Cairo University

PARAMETRIC DESIGN OPTIMIZATION FOR SOLAR SCREENS:

AN APPROACH FOR BALANCING THERMAL AND DAYLIGHT PERFORMANCE FOR OFFICE BUILDINGS IN EGYPT

By

Asmaa Gamal Abdellfattah Elsayed Hassan

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
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FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Acknowledgments

First and foremost, I would like to primarily thank God for leading me to the path of knowledge. Wishing God to honour me by making this research “a knowledge which is beneficial” as our prophet PBUH said.

I would like to express my profound gratitude and appreciation to my supervisors **Prof. Dr. Ahmed Reda Abdin** and **Dr. Sherif Ezzeldin** for their guidance, support, valuable advice, constant effort, and their continuous encouragement throughout the whole research. They taught me persistence to any research challenges and excellence seeking.

My special acknowledgements go to my dear friend **Yomna El-Ghazi** for her continuous support, help and guidance throughout my years of study and through the process of researching and writing this thesis. Thank you for always being there for me.

I would like to thank **Ayman Wagdy** who introduced me to parametric design techniques and for his precious advices, guidance, and critical comments. Also my gratitude goes to my dear supportive friends **Soha Elgohary** and **Nadine Ashraf** who encouraged and helped me

I would like also to convey thanks to **Future University in Egypt (FUE)** staff, you are my second family that I am honored to be part of. And special thanks to **Prof. Dr. Samir Sadek** for his support and helpful advices he offers me in my personal and academic life.

Finally, **my parents and sister** deserve special mention for their continuous and unconditional support and prayers. This accomplishment would not have been possible without them. Thank you.

Dedication

To my Mom, Dad and Sister

For all your Support, Encouