, 3091 and 2632 Lux, respectively. Even though, these high illuminance values, it achieved an acceptable illuminance a contrast ratio of. Moreover, it is failed in preventing glare, as the results showed Disturbing glare 44%.

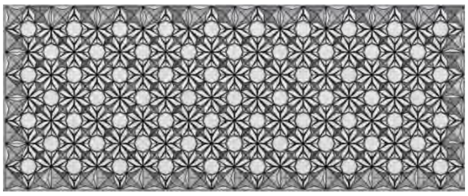
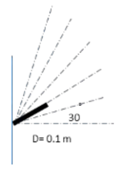
The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The very low PR (38%) of the external shading system with a deep extrusion (0.25m) facilitates controlling the excessive amount of the daylight entering space and permitting only a sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.5m), and 15° inclination angle of the louvers and Octagons with a small radiuses 0.10 and 0.10 m and 0.4 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 28% instead of Intolerable glare 84% in the Base case, also, the daylit area increased from 1.2% in the base case to 98.8% in TABS and the solar radiation reduced from 80 to 38 KWh/m2.

In the light of that, it can be concluded that the system very low PR (38%), extrusion of the shading system, the louvers depth (0.5m), and 15° inclination angle and Octagons with a small radiuses 0.10 and 0.10 m and 0.4 m depth has a contribution regarding the whole system performance, however, the contribution of the shading subsystem outweighed the contribution of daylight redirecting subsystem regarding the whole TABS performance.

21st of December at 3 pm

The results showed that TABS consists of an external shading system (geometrical patterns) with 61% PR and 0.25m extrusion, and the internal daylight redirecting system consists of horizontal louvers with 0.1m depth, and 30° inclination angle and Octagons with radius 0.18 and 0.18 m and 0.4 m depth fulfilled the required performance inside the office space (Table 9.14).

Table 9.14 The TABS system (external shading pattern and internal louvers), 21st of Dec. at 3 pm

Pattern	Section	Perspective	Louver inclination angle
			

The results showed that the Base case achieved 38.4% daylit and 61.6% overlit, concentrated in the area near to the window and the middle and the rear area of space and resulted in an inadequate performance regarding Task points illuminance for points1, 2, 3, 5, 6 and 9 as they received 2026, 14090, 15449, 13340, 14179 and 12880 Lux respectively, in addition to inadequate performance regarding daylight depth for points points1, 2, 3, 4 and 5 as they received 14398, 14209, 14079, 28588, and 13333 Lux respectively. Moreover, Intolerable glare 53%. In contrary, the results showed that the configurations and the associated intermediate PR (61%) of the shading system contributed in minimising and distributing the excessive amount of daylight entering the space, and reducing the overlit area from 61.6 % in base case to 39.6 %, however, it failed in preventing glare, as the results showed intolerable glare, and it caused patches of daylight over supplying in the near area to the window and the middle area of space, resulted in an inadequate illuminance levels for task plan 2, 3, 5, and 6 as they received 13175, 14084, 12616 and 2068 Lux, respectively, and subsequently, resulted in an inadequate daylight depth for points 1, 2, 3, 4 and 5 as they received 13527, 13363, 13040, 12794 and 12586 Lux, respectively, and subsequently these high illuminance values, resulted in an illuminance contrast ratio out of the acceptable range.

On the other hand, the internal daylight redirecting system failed to prevent direct sunlight reaching the space, consequently, caused overlit area in the near area to the window and the middle area of the space, as the results showed 20.8% overlit, resulted in an inadequate illuminance levels for task plan 1, 2, 3, and 9 as they received 2363, 2872, 2832, and 12120 Lux, respectively. Subsequently these high illuminance values resulted in an illuminance a contrast ratio of out of the acceptable range. Moreover, it is failed in preventing glare, as the results showed perceptible glare 36%.

The integration of both subsystems contributed in achieving an adequate performance regarding all the six PIs. The intermediate PR (61%) of the external shading system with a deep extrusion (0.25m) facilitates getting maximum benefit from the naturally available daylight by controlling the excessive amount of the daylight entering space and only permitting a sufficient amount of daylight to enter the space, in addition to, blocking the direct sun rays that could pass through the gaps of the daylight redirecting subsystem. The positioning, depth (0.1m), and 30° inclination angle of the louvers and Octagons with wide radiuses 0.18 and 0.18 m and 0.1 m depth of the daylight redirecting system, successfully contributed in redistributing the daylight that passing throughout the shading system and redirecting it to the deep plan. Subsequently, minimised the possibility of entering direct sunlight to the area near to the window and maximise the daylight depth in space and prevent glare. As the results showed the TABS achieved Imperceptible glare 26% instead of Intolerable glare 53% in the Base case, also, the daylit area increased from 38.4% in the base case to 87.6% in TABS and the solar radiation reduced from 80 to 40 KWh/m2.

In the light of that, it can be concluded that the system intermediate PR, extrusion of the shading system, the louvers depth (0.1m), and 30° inclination angle and Octagons with a small radiuses 0.18 and 0.18 m and 0.4 m depth has a contribution regarding the whole system performance, however, the contribution of the shading subsystem outweighed the contribution of daylight redirecting subsystem regarding the whole TABS performance – see Figure 9.8.

Q6. Does the (TABS) achieve the proper equilibrium that needs to be made between performance merits of people, planet and profit, according to the Triple Bottom Line principle?

The results showed that (TABS) could contribute positively to all the Triple Bottom Line principles of people, planet and profit.

People: the results showed that (TABS) succeeded in fulfilling the required criteria and maintained performance indicators at a certain desired levels such as Task plan illuminance (500 – 2000 Lux), daylight distribution (300 -3000 Lux) at 80% of space and imperceptible glare (≤ 35%) at all the twelve examined times resulting in improving indoor environmental quality regarding visual comfort, and providing pleasant working environments that accompanying with better health and productivity based on previous theoretical approach of the positive impact of daylighting on users health and productivity (Mathew and Kini 2016). Moreover, creating luminous conditions that satisfy the occupants' needs can produce pleasant emotional state within the working space that is leading to greater performance, higher effort, less conflict, and greater willingness help others" (Veitch 2000).

Planet: the results showed that (TABS) succeeded in affording the desired illuminance levels at all the 9 task points inside space as well as improving the daylight depth to 3x in addition to a significant reduction in solar gains levels at most of the twelve examined times resulting in higher potential energy savings compared to conventional building skin. Consequently, in less need for using fossil fuel based energy, and lower load on the earth's environment based on previous theoretical approach of the positive impact of daylighting. For example, (Phillips 2004), states that the energy used by artificial lighting is a significant portion of the energy consumption in buildings, and it is perceived that reduction of artificial lighting will lead to decrease the emissions of carbon dioxide, consequently, will help in the reduction of greenhouse gases and have a vital influence in decreasing global warming. The greater use of daylight will lead to a reduction in the use of electrical energy and assist significantly in the battle of to solve the energy crisis.

Profit: the results showed that (TABS) is capable of continuously maintaining an adequate daylighting performance inside space during the all examined times that represents the four seasons during the entire year by exploiting the natural available daylight without needs to artificial lighting, resulting in a higher potential for energy savings, and consequently leads to reduced owners energy expenses as well as increasing the productivity levels, which considered as economic aspect as well, based on previous theoretical approach of the positive impact of daylighting on energy saving and employee productivity. According to (Thayer 1995), a well-integrated daylighting design can contribute to achieving 50% savings in lighting, cool and ventilation, energy as well as a 15% reduction in employee absenteeism. Also, TABS have an impact on more indirect performance aspects such as the cultural sustainability, by the utilisation of Vernacular architectural elements such as Mashrabiya screen in an innovative way as a source of inspiration, and subsequently representing the identity of the Egyptian culture, which confirm previous theoretical approach of utilising Vernacular architectural elements as a source of inspiration, according to (Radwan), these traditional screens inspired nowadays architects by harnessing the current advanced technologies in designing modern versions of these types of screens as a mean to reflect the local cultural identity in the form of static and active systems. Which was one of the main objectives of designing (TABS).

Therefore, Adaptivity in the building skin offers architects and designers an attractive additional design variable, and confirm the previous theoretical approach of the idea of performance as it can be discussed based on the context of the specific project and understood in a very broad sense, reaching fields like economy, spatial planning, society, culture or technology (Kolarevic 2004).

The aforementioned discussion, showed that providing adequate daylight, making a visually stimulating and healthful interior environment, as well as expressing the cultural identity can be attained by incorporating a well-designed (TABS) that efficiently capable of negotiating with its surrounding environment while addressing its own context identity, and give a fully answer to the main research question.

Chapter Ten

10. Conclusion

Can a (TABS) be efficiently capable of negotiating with its surrounding environment to optimise daylighting performance while addressing its cultural identity?

This research question, introduced in Chapter 1, was answered in nine steps:

- What lessons can be acquired from the historical development of building skin and daylighting strategies, and what characterises indoor daylighting quality of office buildings? (Chapter 2)
- What characterises adaptive behaviour for a building skin? (Chapter 3)
- How have recent advancements in computational tools (parametric, building performance simulation (BPS), and Genetic Algorithms (GAs)) influenced the architectural design process, and what advantages do these tools afford to the design process of a (TABS)? (Chapter 4)
- Which functions can a (TABS) be expected to perform in the context of daylighting quality, and how the geometric configurations of TABS can be designed to influence this performance? (Chapter 5)
- How can the TABS performance at different seasons based on predefined criteria be assessed and optimised? (Chapter 6)
- How to validate the TABS daylighting performance-driven model? (Chapter 7)
- How do an optimised TABS solutions perform at all the twelve examined times regarding each performance indicator in comparison to Base case, (AOWWR), and (AOSBE), and how each subsystem contributed to the whole system performance at each time? (Chapter 8, and 9)

Chapter 10 summarises the findings of this research, evaluates the method used to obtain them, discussed the significance of the study, and presented the research limitations. Also, the thesis procedure has provided additional questions that could not be answered within the scope and time frame of this Ph.D., and these questions and recommendations for future research are presented.

10.1. Findings from the study

Buildings have significant impacts on the people who use them and the physical environment in which the buildings are located. In trying to reduce the impact on people, by improving the conditions in which they operate in a building, there is often an increase in energy use, with a consequential environmental impact. Particularly in hot, arid climates, such as that of Egypt, the building skin plays a major role in determining internal comfort conditions. The form of the external facades takes traditionally is a compromise between competing demands for solar control and good daylight. Technological advances have now made possible dynamic facades (i.e. TABS) that respond intelligently to the external environment to enhance the internal environment.

In this study, the main question asked was whether dynamic facades, inspired by traditional Islamic architectural forms while integrating with dynamic louver systems, could be modelled and optimised to meet predefined daylighting criteria and achieve an acceptable visual environment in a contemporary Egyptian office building.

For the dates and times studied the results demonstrated that a (TABS) was capable of adjusting its geometric configurations on an hourly basis in response to changes in the outdoor climate to improve the daylighting performance inside an office space. At the same time, the office's façade reflected cultural identity as the physical appearance of each optimised facade was an authentic representation of the Mashrabiya form. Consequently, the study proved that a well-designed TABS system could be both a complex geometry that satisfies the aesthetic desires of designing contemporary facades inspired by ornament and renovated traditional patterns, while also addressing concerns over building performance and user comfort throughout the entire year.

The integration of parametric design, genetic algorithm (GA) and building performance simulation (BPS) played an effective role during the three main stages of the TABS development. During the conceptual stage, it facilitated "modelling", "integrating", "activating", and "exploring" the local traditional shading and daylight redirecting strategies in a modernised way as a source of inspiration. During the form generation and evaluation stage, it helped in generating and evaluating a broad range of design alternatives. During the optimisation stage the integration aided in identifying the most successful solutions of the (TABS) at all the examined times with their associated performance based on the predefined criteria. This resulted in integrating and evaluating the ornamental desires of contemporary architecture with the urgent necessity to produce designs that optimise daylight performance.

The results for the dates and times studied demonstrated that it was possible to model and optimise TABS-based facades that delivered against predetermined daylighting and solar gain criteria. The optimised TABS were always able to meet the illuminance criteria within the office space and to distribute natural light deep into the room in a consistent fashion with little risk of creating glare conditions. Also, the TABS provide a substantial reduction in solar gain into the office space in comparison with static "non-adaptive", conventional envelope model such as (AOWWR), and (AOSBE). However, the effectiveness of the system did vary at different times of the day and year.

An important aspect of this study, which does not often appear in other facades parametric optimisation research, was the attempt to test some of the optimised simulation data against physical measurements. The agreement for overcast sky was excellent, while for the more difficult-to-represent, clear sky situation there was broad agreement on the nature of the illuminance variations across the office.

The TABS was effective in improving the daylight performance and reducing the energy that would be used by lighting control systems. These improvements are realised in the four distinct seasons of the year. However, the envelope's effectiveness decreases as environmental conditions become more extreme, especially when the sun angle is low, such as during the winter. Conversely, the envelope's effectiveness increases when the sun angle is high during the summer season. Moreover, incorporating the ability of monitoring of ambient environmental stimuli, occupant needs, and building energy consumption, via building management and TABS control systems, combined with a capacity to predict future changes in the weather and user/energy requirements, would increase the system efficiency. These systems would afford the capability to take lessons from past situations, and efficiently make trade-offs between objective functions, and thereby minimise inadequate responses.

This research did not identify a time or season that the TABS failed to utilise the full range of the predefined adaptive response variables available through the methodology, except for 21st December at 12 pm, when the TABS used the maximum constraint value set for Louver Depth parameter and failed to achieve the requisite performance. It was required to extend the maximum value from 0.4 m to 0.5 m to achieve the required performance.

Generally, TABS optimised scenarios during the four seasons reached the limits set for each respective response variable (maximum or minimum constraint), to fulfil the predefined criteria at all the twelve examined times. Subsequently, this indicates that the larger the range between minimum and maximum limits of design parameters, then the more chances for the TABS to find optimal responses to specific conditions.

The efficiency of TABS to negotiate with its surrounding environment to exploit the maximum benefits of the naturally available resources, while eliminating potential hazards or drawbacks, is expected to improve as more adaptability is embedded into the building skin. Moreover, the well manipulated whole TABS rather than individually separated adaptive possibilities make it more likely that unexpected drawbacks in the system configuration would be eliminated, resulting in smooth control over the system to maintain satisfactory performance.

The importance of each design parameter varies between times and seasons. In this research, TABS external subsystem's parameters that controlled form and perforation ratio in addition to the TABS internal subsystem parameters, which controlled the subsystem's elements' depths, were found to be the most frequently reported variables of importance to optimise daylighting performance and reducing direct solar radiation. Therefore, it is recommended that these design parameters are dominant for developing such integrated systems. These parameters would have the greatest effect on controlling the daylighting performance, consequently reducing lighting energy and affecting heating and cooling energy consumption. However, the percentage of daylight performance improvement or reduction in solar radiation that these parameters separately account for, in the absence of other design parameters, cannot be identified with the available data.

TABS was effective in handling the variety of different needs and performance indicators (six performance indicators, in addition to maintain external view), throughout all the examined times that represented the four seasons, such as optimising task points illuminance levels, daylight penetration depth (2x) and adequate daylight distribution (80% of the space), along with reducing solar radiation to prevent excessive heat gains in the area near to the window and maintain imperceptible glare (≤ 35%).

Increasing the number of targeted performance indicators will limit the system's capability to adapt to different scenarios, or reduce the number of successful alternatives for each scenario. For example, the occupant's external view or maintaining visual connectivity with the external environment wasn't a part of the predefined criteria as a performance indicator. However, it is important to note that it is a part of the fenestrations function itself. Therefore, it is considered during the selection of the final successful solution out of the group of successful solutions for each time, as the preference was determined to select the successful solution that fulfils the predefined criteria, with geometric configuration that achieves the highest possible PR and louver with minimum depth and inclination angle between -15 to 30 if it is available, to ensure an external view to the occupants.

In the light of that, the addition of a control parameter that sets to maintain a minimum view possibility during working hours is expected to reduce the system capability as a result of the system would have to rely more on the maximum PR and minimum internal elements depth and inclination angles for the control of solar radiation and natural lighting. Consequently, even for successful solutions, it would be expected that energy use for cooling demand could be increased under extreme weather conditions as the TABS would be restricted to maintaining the occupant's view leading to increasing the possibility of additional direct solar radiation entering the space.

TABS would afford a significant advantage for meeting changing users' preferences, as the system can respond to existing conditions to provide the optimal geometric configurations to cope with changes in users need and unforeseen future conditions.

The integration of two daylighting systems in one integrated system (TABS), consisting of both shading and daylight redirecting sub-systems, accomplished a compatibility regarding both aesthetic and functional aspects.

Functionally, both sub-systems succeed individually in fulfilling a variety of performance indicators on different occasions. However, both sub-systems failed in fulfilling the complete six performance indicators except in a few occasions. In contrary, the full system succeeded in fulfilling all the performance indicators at all the examined times. However, it is necessary to highlight that the TABS was optimised as an integrated system and not as a combination of individually optimised subsystems.

Regarding, the aesthetic aspects, the geometric integration of both systems did not affect the visual appearance of the optimised TABS solutions.

As proved in this study, (TABS) achieved the proper equilibrium that needs to be made between performance merits of people, planet and profit. As the idea of performance discussed here was based on the Egyptian context of a specific building type. However, it can be applied and understood in a very broad sense, reaching fields like economy, society, culture and technology.

10.2. The significance of the study

The findings of this study will contribute considerably to both the general benefits of all the three aspects of the Triple Bottom Line principles: people, planet and profit, and the specific local Egyptian concerns discussed in the problem statement of this research. As proved in this research, architecture can play a dominant role, along with science and technologies, in solving human concerns, aiming for healthier and economic life conditions.

The greater demand for pleasant interior environments, energy savings, and cultural identity conservations within the current dynamic societies and the fluctuating environmental conditions justifies the need for more efficient building skin approaches, such as (TABS).

Egypt and other Middle Eastern countries that apply the recommended approach derived from the findings of this study will be able to get benefits from the currently necessary Western technology and construction's expertise without mimicking Western buildings. Instead, buildings can reflect local contextual needs and cultural identity in a modernised way that mirrors the dynamic nature of current societies and the advancements of current technologies.

For researchers and designers, this study will help in uncovering critical areas in the design process of such approaches that they were not able to explore previously. This research assists as an exploration into the effectiveness of future (TABS) for office buildings in a hot desert climate and their possible limitations in satisfying the multi-dimensional criteria derived from tangible forces, such as the weather conditions, or intangible forces, such as the forces arising from cultural and regional heritage that are defining the surrounding context of the building. Although the TABS discussed within the context of this thesis regards the Egyptian local context, the concept and the methodology utilised are applicable in different cultural contexts and climatic conditions.

Moreover, with the rise of the digital age, the ornament can make a comeback in design (Gleiter 2012), as an expression of contemporary culture and spirit. However, the current practice with computational tools is usually aesthetically oriented and rarely addresses the functional and performance issues.

Furthermore, integrating standard and semi-standard traditional daylighting devices, such as louvers and light shelves, with the contemporary complex pattern geometries and highly articulated buildings' forms within the design process become a challenge, not only regarding their design but also regarding their performance evaluation.

A methodology for aesthetically and functionally satisfying the ornamental desire of contemporary architecture in a performative way is presented in this thesis by recalling local vernacular patterns and architectural elements, through the process of modelling, activating, and exploring this kind of patterns and features. Also, integrating these patterns with louver systems can generate a broad range of design alternatives associated with their performance and the capability of design optimisation at specifically chosen times to meet a required performance based on a predefined multi-objectives criteria to aesthetically and functionally satisfying its "Territorial" requirements.

Finally, investigating the integration of performance simulation techniques and computational methods, especially in early design stages, will open up a much better understanding and improvement in architectural practice in Egypt. The algorithms and resulting data provide quantitative knowledge on theoretical building performance and will help guide future design decisions relating to the applicability of adaptive building envelopes in Egypt.

By exemplifying how to acquire data and use it to inform design decisions will help shift the complexity of contemporary forms from product to process. Resulted in understanding the trend of computational design root itself in purpose and meaning and begin to engage with real issues. Finally, the representation of this data in and on buildings may become a new method of architectural ornamentation that stands for something further than the flashy image of the final product of parametric design.

10.3. Methodological considerations and research limitations

Although the research has reached its aims, there were some unavoidable limitations. Mainly, the study is limited by the extensive simulation and optimisation computer processing times, which are required to achieve quality results for a large number of building models at twelve examined times regarding six performance indicators (PIs), which required a variety of daylight, solar irradiation and glare simulations. This had an effect that can be summarised in five main points: Number of cases studies, Performance Indicators, Quality of results, Genetic algorithms, and the absence of surrounding context and furniture inside the space. Each point is discussed in the following sections.

Number of cases studies

There are a broad range of facade design strategies regarding daylight, such as, but not restricted to, building mass and orientation, window-to-wall ratio (WWR), glazing type, solar screen, horizontal and vertical louver, light shelf, and a wide range of dynamic systems, and not just those discussed in the previous chapters: (AOWWR), (AOSBE), and TABS. Due to time limitations, and the intention to evaluate the TABS sub-systems' contributions regarding the whole system’s performance at all the twelve examined times, only these three cases were studied, in addition to the Base case. As this study was mainly planned to be a comparative performance study of TABS regarding other traditional alternatives, then increasing the number of alternative daylight strategies and considering different building orientations would be efficient for widening the scope of this thesis to identify the capabilities and limitations of TABS.

Performance indicators

The science of daylighting assessment includes a variety of aspects, such as brightness (comparative luminance) of room surfaces; task illuminance; task contrast; source luminance (glare); daylight (view); spatial and visual clarity; visual interest; psychological orientation and occupant control and system flexibility. Due to time limitations, only a limited number of indicators were studied, thus narrowing down the scope of this thesis to include: Task plan illuminance, luminous distribution, contrast ratio and glare in addition to two associated parameters, which are daylight penetration depth, and solar radiation). Considering other parameters would improve the process of the TABS performance assessment, but add enormously to the computational processing time.

Quality of results

Due to the complexity and number of simulations performed in this study, it was crucial to choose validated simulation tools and recommended simulation parameters. Thus, DIVA, a plug-in for the Rhinoceros and Grasshopper environment, was used in this study as it supports a broad range of performance evaluations by utilising validated tools, including Radiance, Daysim, and Evalglare, for the prediction of illuminance calculations, various radiant, and glare, using sun and sky conditions derived from standard meteorological datasets; the results were dependent upon both the building's location and orientation, in addition to the facade composition and configuration.

For the setting of radiance parameters in DIVA, an ambient bounce (ab- 6), is recommended for better quality of results.

Due to the complexity of the TABS geometry and the number of simulations performed in this study, in which runtime was very long and the number of runs was very large, some simplification regarding the parameters of RADIANCE was assumed. An ambient division of 1000 was used since screens do not result in high brightness variation. Ambient accuracy was chosen to be 0.1, which was adequate for the nature of the screens tested in this research, in which the screens was limited in size (10 m). Also, ambient bounces were selected to be (ab = 2) (to reduce the extraordinary long processing time that resulted from the complication of the TABS configurations. The effect of this assumption on the accuracy of the results was tested using DIVA for Rhino (point-in-time illuminance with illuminance values Min. 300, and Max. 3000 Lux), where the deviation of results from the commonly assumed bounces (ab- 6) was measured. The same Two optimised (TABS) designs that were chosen for the validation process were selected for this testing: optimised (TABS) designs of the 21st of June at 12 pm, and 21st of December at 12 pm, as a representation of summer and winter seasons. Deviation in both cases was very limited. The deviation of illuminance values was only 0–0.08%, increasing in the "overlit" area, and 21-32%, rising in the Mean illuminance values for summer and winter screen, respectively.

The effect of this deviation on research conclusions "under two conditions" was considered unimportant in comparison with the processing time saved.

First, excluding the successful alternatives that achieved task point illuminance values close to the upper threshold (2000 Lux) during the selection of the successful solution of each examined times during the optimisation process using Diva for Grasshopper.

Second, all the twelve final optimised TABS solutions should achieve 80% daylit area of space using DIVA for RHINO (point-in-time illuminance), with RADIANCE ambient bounces parameter (ab- 6). Otherwise, the solution is not considered, and the optimisation process should be repeated to find another successful solution.

However, for a better quality of results in future, using the recommended simulation setting parameters would improve the process of the TABS performance assessment, and should be considered.

Genetic algorithms

The Genetic algorithm Galapagos employed in the simulation methodology of this research succeeded in identifying a group of successful solutions that meet the required performance at all the examined times. In this section, certain limitations of Galapagos will be discussed.

First, the main limitation of the evolutionary algorithms is that it is slow and sometimes needed days of computing time to define a successful group of solutions. This because the Galapagos component is requested to Diva components to simulate the building for both illuminance calculation and solar radiation, with each alteration to the TABS parameters.

Therefore, due to the complexity of the TABS configuration, the Grasshopper definition utilised in this research endured many enhancement stages, using more advanced modelling techniques to improve the smoothness of the definition and minimising the time required for each alteration occurred to the TABS parameters. However, for a faster process in the future, more advanced or different modelling techniques could save more time.

Second, regarding the accuracy of the obtained results in the optimisation process, one of the limitations is using a single objective Genetic Algorithm tools (Galapagos) in solving multi-objectives problem. However, there is another multi-objectives solver (Octopus) that can optimise a problem with up to five fitness functions.

Octopus is a comparatively newly developed plugin for the Grasshopper, and only a limited number of researchers have used it. Therefore, Galapagos was chosen as it is widely used and more validated than the newly developed Octopus.

The optimisation problem, related to the selection of successful TABS in an office building for each examined time, was solved using a daylight-related function (optimising the task point's illuminance of 9 nodes inside the space). Moreover, the listing, sorting, dispatching, and the mathematical components of Grasshopper were utilised effectively to overcome the limitation of Galapagos and evaluating other performance indicators, and successfully identifying a group of successful solutions at all the examined times that fulfilled the six PIs. However, for a less complicated process in the future, exploring the capabilities of other multi-objective solvers, such as Octopus or any newly released tools with advanced capabilities in solving such design problems, would be efficient.

Third, these algorithms do not guarantee a solution. Unless a well-defined setup for the problem has been defined or increasing the number of generations and populations in each generation to increase the number of the explored alternatives, consequently increasing the possibility of identifying the successful solution.

Due to the time limitation and a large number of the optimisation processes endured during this study, and the intention to identify a group of successful solutions, rather that identifying the absolute optimum solution for each time an intermediate number of individuals per generation was used (35 out of 50 recommended).

Despite this reduction of the evaluated alternatives for each optimised times, a minimum of 1000 up to 2500 design alternatives were generated and evaluated for each time and a group of successful solutions was identified as the results showed a significant performance of TABS at all the examined times, if compared to other optimised "traditional" solution. From the author's viewpoint, this is considered as a proof of the effectiveness of the proposed methodology.

However, for exploring a wider range of design alternatives and achieving a higher performance in future researches, increasing the numbers of generation and individuals per generation will improve the quality of the research results. It was remarked that the performance of the design alternatives is improving from one generation to the next, indicating that allowing Galapagos to generate more generations would result in more improved solutions with higher performances.

The absence of surrounding context and furniture inside space

The internal and external surfaces, such as the internal furniture and the surrounding context surfaces have certain reflectance, which could have impacted upon the indoor luminous environment depending on the location of the office. Both were excluded during the simulation. Consequently, this limitation could have affected the behaviour of daylighting inside the space.

Due to the intention to focus on the TABS performance, without any internal of extra external impacts other than the internal enclosure surfaces of the office space, the decision to exclude the furniture and surrounding context surfaces was made.

However, for more realistic results and better understanding of the capabilities and limitations of TABS, considering theses impacts would improve the process of the TABS performance assessments.

10.4. Applicability of the research framework and design

This study has presented a methodology for modelling, form generating, evaluating and optimising the daylighting and solar control performance of TABS inside a south facing office space in Cairo, Egypt, based on predefined criteria by using it is own predefined geometric configuration capabilities.

The TABS system integrated two main subsystems: an external shading sub-system, inspired by traditional Egyptian patterns and solar screens “Mashrabiya”, and an internal daylight redirecting sub-system consists of horizontal louvers and Octagons forms.

The findings demonstrated how the TABS system with it is own predefined geometric configuration’s capabilities, has continually been able to adjust its overall geometric configuration to significantly improve the daylight performance and decrease the amount of solar radiation transmitted into the tested space at all the twelve examined times that represents the four seasons of the entire year.

Moreover, analytical studies were endured to evaluate the performance of each sub-system subsystems, so that a clearer understanding of the relative importance and the contribution of each subsystem regards each performance indicator were made. Such approach is helpful in demonstrating the capabilities and limitations of integrating different daylighting systems, as well as reduce the complexity of a TABS system by recognising which role each sub-system can play in improving the whole system performance, in addition to which sub-system’s components might be designed as dynamic or fixed elements.

The framework developed and examined in this study makes such an approach feasible in the future. Furthermore, as proved here, the combination of parametric design, building performance simulation (BPS), and Genetic Algorithms tools in an integrated daylighting performance driven design model is a valid strategy for exploring, evaluating, and optimising solutions to building environmental performance problems. A comprehensive setting of the design problem and further improvement in the simulation tools could overcome the main difficulties found in this research.

Finally, although the methodology was tested for a certain design problem, in one specific cultural context and environmental condition, that could correspond to an advanced stage of the design process of office buildings in Egypt, a similar approach can be used in order to optimise problems for other building types in Egypt such as educational facilities, hospitals, residential buildings and factories, as each building considered to be a fragment of the city image, that reflects it is territorial tangible and intangible forces. Moreover, it can be applied in different cultural contexts as each country has its contextual climatic conditions and magnificent cultural "Identity.".

10.5. Further research

Within the context of this study, many questions were raised regarding the sources of inspiration, methodology, performance indicators (PIs), and design parameters' domains of variables, modelling, exploring, optimising and performance assessment tools and assumptions underlying this research.

The final resultant decisions were made based on the desire of how to efficiently investigate the capabilities of a theoretical (TABS), balancing the design model within a hypothetical logical system with an acceptable range of feasibility concerns while assuring a detailed methodology with enough specificity for Architects, designers and researchers to expand on.

To this extent, the output of this research provides a starting stage for other researchers to explore how TABS can perform in different Territorial contexts while still improving occupant comfort and minimising energy consumption. Further researches can be done in different cultural contexts and weather conditions with the aim of achieving various objectives, as many variables remain to be examined to define the applicability of this theoretical (TABS) in different cultures and climates. Moreover, the multidimensional criteria that currently exist due to the desire of integrating multiple functions into a single environmental barrier added more complexity to the building skin's design, manufacturing and maintenance. Therefore, successfully balancing all these objectives required a well-studied trade-off process to achieve successful solutions.

Several general questions identified within this research that was not explored and which deserve consideration for further work are presented in the following sections:

• The adaptation mechanism that TABS sub-systems utilised is categorised as a macro scale of adaptation that was accomplished via the changes in the building skin's configuration associated with the apparent movement of its parts such as rotating, folding, sliding, etc. Utilising the demonstrated methodology for evaluating the performance of a system that integrates both macro and micro scale adaptation mechanism will add more opportunities to explore the capabilities of integrating different adaptation mechanism in one integrated TABS system.

• Modification of the utilised methodology could be carried out to improve the model and alternative methods and objective assessments that are not addressed in this study. Using additional or similar modelling, simulation, and optimisation tools, design parameters, performance indicators and working assumptions, to refine and simplify the methods used while maintaining accurateness.

• The results of this study can be reviewed and compared for other environmental aspects such as thermal comfort, natural ventilation, energy consumption, digital fabrication and life cycle costs.

• Future studies can be built upon the current one and explore an expanded set of optimisation criteria, combining thermal comfort indicators with visual comfort ones.

• Extending the scope of environmental stimuli to include the wind, air pollution, and rain would be relevant as these parameters could negatively affect the indoor spaces. Consequently, TABS system capable of mitigating these adverse impacts will ensure a pleasant and productive indoor spaces.

• For the purpose of examining the performance of TABS, furniture and contextual surrounding buildings has been eliminated from the simulation, for quick-easier runs and more controlled simulation environment in addition to ensuring similarity between the simulation and the scaled model during the validation process.

The existence of furniture and the context of which a building with TABS allocated along with its interior functions will significantly affect how the skin responds to environmental stimuli. Therefore, surrounding context, including height from the ground, solar obstructions due to neighboring buildings, types of building function, and temporary and permanent functional changes in interior space, are examples of numerous variables that should be examined to outline the functionality of TABS.

• The application area of the TABS in this research was limited to the south facing skin. Further research considering different orientations and implementation areas such as building roofs would be an appropriate direction for the future research to outline the functionality of TABS.

• The current study was limited to designing, evaluating and optimising TABS, in addition to deconstructing the TABS to two main sub-systems to evaluate the contribution of each sub-system regarding the performance of the whole system.

In future, applying further studies aiming for deconstructing the TABS sub-system to individual parameters could be an assistance as it may expose vital knowledge about the importance of each parameter and give an impact weighting for each of them at different times during the entire year.

This approach could be helpful in reducing the complexity of the system by recognising which variables are valued being designed as adaptable or fixed. Moreover, simplifying the required movements of the TABS parts to the minimum could be important towards a less complexity, are appropriate directions for the future research.

• In addition to office buildings, further analyses could be conducted to explore the advantages of applying TABS to a variety of building types, such as educational facilities, hospitals, residential buildings and factories can be explored, as a variety of performance requirements according to the building program, the tasks and activities of the users, regarding daylighting quality, will be a relevant direction for future research.

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Appendices

Appendix A

Stage One: Results of the Performance of TABS System and Sub-Systems.

First Phase:

- TABS System and Sub-Systems performance on 21st of March, June, September and December at 9am and 15 pm regarding performance indicators: Task point's illuminance, Illuminance distribution, Illuminance contrast ratio, Daylight depth and solar radiation.

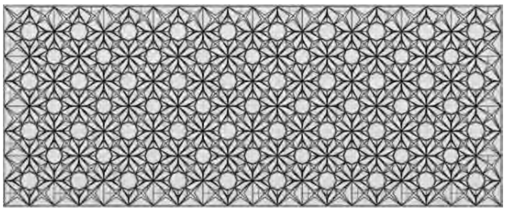
Second phase: Daylight Glare Probability (DGP).

- TABS System and Sub-Systems performance on 21st of March, June, September and December at 9am and 15 pm regarding performance indicators: Daylight Glare Probability (DGP).

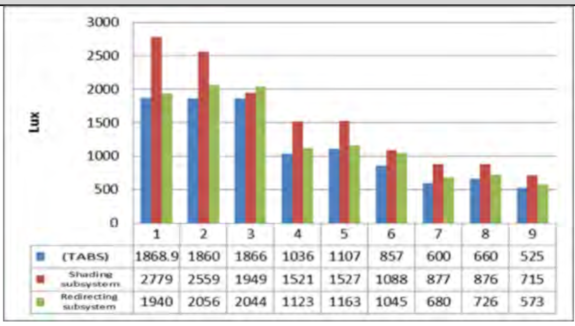
Stage One (First Phase):

21st of March at 9 am:

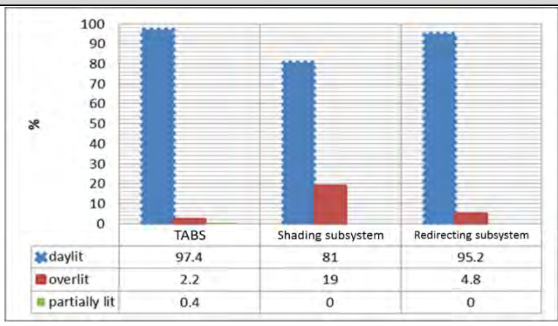
TABS configuration for Mar. 21st at 9 am

	Pattern	Section	Perspective
9 am			

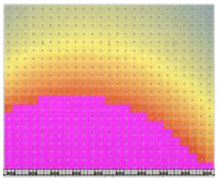
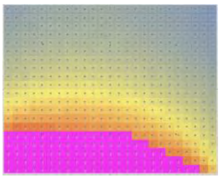
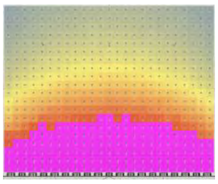
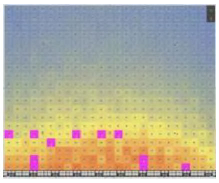
Task points Illuminance



daylight distribution



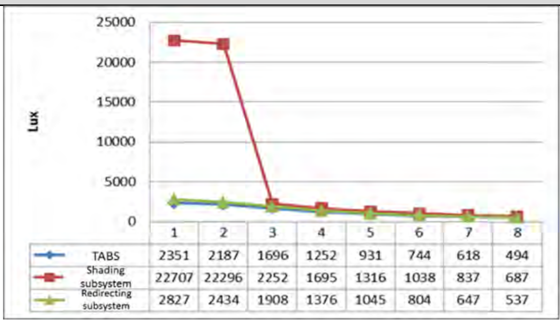
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
9 am					

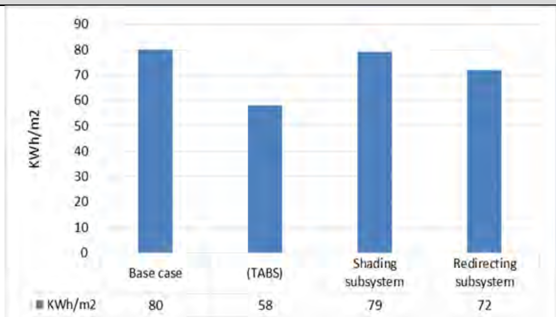
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	2351	494	1:5
TABS's shading subsystem	22707	687	1:33
TABS's redirecting subsystem	2827	537	1:5

Daylight depth

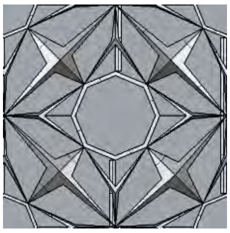
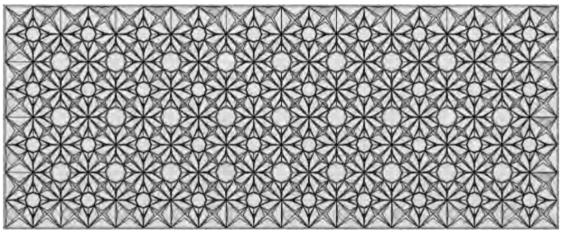


Solar radiation

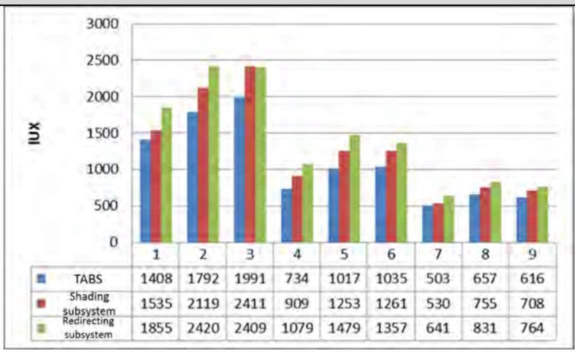


21st of March at 3 pm:

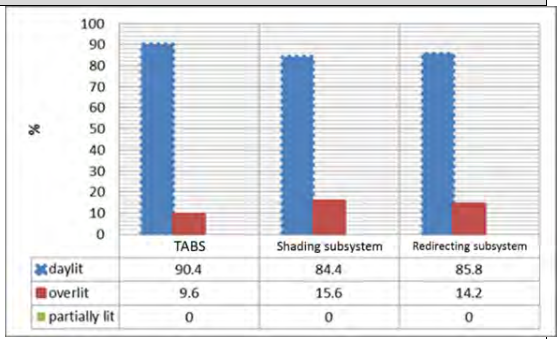
TABS configuration for Mar. 21st at 3 pm

	Pattern	Section	Perspective
3 pm			

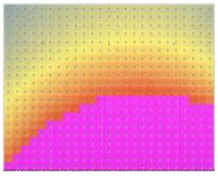
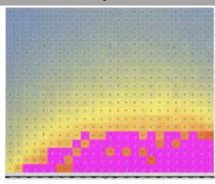
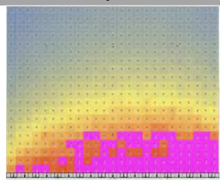
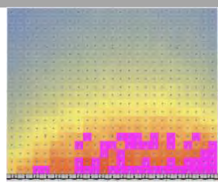
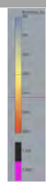
Task points Illuminance



daylight distribution



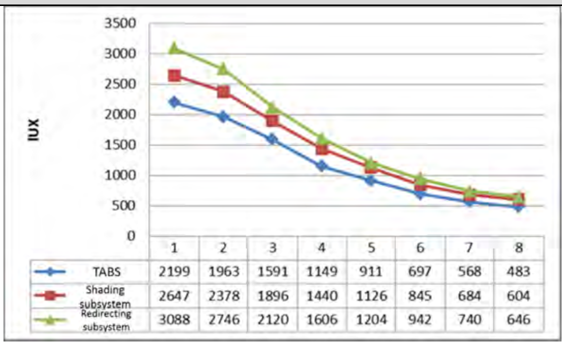
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
3 pm					

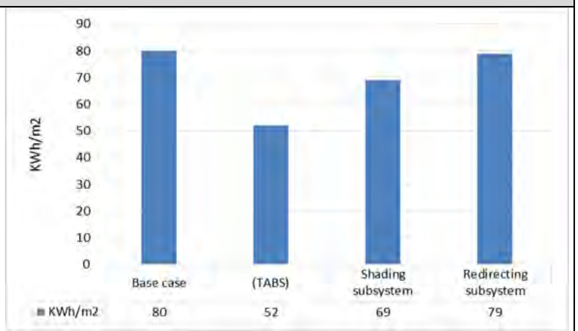
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	2199	483	1:4.5
TABS's shading subsystem	2647	530	1:5
TABS's redirecting subsystem	3088	641	1:4.8

Daylight depth

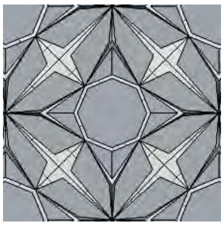
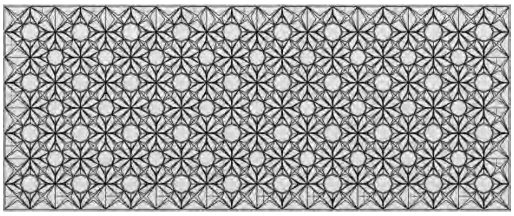


Solar radiation

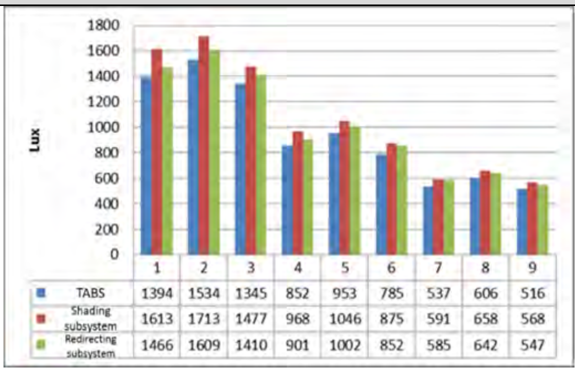


21st of June at 9 am:

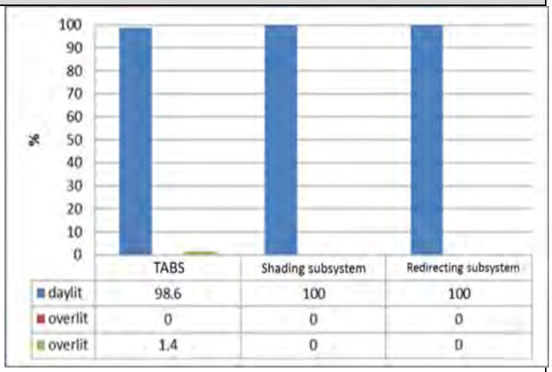
TABS configuration for June. 21st at 9 am

	Pattern	Section	Perspective
9 am			

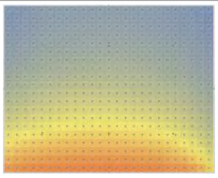
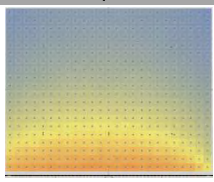
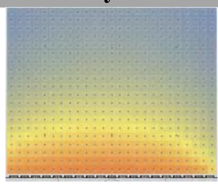
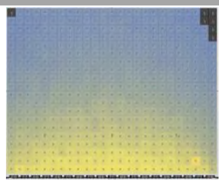
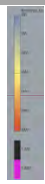
Task points Illuminance



daylight distribution



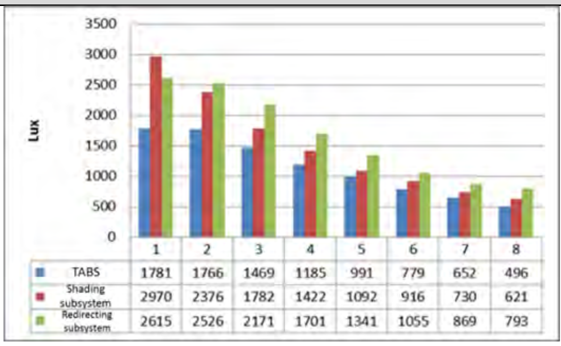
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
9 am					

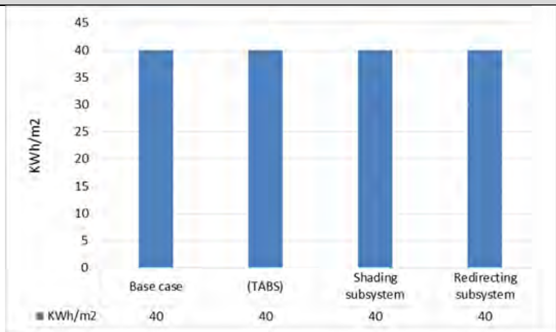
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	1781	516	1:3.4
TABS's shading subsystem	2970	568	1:5.2
TABS's redirecting subsystem	2615	547	1:4.7

Daylight depth

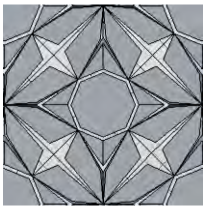
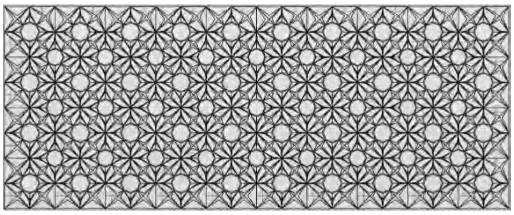


Solar radiation

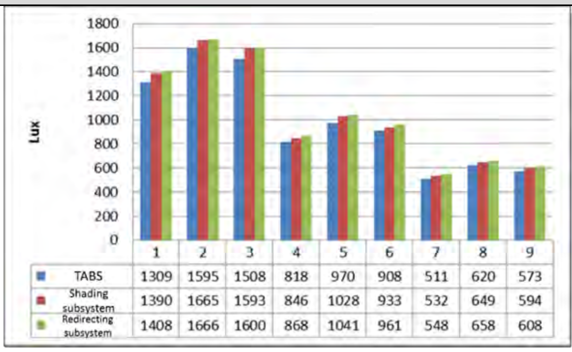


21st of June at 3 pm:

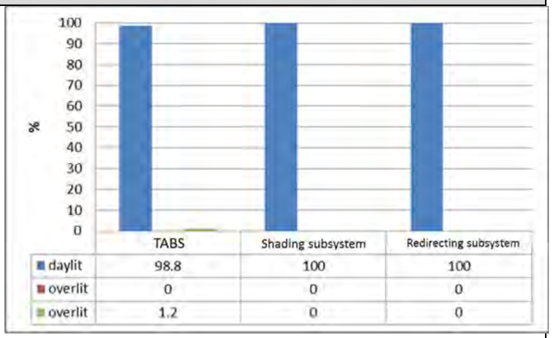
TABS configuration for June. 21st at 3 pm

	Pattern	Section	Perspective
3 pm			

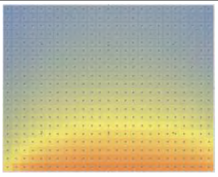
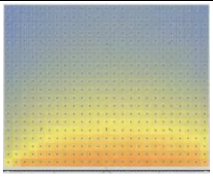
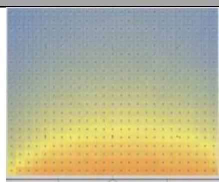
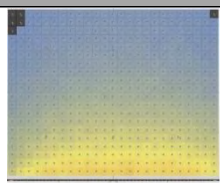
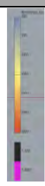
Task points Illuminance



daylight distribution



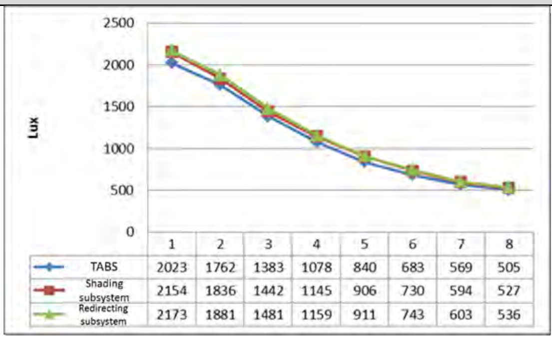
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
3 pm					

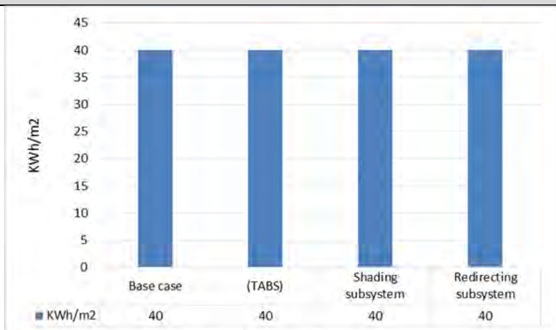
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	2023	505	1:4
TABS's shading subsystem	2154	527	1:4
TABS's redirecting subsystem	2173	536	1:4

Daylight depth

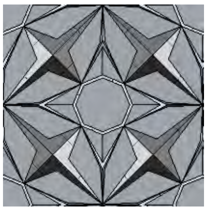
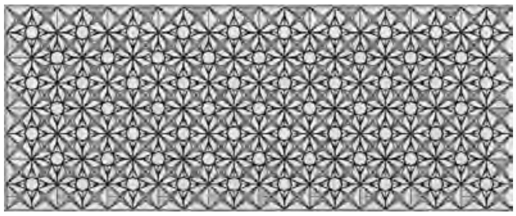


Solar radiation

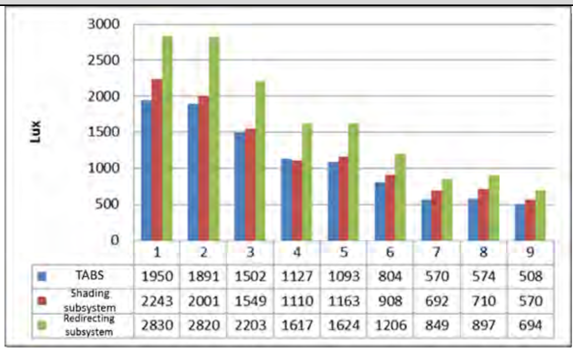


21st of Sep. at 9 am:

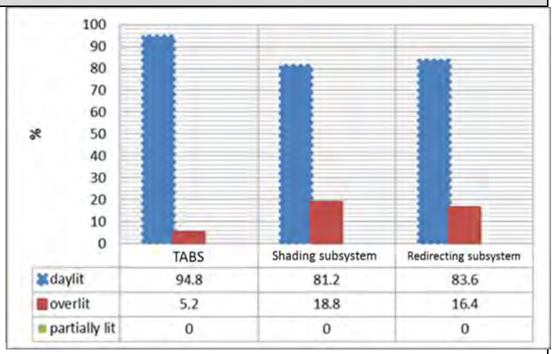
TABS configuration for Sep. 21st at 9 am

	Pattern	Section	Perspective
9 am			

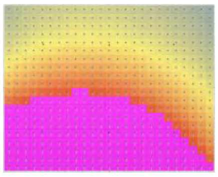
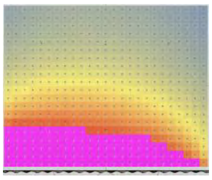
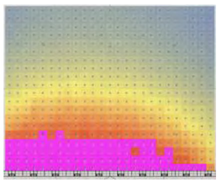
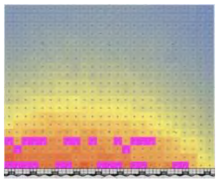
Task points Illuminance



daylight distribution



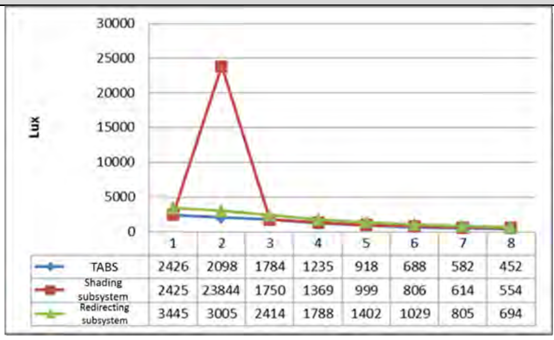
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
9 am					

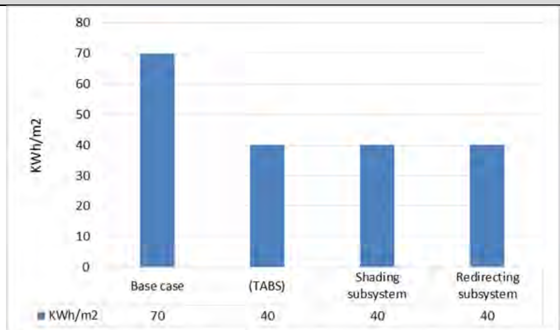
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	2426	452	1:5
TABS's shading subsystem	23844	554	1:43
TABS's redirecting subsystem	3445	694	1:5

Daylight depth

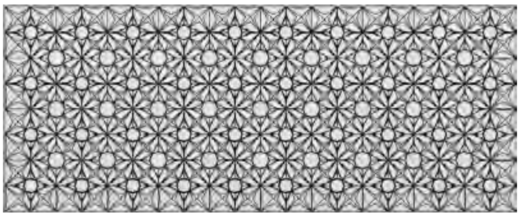


Solar radiation

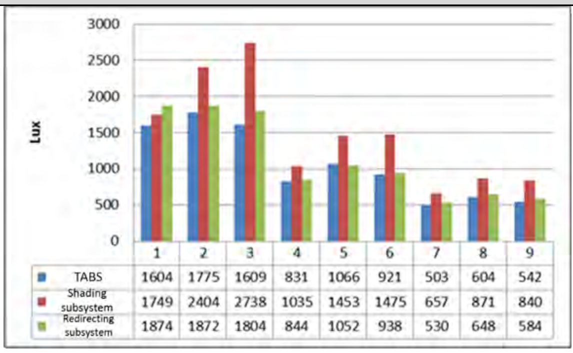


21st of Sep. at 3 pm:

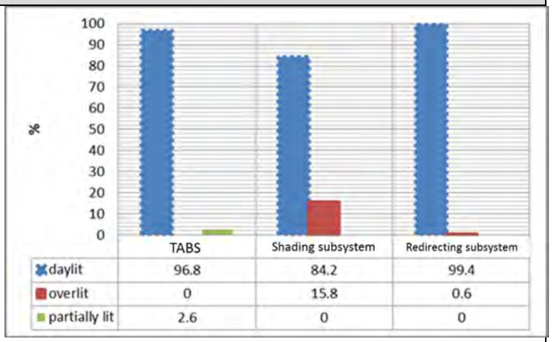
TABS configuration for Sep. 21st at 3 pm

	Pattern	Section	Perspective
3 pm			

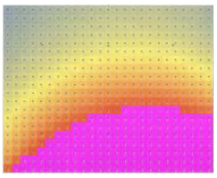
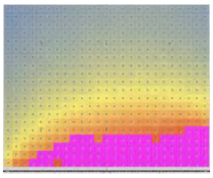
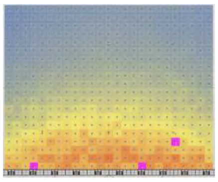
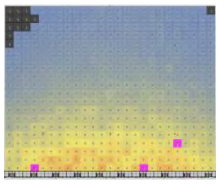
Task points Illuminance



daylight distribution



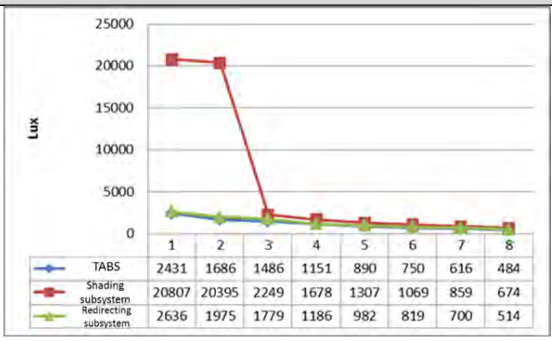
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS
3 pm				 

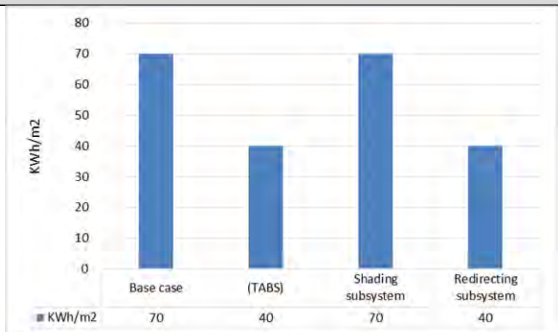
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	2431	484	1:5
TABS's shading subsystem	20807	674	1:30
TABS's redirecting subsystem	2636	514	1:5

Daylight depth

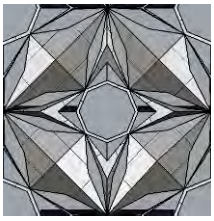
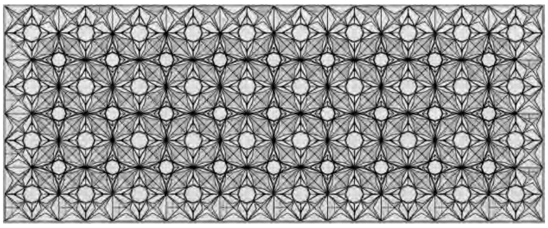


Solar radiation

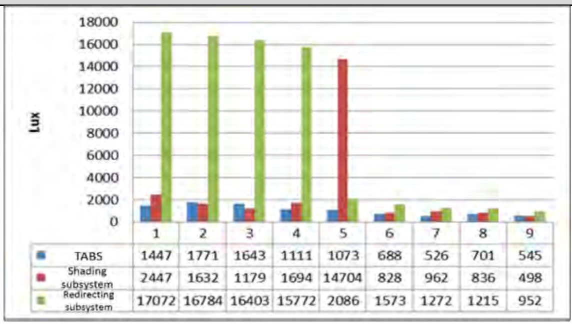


21st of Dec. at 9 am:

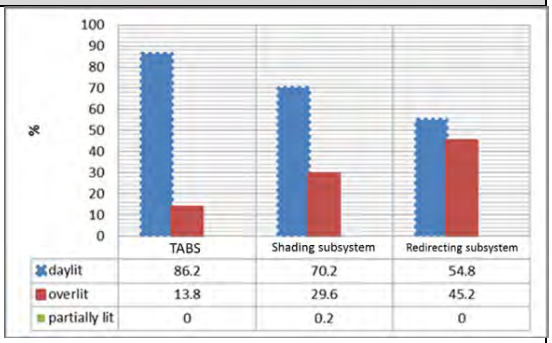
TABS configuration for Dec. 21st at 9 am

	Pattern	Section	Perspective
9 am			

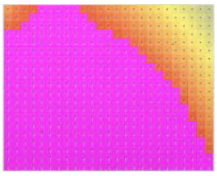
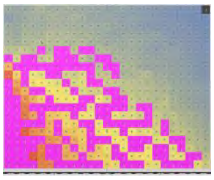
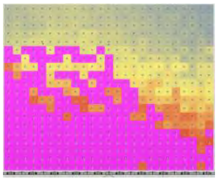
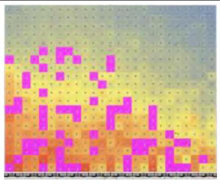
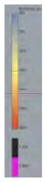
Task points Illuminance



daylight distribution



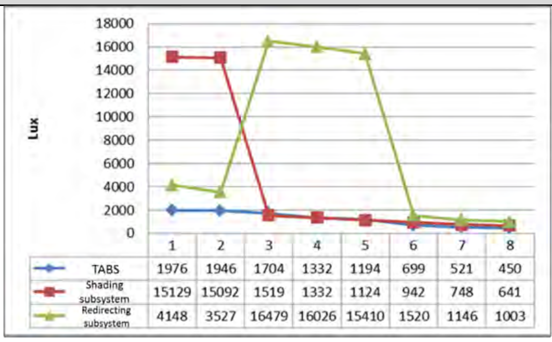
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
9 am					

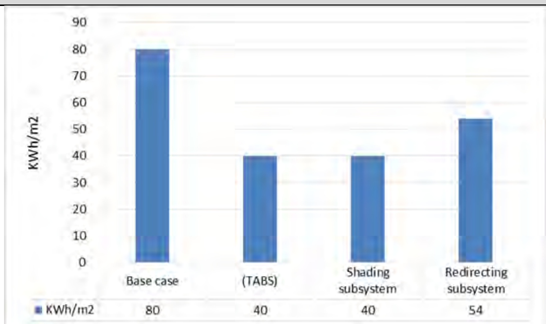
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	1976	450	1:4
TABS's shading subsystem	15129	498	1:30
TABS's redirecting subsystem	17072	952	1:17

Daylight depth

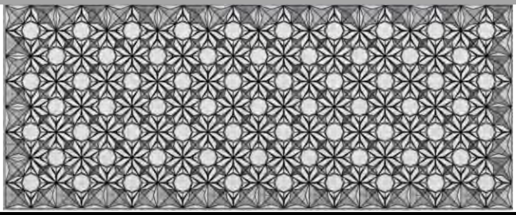


Solar radiation

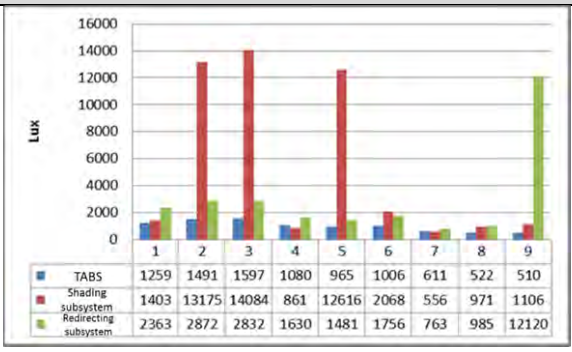


21st of Dec. at 3 pm:

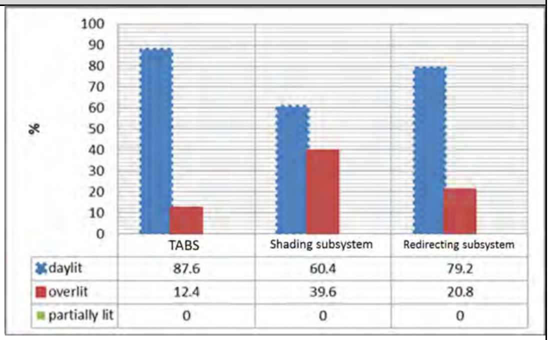
TABS configuration for Dec. 21st at 3 pm

	Pattern	Section	Perspective
3 pm			

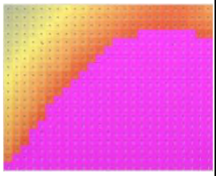
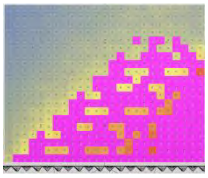
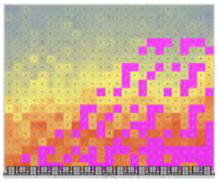
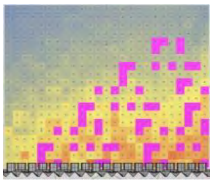
Task points Illuminance



daylight distribution



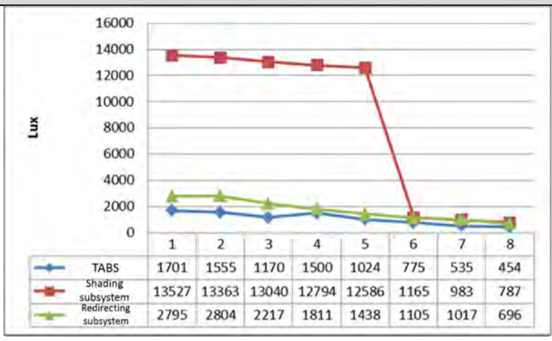
Daylight distribution

Time	Base case	Shading subsystem	Redirecting subsystem	TABS	
3 pm					

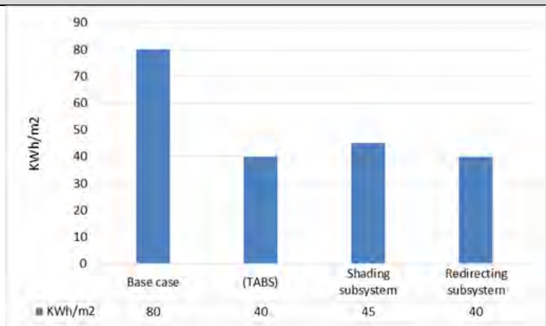
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
TABS	1597	454	1:3.5
TABS's shading subsystem	13527	556	1:24
TABS's redirecting subsystem	12120	696	1:17.4

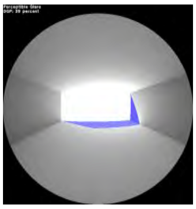
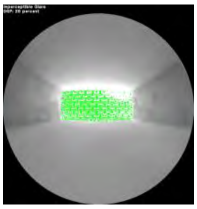
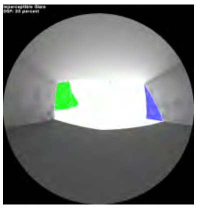
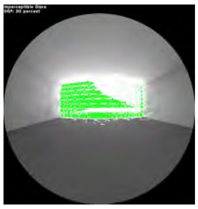
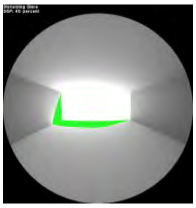
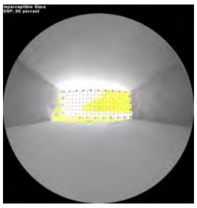
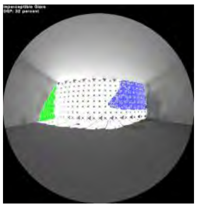
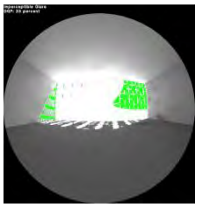
Daylight depth

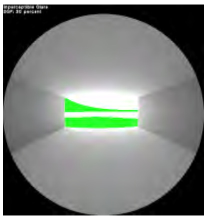
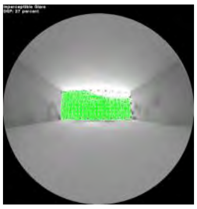
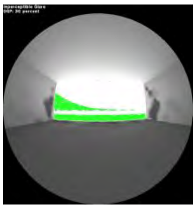
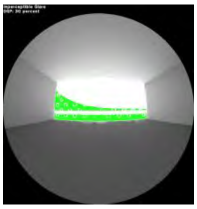
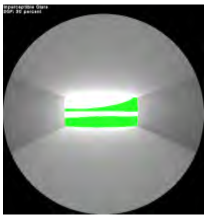
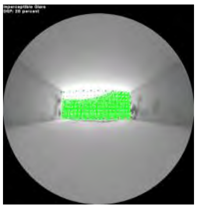
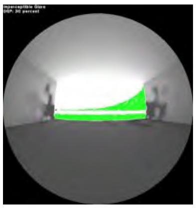
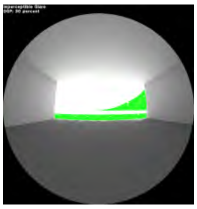


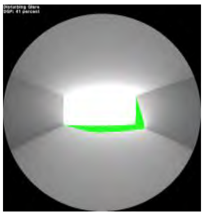
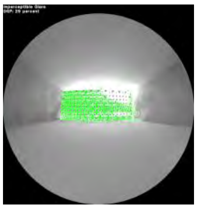
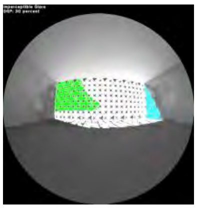
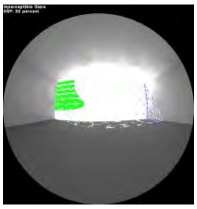
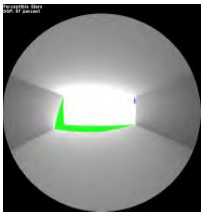
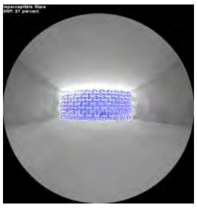
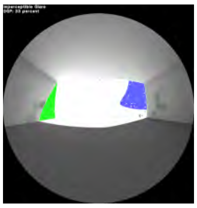
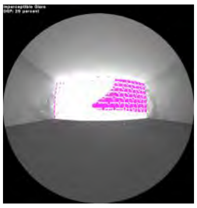
Solar radiation

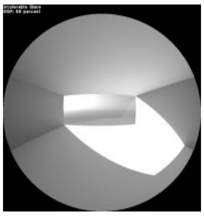
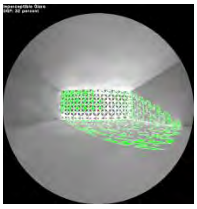
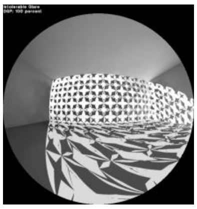
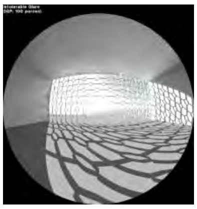
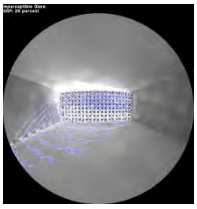
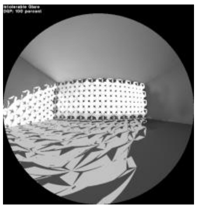
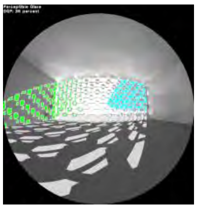


Stage One (Second phase):

Daylight Glare Probability (DGP) for each scenario on 21st March at 9 am and 3 pm				
Time	**Base case**	**TABS**	**Shading subsystem**	**Redirecting subsystem**
9 am				
Glare Performance	**Perceptible: 39%**	**Imperceptible: 28%**	**Imperceptible: 33%**	**Imperceptible: 30%**
3 pm				
Glare Performance	**Disturbing: 40%**	**Imperceptible: 30%**	**Imperceptible: 32%**	**Imperceptible: 33%**

Daylight Glare Probability (DGP) for each scenario on 21st June at 9 am and 3 pm				
Time	**Base case**	**TABS**	**Shading subsystem**	**Redirecting subsystem**
9 am				
Glare Performance	**Imperceptible: 30%**	**Imperceptible: 27%**	**Imperceptible: 30%**	**Imperceptible: 30%**
3 pm				
Glare Performance	**Imperceptible: 30%**	**Imperceptible: 28%**	**Imperceptible: 30%**	**Imperceptible: 30%**

Daylight Glare Probability (DGP) for each scenario on 21st of Sep. at 9 am and 3 pm				
Time	**Base case**	**TABS**	**Shading subsystem**	**Redirecting subsystem**
9 am				
Glare Performance	**Disturbing: 41%**	**Imperceptible: 29%**	**Imperceptible: 30%**	**Imperceptible: 32%**
3 pm				
Glare Performance	**Perceptible: 37%**	**Imperceptible: 27%**	**Imperceptible: 33%**	**Imperceptible: 29%**

Daylight Glare Probability (DGP) for each scenario on 21st Dec. at 9 am and 3 pm				
Time	**Base case**	**TABS**	**Shading subsystem**	**Redirecting subsystem**
9 am				
Glare Performance	**Intolerable: 59%**	**Imperceptible: 32%**	**Intolerable: 100%**	**Intolerable: 100%**
3 pm				
Glare Performance	**Intolerable: 53%**	**Imperceptible: 26%**	**Intolerable: 100%**	**Perceptible: 36%**

Appendix B

Stage Three: the results of the performance-based comparison of different systems

First Phase:

- Results of the base case, AOWWR, AOSBE, and TABS performance on 21^{st} of March, June, September and December at 9am and 15 pm regarding performance indicators: Task point's illuminance, Illuminance distribution, Illuminance contrast ratio, Daylight depth and solar radiation.

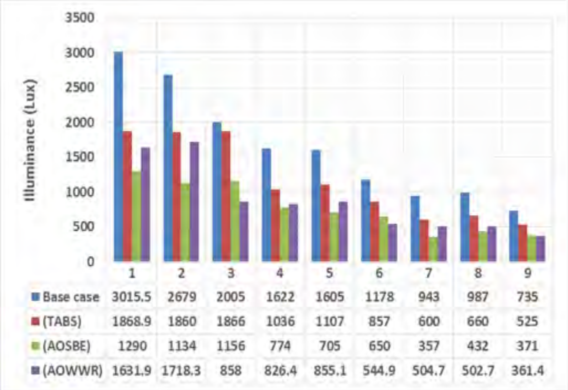
Second phase: Daylight Glare Probability (DGP).

- Results of the base case, AOWWR, AOSBE, and TABS performance on 21^{st} of March, June, September and December at 9am and 15 pm regarding performance indicators: Daylight Glare Probability (DGP).

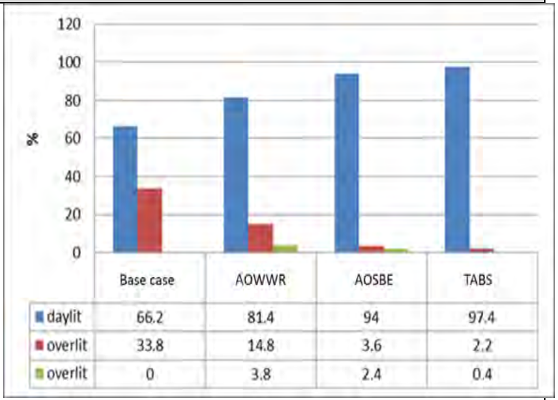
Stage Three (First Phase):

21st of March at 9 am:

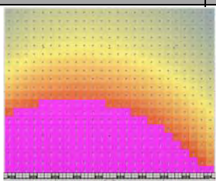
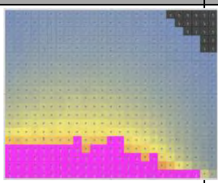
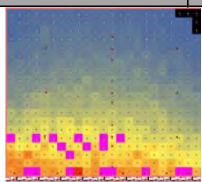
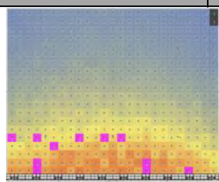
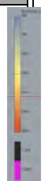
Task points Illuminance



daylight distribution



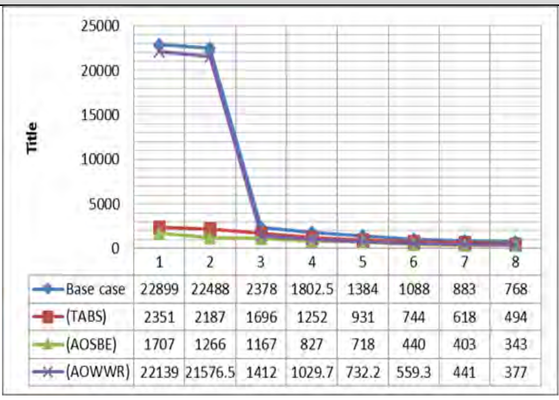
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS	
9 am					

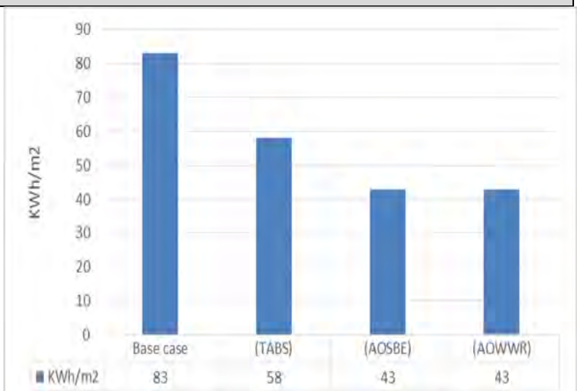
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	22899	735	1:31
(AOWWR)	22139	361.4	1:61
(AOSBE)	1707	343	1:5
TABS	2351	494	1:5

Daylight depth



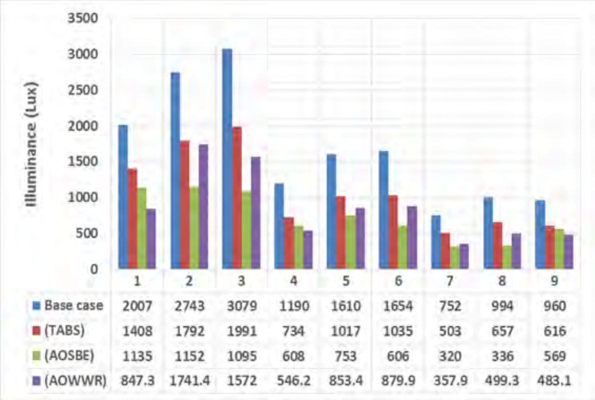
Solar radiation



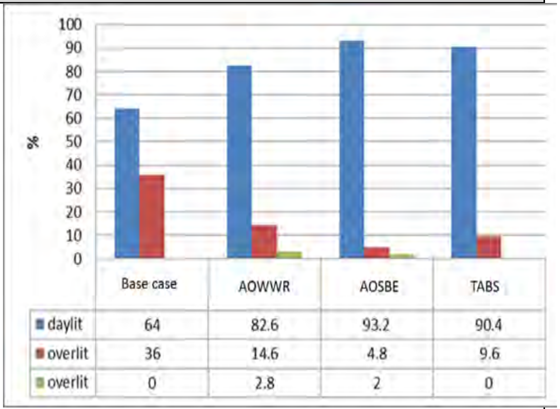
Stage Three (First Phase):

21st of March at 3 pm:

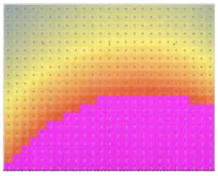
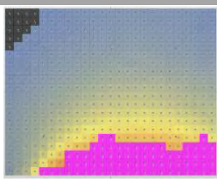
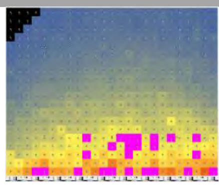
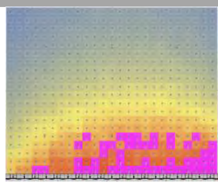
Task points Illuminance



daylight distribution



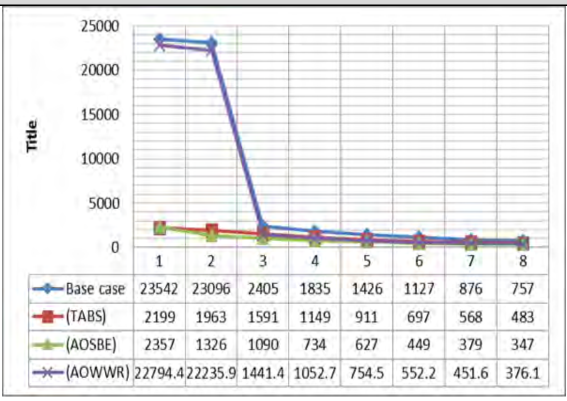
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS	
3 pm					

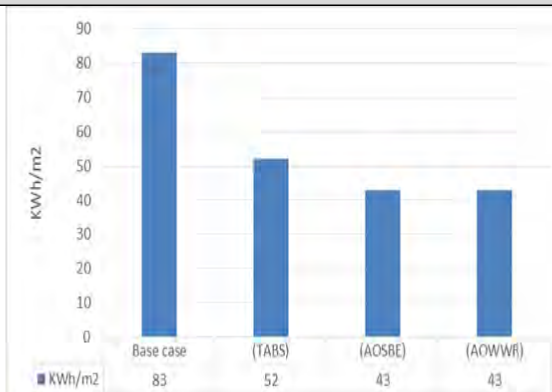
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	23542	752	1:31
(AOWWR)	22794.4	357.9	1:63
(AOSBE)	2357	320	1:7
TABS	2199	483	1:4.5

Daylight depth



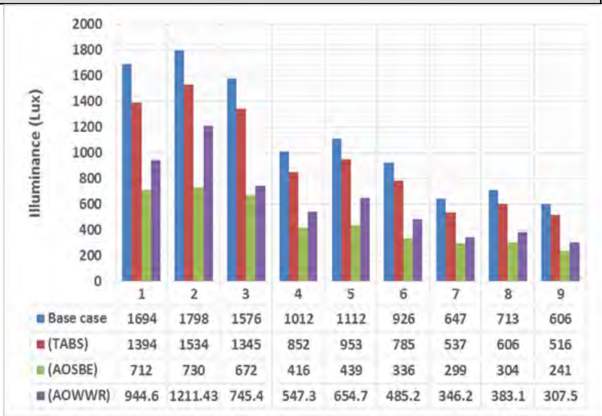
Solar radiation

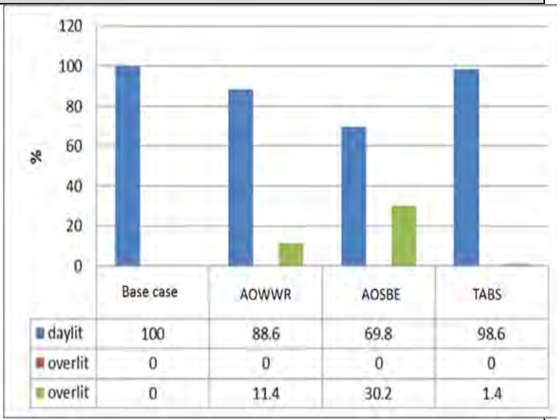


Stage Three (First Phase):

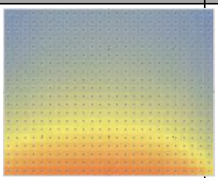
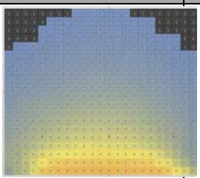
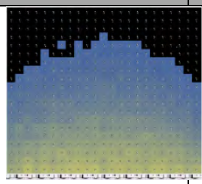
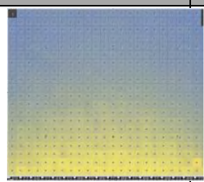
21st of June at 9 am:

Task points Illuminance | **daylight distribution**





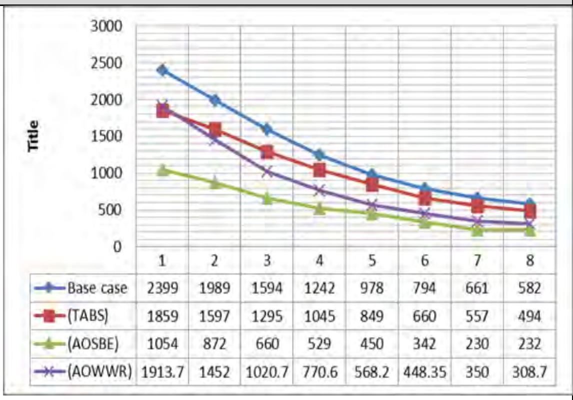
Daylight distribution

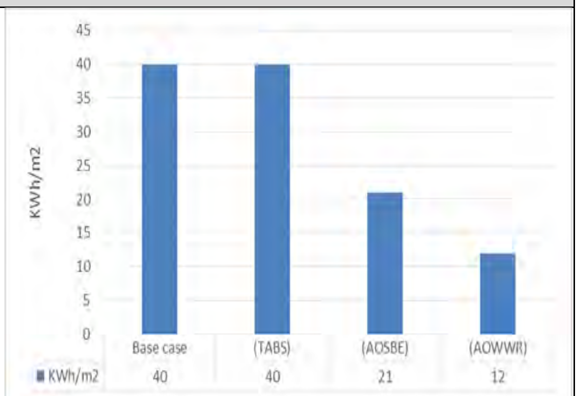
Time	Base case	(AOWWR)	(AOSBE)	TABS	
9 am					

Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	2399	582	1:4
(AOWWR)	1913.7	307.5	1:6
(AOSBE)	1054	230	1:4.5
TABS	1859	494	1.3.7

Daylight depth | **Solar radiation**

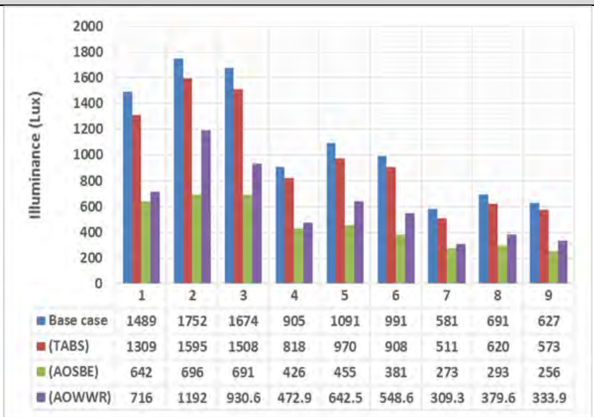




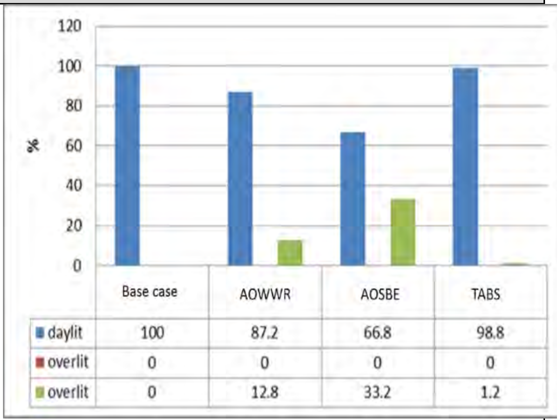
Stage Three (First Phase):

21st of June at 3 pm:

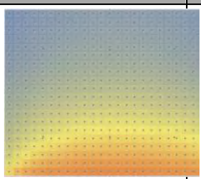
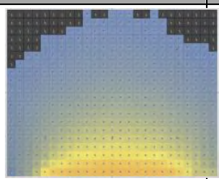
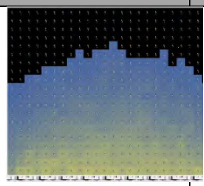
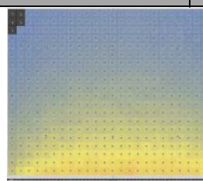
Task points Illuminance



daylight distribution



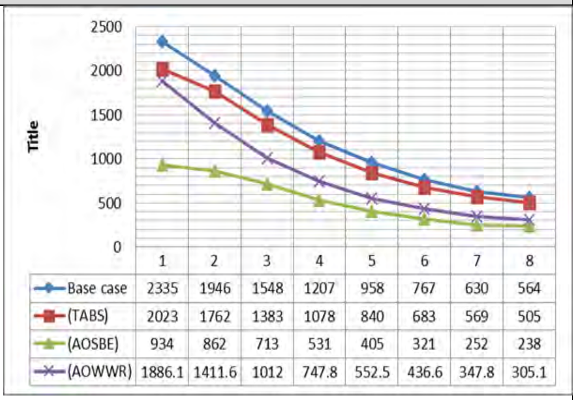
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS
3 pm				

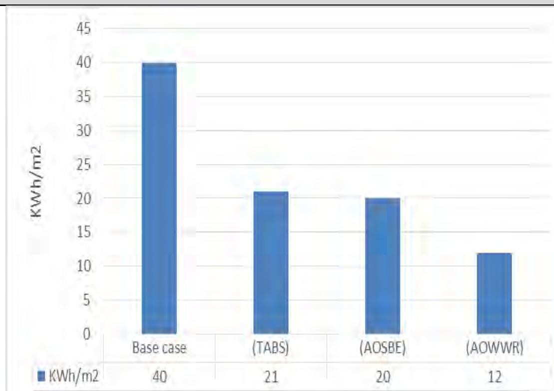
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	2335	505	1: 4.6
(AOWWR)	1886.1	305.1	1:6
(AOSBE)	934	238	1:3
TABS	2023	505	1:4

Daylight depth



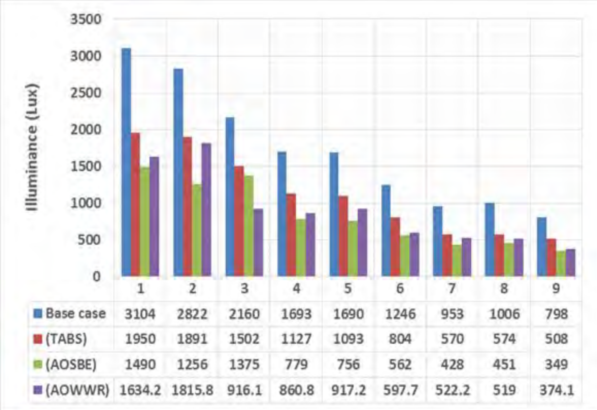
Solar radiation



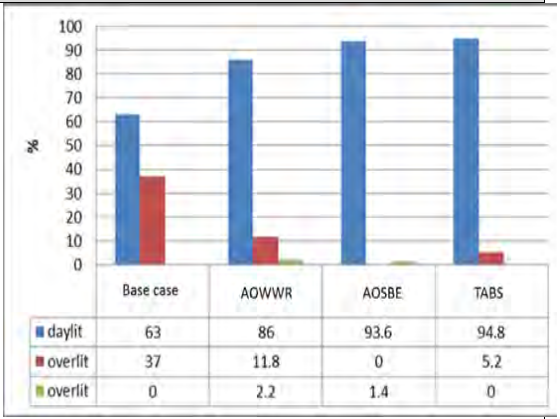
Stage Three (First Phase):

21st of Sep. at 9 am:

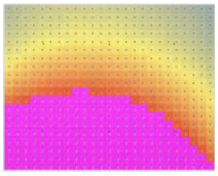
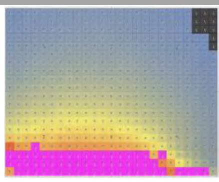
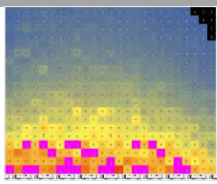
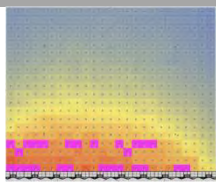
Task points Illuminance



daylight distribution



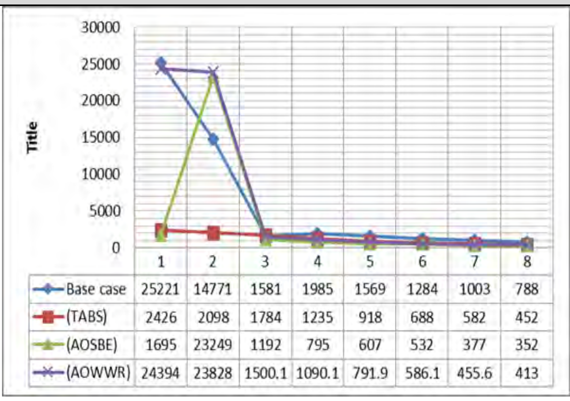
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS	
9 am					

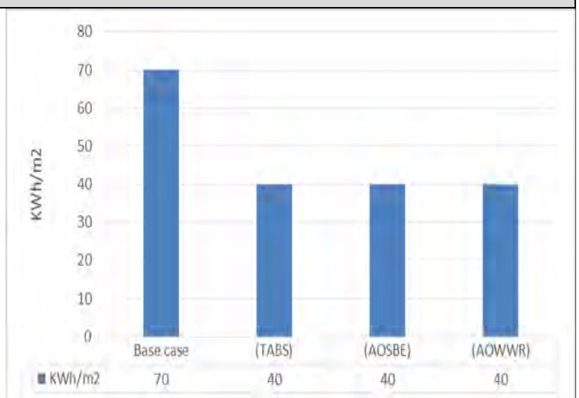
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	25221	788	1: 50
(AOWWR)	24394	374.1	1:65
(AOSBE)	23249	349	1:66
TABS	2426	452	1:5.3

Daylight depth



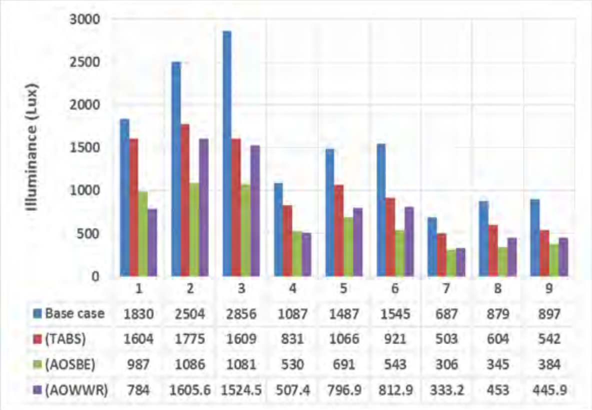
Solar radiation



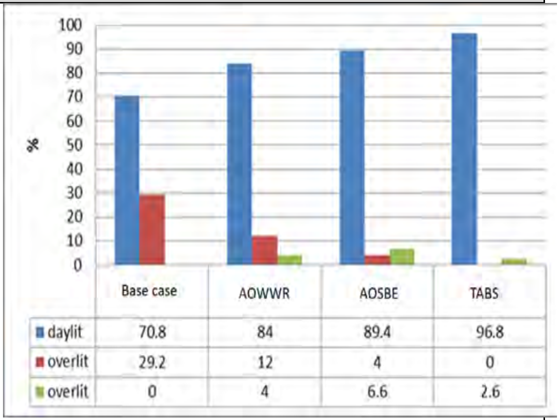
Stage Three (First Phase):

21st of Sep. at 3 pm:

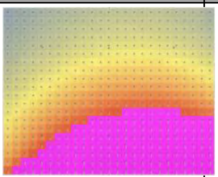
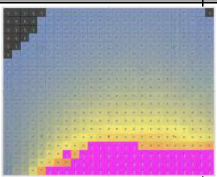
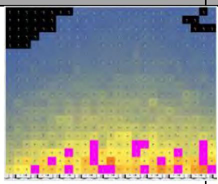
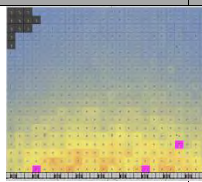
Task points Illuminance



daylight distribution



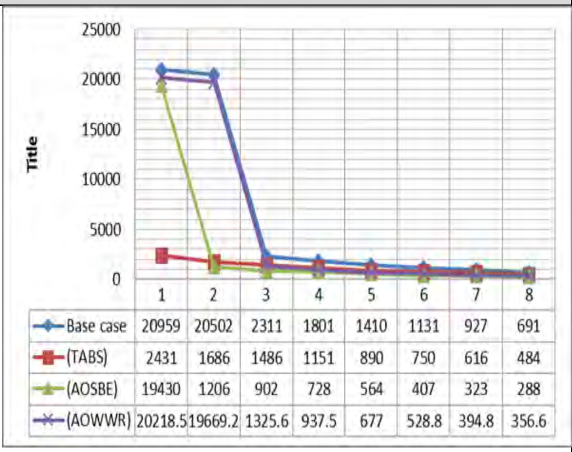
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS
3 pm				

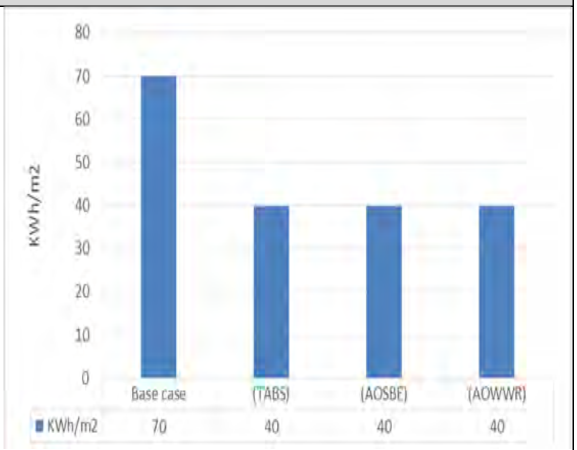
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	20959	687	1: 30
(AOWWR)	20218.5	333.2	1:60
(AOSBE)	19430	288	1:67
TABS	2431	484	1:5

Daylight depth



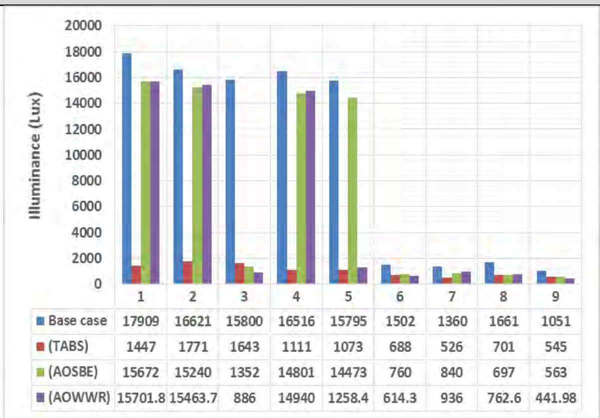
Solar radiation



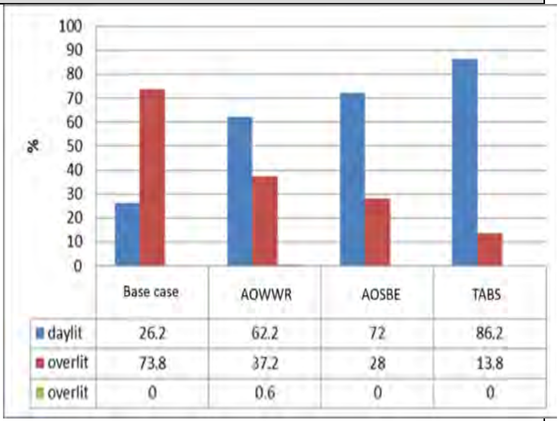
Stage Three (First Phase):

21st of Dec. at 9 am:

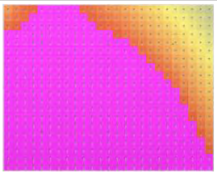
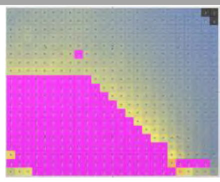
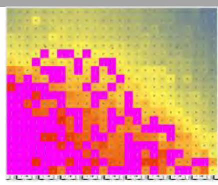
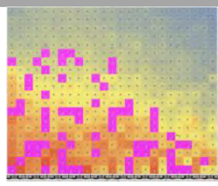
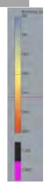
Task points Illuminance



daylight distribution



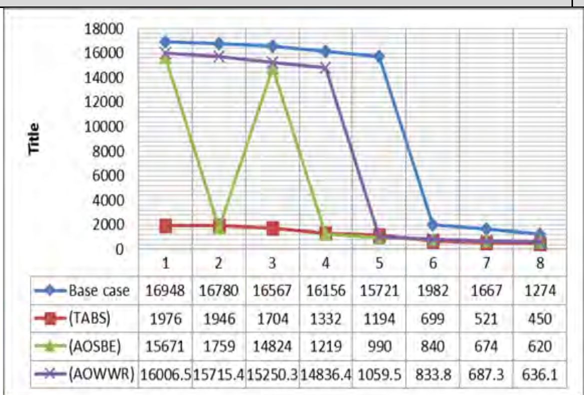
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS
9 am				 

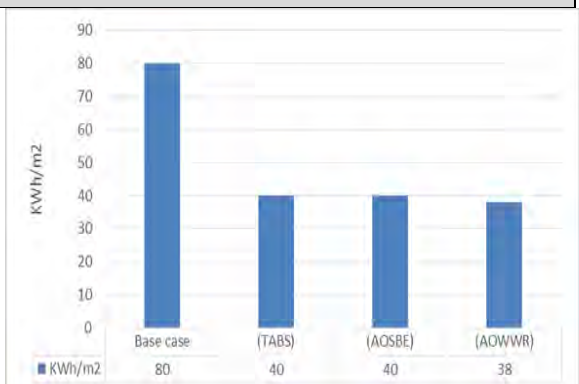
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	17909	1051	1: 17
(AOWWR)	16006.5	441.9	1:36
(AOSBE)	15672	563	1:27
TABS	1976	450	1:4

Daylight depth



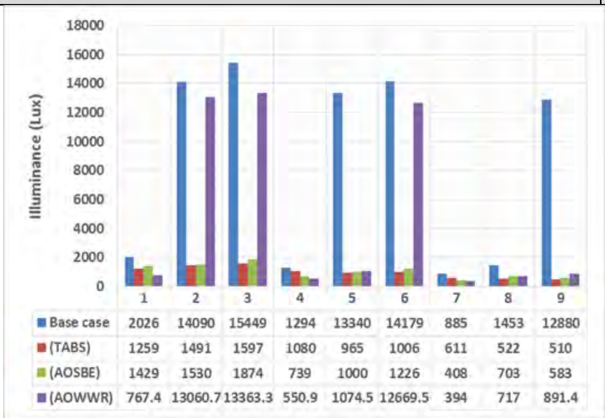
Solar radiation



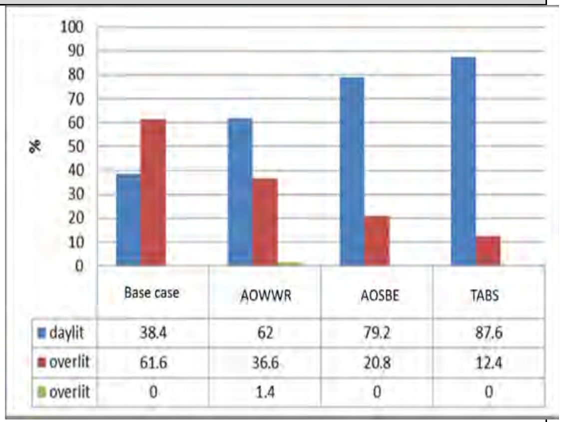
Stage Three (First Phase):

21st of Dec. at 3 pm:

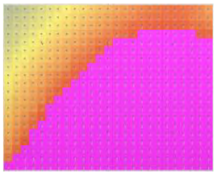
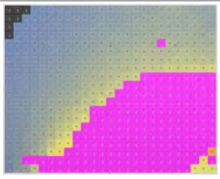
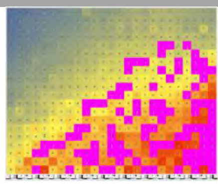
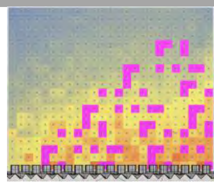
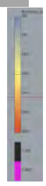
Task points Illuminance



daylight distribution



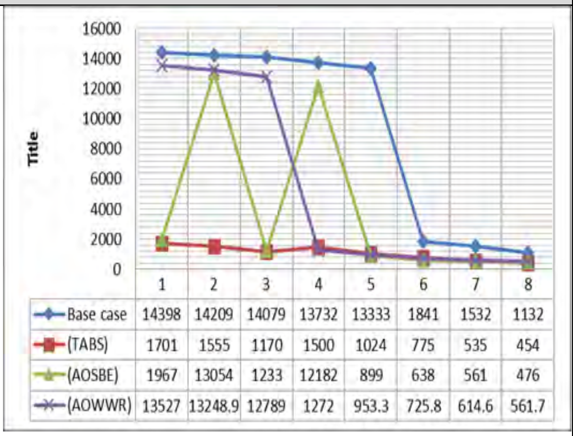
Daylight distribution

Time	Base case	(AOWWR)	(AOSBE)	TABS
3 pm				 

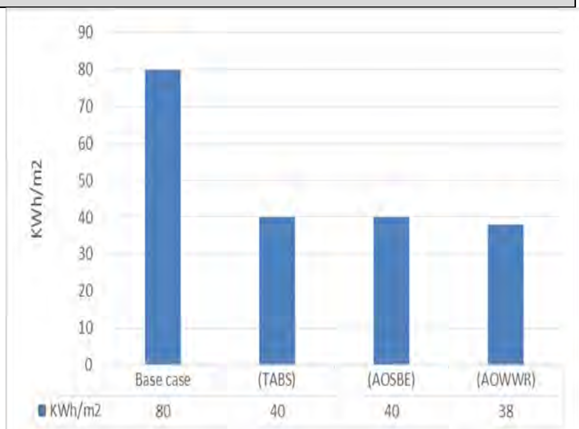
Contrast ratio

System	highest illuminance value (Lux)	lowest value (Lux)	contrast ratio
base case	15449	885	1: 17
(AOWWR)	13363.3	394	1:33
(AOSBE)	13054	408	1:31
TABS	1701	454	1:3.5

Daylight depth

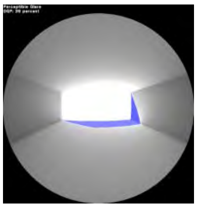
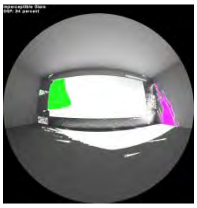
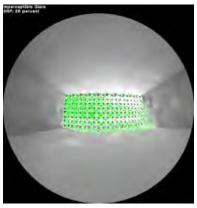
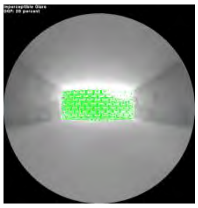
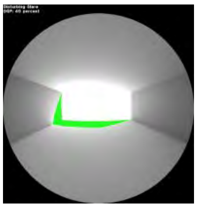
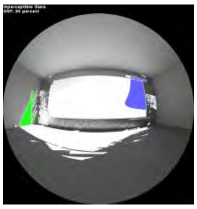
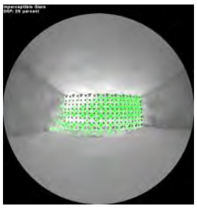
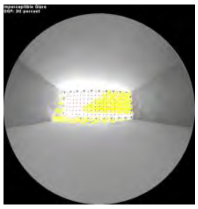


Solar radiation

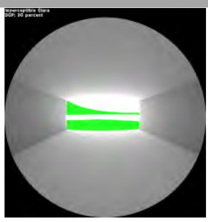
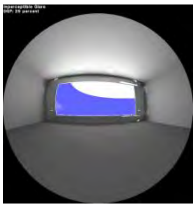
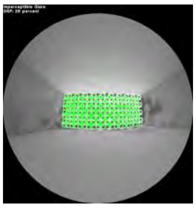
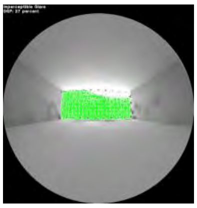
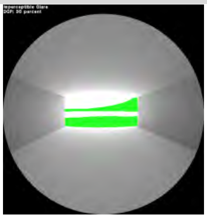
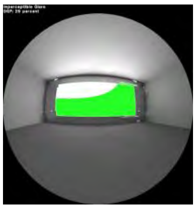
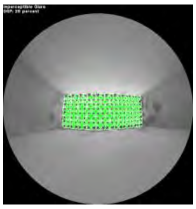
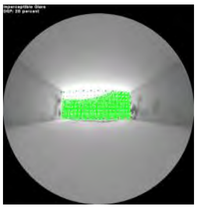


Stage Three (Second phase):

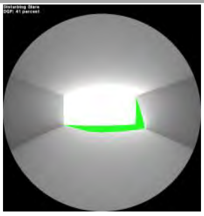
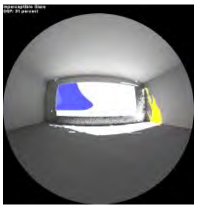
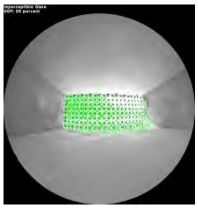
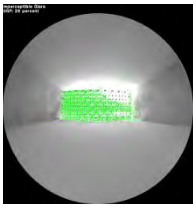
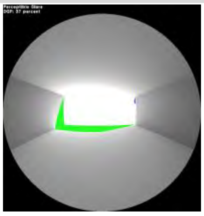
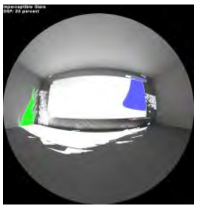
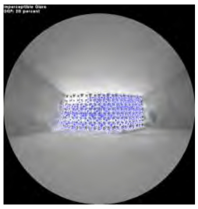
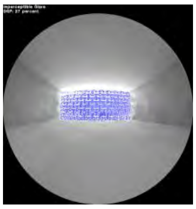
Daylight Glare Probability (DGP) for each scenario on 21st March at 9 am and 3 pm

Time	Base case	(AOWWR)	(AOSBE)	TABS
9 am				
Glare Performance	Perceptible: 39%	Imperceptible: 34%	Imperceptible: 28%	Imperceptible: 28%
3 pm				
Glare Performance	Disturbing 40%	Imperceptible: 35%	Imperceptible: 29%	Imperceptible: 30%

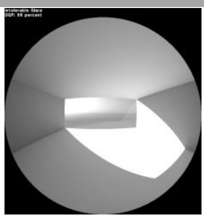
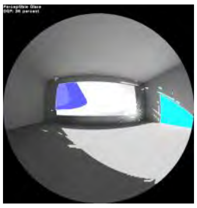
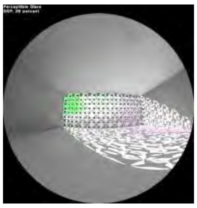
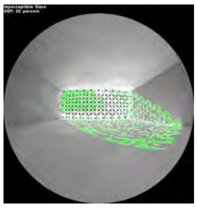
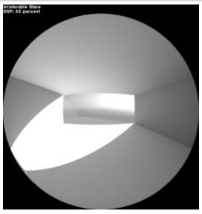
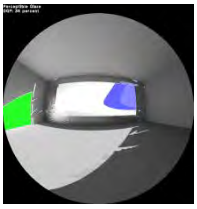
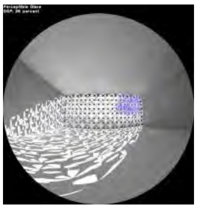
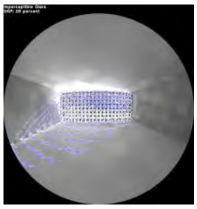
Daylight Glare Probability (DGP) for each scenario on 21st of June at 9 am and 3 pm

Time	Base case	(AOWWR)	(AOSBE)	TABS
9 am				
Glare Performance	Imperceptible: 30%	Imperceptible: 29%	Imperceptible: 26%	Imperceptible: 27%
3 pm				
Glare Performance	Imperceptible: 30%	Imperceptible: 29%	Imperceptible: 26%	Imperceptible: 28%

Daylight Glare Probability (DGP) for each scenario on 21st of Sep. at 9 am and 3 pm

Time	Base case	(AOWWR)	(AOSBE)	TABS
9 am				
Glare Performance	Disturbing: 41%	Imperceptible: 31%	Imperceptible: 28%	Imperceptible: 29%
3 pm				
Glare Performance	Perceptible: 37%	Imperceptible: 33%	Imperceptible: 28%	Imperceptible: 27%

Daylight Glare Probability (DGP) for each scenario on 21st Dec. at 9 am and 3 pm

Time	**Base case**	**(AOWWR)**	**(AOSBE)**	**TABS**
9 am				
Glare Performance	Intolerable: 59%	Perceptible: 36%	Perceptible: 39%	Imperceptible: 32%
3 pm				
Glare Performance	Intolerable: 53%	Perceptible: 36%	Perceptible: 36%	Imperceptible: 26%

Appendix C

Publication: Elkhatieb, M. and S. Sharples "Climate Adaptive Building Shells for Office Buildings in Egypt: A Parametric and Algorithmic Daylight Tool." Proceedings of SBE16 Dubai, 17-19 January 2016, Dubai-UAE

Climate Adaptive Building Shells For Office Buildings in Egypt: A Parametric and Algorithmic Daylight Tool

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Abstract

There is an emerging need to include sustainability–related performance features within the conceptual design stages of a building, especially for parameters such as daylighting and energy usage. Advances in digital architectural design now mean there are innovative possibilities for designing and evaluating dynamic façades capable of generating predetermined environmental performance criteria within a space. It is possible to update the traditional concept of the building envelope from acting not as a passive barrier but as an active negotiator with the surrounding environment. A framework is introduced in which the interdisciplinary integration and performance optimization of climate adaptive building shells (CABS), inspired by traditional Egyptian patterns, were synthesized to evaluate a wide range of façade design alternatives. A multi-objective optimization model for shape exploration is presented to assist designers in creating performance-driven forms at the early design stages. Daylighting was the key performance criterion used to design a CABS system using parametric design and optimization tools for an office space in Cairo, Egypt. The results demonstrated that the CABS system could achieve the desired daylight criteria using its own predefined capabilities.

Keywords: CABS (Climate Adaptive Building Shells), daylighting, performative design, genetic algorithms.

1 INTRODUCTION

According to the United States Energy Information Administration (EIA), almost 40% of total energy consumption in 2012 was by the residential and commercial sectors in the U.S [1]. Consequently, architects have a responsibility to search for ways to reduce energy consumption without affecting the building user's comfort. One of the possible ways to achieve this target is by controlling the daylighting that enters the building through its envelope to improve indoor environment, while reducing the energy consumed by artificial lighting, cooling and heating loads [2][3]. In addition, daylight and sunlight are significant for health and well-being. Recent studies have emphasized the need for more interesting work place environments, with the benefit of improved productivity [4]. However, sunlight needs to be controlled in terms of sufficiency vs. excess in order to satisfy the occupant's comfort requirements. This is especially true for a climate such as Egypt's, which is characterized by high direct solar radiation and clear skies [5]. This climate's sky conditions could contribute greatly to the utilization of daylighting. On the other hand, this climate may also cause excessive heat gain or visual discomfort [6]. All these facts highlight the need of updating the traditional approaches of the building envelope from acting only as a passive barrier towards a building envelope which acts as an active negotiator with the surrounding environment.

Climate Adaptive Building Shells (CABS) is an example of this updated approaches. CABS have the ability to dynamically control the exchange of energy through a building's shell over time in response to the meteorological conditions and occupants' requirements; this attitude affords many gains such as energy saving and higher performance's recognition [7]. CABS is one title for a concept that has been branded by a range of terms, such as *interactive* [8], *responsive* [9] and *smart* [10]. The integration of daylighting performance into the conceptual phase of designing, using CABS for an office building in Cairo, is examined in this study.

2 PERFORMATIVE ARCHITECTURE

Integrating performance-based approach in the early conceptual design stage is significant to achieve innovation and efficiency. A parametric model can become a controlled environment for design exploration in which the search for a fitter design alternative according to pre-defined fitness criteria can be easily carried out [11]. A carefully designed CABS system can provide energy savings and indoor comfort [12, 13], for example, the façade design of the Arab World Institute (AWI) in Paris by Jean Nouvel (Fig.1) and Aedas Architects' Al Bahar Towers in Abu Dhabi (Fig. 2), with a responsive facade inspired by the '*mashrabiya*', a traditional Islamic lattice shading device (Fig.2).

Figure 1. AWI kinetic façade system.

Figure 2. Al Bahar Towers

In this study a CABS building facade to enhance daylighting performance in a Cairo office building has been tested. The CABS façade pattern was inspired by projects of the famous Egyptian architects Hassan Fathy. The use of claustra is one of Fathy's most characteristic visual elements, and relates to an urban precedent in the wooden lattice windows (mashrabiya) of houses in old Cairo [14].Hassan Fathy used Claustra as shading devices to permit diffuse light, prevent direct sunlight, and control glare (Fig.3).

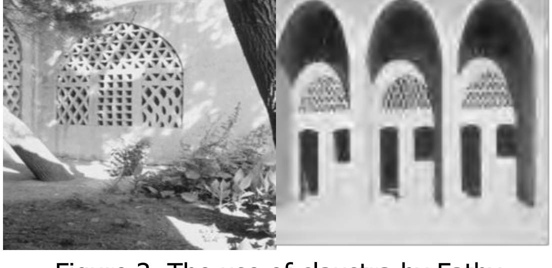


Figure 3. The use of claustra by Fathy

3 METHODOLOGY

Using parametric design a three dimensional geometric façade configuration, inspired by traditional Egyptian claustra and mashrabiya, was developed and integrated with horizontal and vertical louvers system that are proposed as a CABS outer skin for the aerated. Focusing on a south facing office space in Cairo a CABS system was developed aiming to enhance the indoor daylight quality at 12.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice). An algorithm was employed in this parametric study to examine the advantages of using CABS system for improving the daylighting performance in office spaces. The flexibility of the parametric model provided a wide variety of shapes and sizes of folds, and sizes of openings. With the help of the evolutionary solver, a balance was found among these variables that minimised heat gain whilst also providing adequate daylight for the occupants. The idea was to design CABS system consisting of 40 units each unit 1m * 1m and they were randomly divided into 4 groups each having different scale based on 30 different random distribution scenarios for a south facing façade inspired by traditional Egyptian pattern (see Figure 6) which have the capability to change its configurations in response to the surrounding environment based on a desired predefined design criteria. The whole system could be fully closed when daylight is not favourable or fully opened when daylight is favourable. Figures 4, 5, 6 and 7 show the development of the CABS system with louvers.

Figure 4. Extracting the concept of the designed pattern.

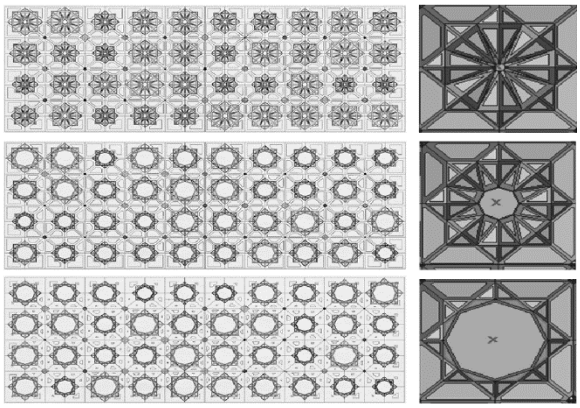


Figure 5. CABS system opening ratios ranging from 10% to 90%

Figure 6. Shows the random distribution of the system's groups.

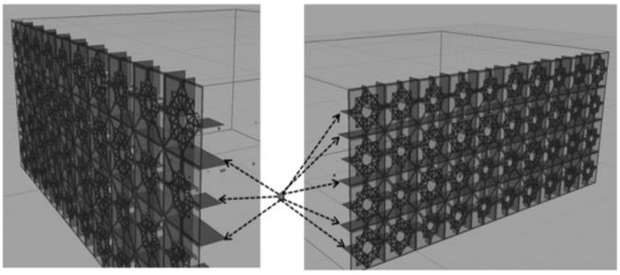


Figure 7. Integration of louvers with pattern.

3.1 Daylight Design Criteria

This paper considered five indicators (illuminance, illuminance contrast ratio, daylight depth, glare and solar irradiation), based on the recommended office illumination levels from the Illuminating Engineering Society of North America (IESNA). [15]; the NRC Institute for Research in Construction [16]; and the European Standard for Light and Lighting for Indoor Work Spaces [17]. The study was applied in three main phases. The first phase was concerned with daylighting adequacy, ensuring that all work planes received a minimum of 500 lux and a maximum of 2000 lux, while reducing excessive direct sunlight penetration. The second phase was concerned with daylight distribution and all the selected alternatives had to ensure that at least 80% of the total office space area was daylit at the four required times of the year representing the four seasons to ensure visual comfort during the entire year. Three zones described the space as being either 'daylit' (illuminance levels between 300 and 3000 lux); 'partially daylit' (less than the minimum illuminance of 300 lux) and 'over lit' (daylight illuminance exceeds the maximum illuminance of 3000 lux). The 'over lit' area signifies the potential for heat gain and glare risk [18] [19]. The third phase investigated all the selected alternatives to ensure visual comfort inside the space. A point-in-time glare simulation using DIVA software was carried out at a height 1.3m (sitting position and looking towards the widow). The Daylight Glare Probability (DGP) metric was used in the visual comfort evaluation which considers the overall brightness of the view, position of 'glare' sources and visual contrast. DIVA is an environmental analysis plugin for Rhino that uses Evalglare to calculate DGP from a luminance image based on total vertical eye illuminance and contrast [19]. Glare was considered being intolerable if DGP >45%, disturbing when it is between 40% and 45%, perceptible when it is between 40% and 35%, and imperceptible when it is less than 35%. To summarise, the study was seeking to design a CABS system to fulfil the criteria in outlined in Table 1.

A generic south-facing office 10m x 8m x 4m high, located in Cairo, was selected for this study with no external obstructions. Such an office can hold 9 workstations. The office space and CABS system were modelled using Grasshopper for Rhinoceros. The recognition of and CABS geometry were constructed in the multiple parameters that control the surface.

Table 1. Criteria

Indicator	Illuminance
Target for working plane	Min of 500 lux, max of 2000 lux and at least 80 % of the rest of the space between 300 lux and 3000 lux.
Daylight depth	2X
illuminance contrast ratio	1:8
Glare	DGP<35%
Solar radiation	Minimum

The parameters of the office space and CABS system configurations are illustrated in [Tables 2 and 3]. The CABS system consist of a parametrically designed pattern integrated with horizontal and vertical louvers; the system was controlled by 17 parameters to insure adequate daylight in term of quantity and quality for the four required times all the parameters are fixed except eight parameters.

All variables were governed automatically through the algorithms to start generating the permutations were based on the daylight and solar radiation simulation results.

Table 2. Model and CABS parameters

Space Parameters	
Walls	Reflectance = 50%
Ceiling	Reflectance = 90%
Floor	Reflectance = 20%
CABS	Reflectance = Metal diffuse for façade's frames and Glazing_DoublePane_LowE_65 for glazing

Table 3. CABS Parameters

No	Parameters	Possible Values
1	Pattern's random distribution	30 random distribution's scenarios with different scales.
2	Main pattern opening ratio	10, 20, 30, 40, 50, 60 , 70,80 and 90 %
3	Hex opening diameter	100, 200, 300, 400 and 500 mm
4	Main Horizontal and vertical Louvers Rotation	-75°, -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60° and 75°
5	Secondary Horizontal and vertical Louvers Rotation	-75°, -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60° and 75°
6	Louvers Depth main and secondary louvers	100, 200, 300, 400 and 500 mm
7	Background opening ratio (four groups)	10, 20, 30, 40, 50, 60 , 70,80 and 90 %
8	Pattern extrusion	100, 150, 200, 250, 300 mm

3.2 Simulation Parameters and Procedure

CABS must respond to particular environmental conditions at its location. For the purpose of this case study, Cairo (30° 2' N, 31° 14' E) and its weather file (Cairo Intl Airport 623660 (ETMY)) were used for the analysis [20].

3.3 CABS System Configurations

The tool was developed as a parametric model in which variable geometries are defined with associated constraints. The 3D model and components were then actuated through the algorithm simulating intelligently evaluated independent CABS system configurations. The design of the CABS originated in Grasshopper. All variables for CABS alterations were defined; the CABS geometry was connected to the daylighting analysis component DIVA, which uses Radiance as the daylighting calculation engine. DIVA plugin for the Rhinoceros and Grasshopper environment supports a series of performance evaluations by using validated tools including RADIANCE, Daysim, Evalglare and Energy Plus software. DIVA performs a daylight analysis on an existing architectural model via integration with Radiance and Daysim [18]. This method allows the rapid visualization of the daylight and energy consequences of an architectural design model where multiple design variants for daylight and energy performance can be easily tested without manually exporting to multiple softwares. DIVA was chosen so that all modelling and daylight simulations could be carried out within the Rhino and Grasshopper environments for the prediction of various radiant or illuminance calculations using sun and sky conditions derived from standard meteorological datasets.

The results are dependent both on the building location and orientation, in addition to the CABS composition and configuration. Two groups of nodes were generated – the first being a horizontal group for the illuminance measurements, located 0.76m above the floor, consisting of seventeen points representing the nine workstation locations and eight points to provide an indication of adequate daylight depth (Fig.8).

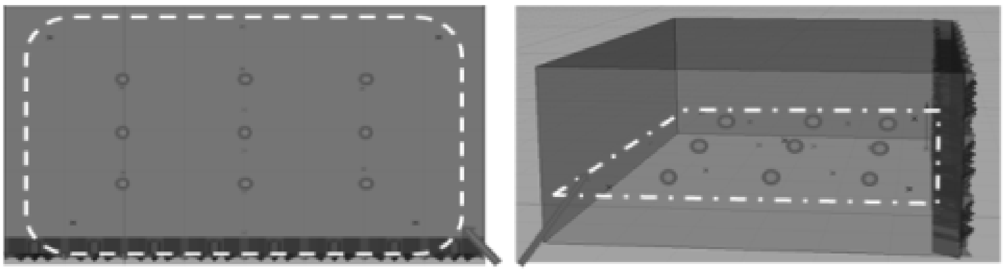


Figure 8. Measuring nodes for illuminance

The second group was a vertical grid for the south façade's solar radiation calculation located 200mm inside the space, just behind the CABS system, to measure solar radiation which had passed through the CABS; this involved 40 points covering 100% of the glazing area distributed as one point for each m^2 of glazing. (Fig.9). All surfaces, materials and nodes were defined and linked to the DIVA plug-in for both Illuminance and solar radiation analysis.

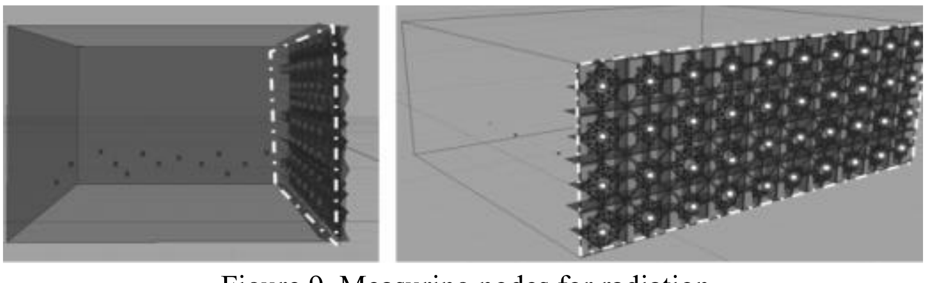


Figure 9. Measuring nodes for radiation

The overall definition of a solution generated in Grasshopper can be divided into five distinct groups: model geometry, folded façade, performance simulation, optimization and data recording. All results are examined simultaneously by evaluation functions of the algorithm and filtered based on the predefined criteria. The algorithm evaluated the space for three particular criteria: (i) 100 % of the nine nodes on the working plane are within the desired illuminance range (500-2000 lux); (ii) the illuminance contrast ratio in terms of contrast ratio between highest and lowest node values exceeds 1:8 and (iii) 100 % of the eight tested nodes (out of the working plane) are with the range 300-3000 lux. All values are then sent to the genetic algorithm. The main objective of the study was to achieve all seventeen calculation points being within the range of acceptable illuminance values.

At the same time as results were evaluated for illumination levels, another function of the algorithm was testing the results for illuminance contrast ratio evaluation. Since the illuminance values had been sorted in a descending order, the highest point will have an index of '0' and the lowest value will have an index of '16'. Both values were extracted using the 'list item' component and divided by each other. If the result is within 1:8 ratios for contrast ratio, the solution is considered acceptable and sent for solar radiation calculation (40 vertical measuring nodes); otherwise, it is considered unacceptable and neglected.

For the purpose of optimization Galapagos is used, which is a genetic algorithm imbedded in Grasshopper and running in Grasshopper through the Rhino interface. By using Galapagos a wide range of alternatives can be explored and evaluated, basically, evolutionary computing works by giving each variable, or gene, an assigned fitness value, then iterates through different mutations of genes with the optimized solutions surviving, every iteration plays an important role in the way the genes combine.

In this step, the architect determines the suitable optimization algorithm and the heuristic algorithm will manage the flow of parameters and performances between the simulation and the modelling software, the algorithm takes the parameters of the CABS with their performance from the simulation program.

Then, based on the rule governing the selection of the optimum solution (parameters), the algorithm starts sending new parameters to the simulation program and receives the results and the previous steps are iterated until the optimum solution is reached.

Galapagos has been integrated to search for the best CABS configuration at specific dates and times. The genetic algorithm works on finding an optimal solution that fits the predefined criteria. Galapagos works on minimizing the solar radiation for the successful solutions. The algorithm operates by randomly generating numerous CABS configuration, evaluating a different combination each time, and TT-Toolbox is used for data recording. Finally, a group of CABS configurations that maximize the quality of daylighting within the predefined criteria and have the minimum solar radiation value as desired was reached.

All the optimum groups of solutions (population) were examined and compared architecturally. For results verification, four successful solutions were selected as optimum solutions (one solution for each of the following times: 12.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice). Advanced simulation and data verification were carried out in two main stages:

Stage 1: In order to verify the results, successful solutions were compared twice using DIVA for Grasshopper for the same conditions (material, space dimension, weather file and time, etc) with:

- A base model without CABS.

- Alternative with lower fitness value.

Stage 2: Advanced simulation carried out for all the space using DIVA for Rhino, which has more capabilities for results' verification and in-depth analysis.

Optimum solutions for all of the times were selected, then a point in time illuminance analysis was carried out to examine the daylight adequacy of all the space by measuring the illuminance values of nodes for a grid spacing of 0.42 m (190 nodes) to make sure that at least 80% of the space received illuminance between 300 lux and 3000 lux, and for glare probability to make sure that the users didn't receive intolerable glare (DGP > 45%). All simulations were carried out using DIVA for Rhino for results verification and compared with a Base model without CABS using the same conditions (material, space dimension, weather file and time) to examine: (i) Point in time illuminance and (ii) Point in time glare probability.

4 RESULTS:

The optimised CABS systems were compared to the base model without CABS system in two phases. The first phase considered illuminance, luminous distribution and solar irradiation and the second phase daylight glare probability (DGP). Examples of some of the results are described below.

4.1 First phase: illuminance, illuminance contrast ratio, daylight depth and solar irradiation.

Table 4 shows graphically the daylight illuminance distributions for the dates/times investigated with and without the optimized CABS. The large dark coloured areas in the 'without CABS' office represent illuminance levels greater than 3000 or less than 300 lux (over lit and partially lit areas) whereas the light coloured areas, indicating values between 300 lux and 3000 lux.

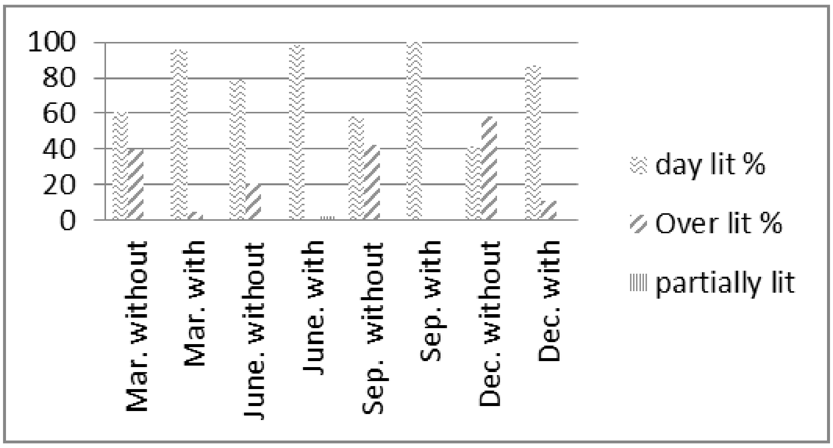
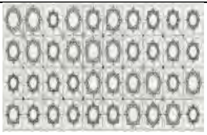
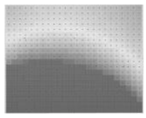
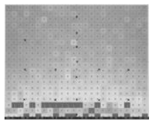
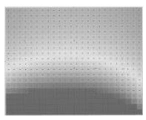
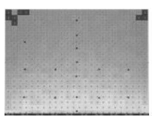
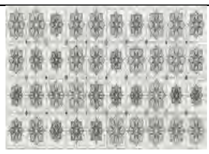
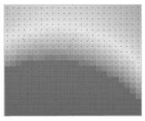
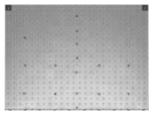
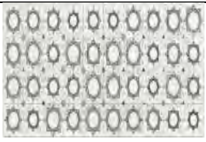
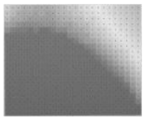
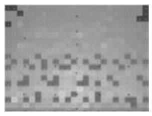


Figure 10. Daylighting performance with and without CABS

Table 4. The daylighting performance with and without the optimized CABS.

Date	Façade Design	Without CABS	With CABS
Mar. 21st			
June 21st			

Sep. 21st			
Dec. 21st			

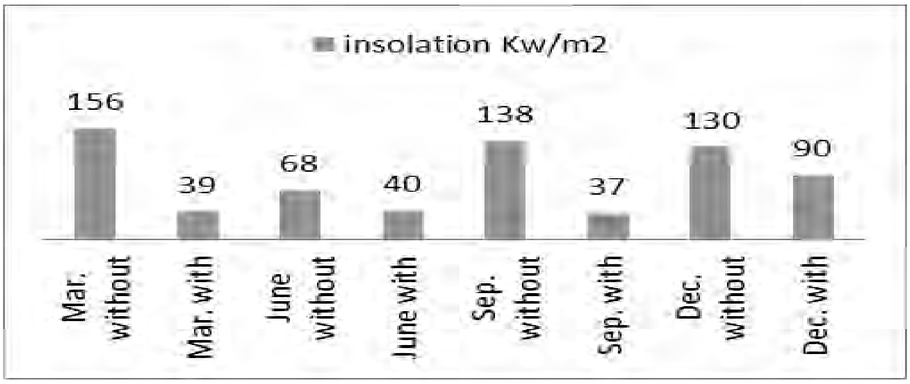


Figure 11. Solar Irradiation with and without CABS

4.2 Second phase: Daylight Glare Probability (DGP).

A point-in-time glare simulation in DIVA was carried out and the visual comfort of a person under the simulation conditions at the camera viewpoint examined.

An annual glare simulation was undertaken for the office without CABS with hourly calculation (Fig. 12)

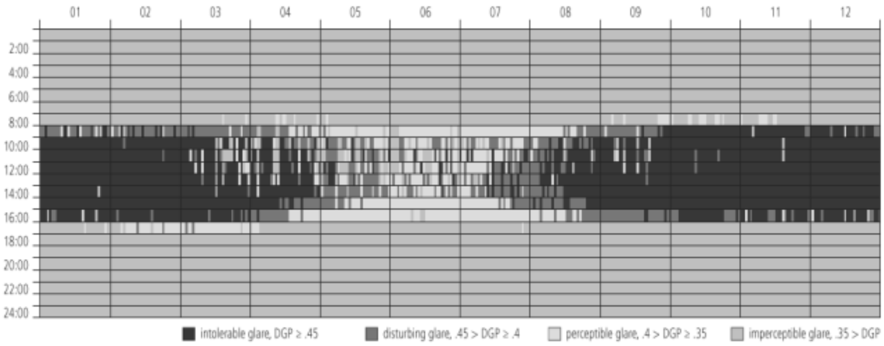


Figure 12. Temporal Maps of Annual DGP Throughout the Day Without CABS

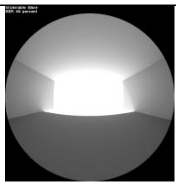
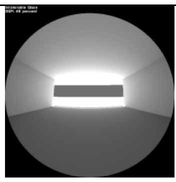
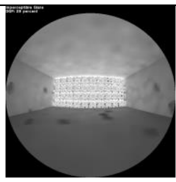
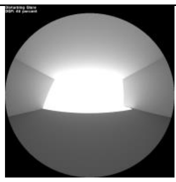
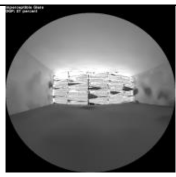
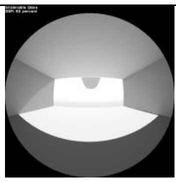
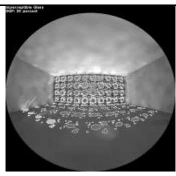
- The annual DGP throughout the day without CABS shows that the examined point received an intolerable glare > 45 within the working hours (from 8 am to 4 pm) during the year especially in the winter season.

Results from point in time DGP calculations for a point in the middle of the office space at a height of 1.3m above the floor (sitting position and looking towards the widow) with the optimized CABS at the four examined times are described below.

- The results with the optimised CABS system indicted that the examined point received an Imperceptible glare (which fillfull the design criteria) at all the examined times except at March it received a disturbing glare. (See table 5)

Table 5 presents graphically the results of point in time glare for the optimised CABS (21st of March, June, September and December at 12.00pm).

Table 5: Percentage of Daylight Glare Probability (DGP) for each scenario.

Time	Without CABS	With CABS
March 21st		
	Intolerable glare 46%	Disturbing glare 41%
June 21st		
	Intolerable glare 46%	Imperceptible glare 29%
Sep. 21st		
	Disturbing glare 45%	Imperceptible glare 28%
Dec. 21st		
	Intolerable glare 63%	Imperceptible glare 32%

5 CONCLUSION

This paper demonstrates a CABS system governed by daylight performance criteria. The system has been tested through integrating daylighting simulation tools and genetic optimization with a parametric facade model inspired by the works of Egyptian architect Hassan Fathy. The simulations were conducted for a south facing façade of an office space in Cairo, Egypt. Several CABS parameters were modelled to be used for the optimization process. The CABS system's capabilities were examined during the specified four times and proved its capacity of providing an adequate daylighting performance that fulfilled the required criteria using its predefined configurations and capabilities. The results proved that integrating daylighting simulation tools and a genetic algorithm to drive parametric façade designs can contribute in reaching better daylighting performance. In the future this study will be extended to consider the parametric optimization of façade designs in terms of thermal loads and occupant thermal comfort.

In conclusion, this study has demonstrated that a CABS system with a complex geometry can be successfully modelled, tested and capable of satisfying the desire of combining aesthetic values, building performance and user comfort in office buildings.

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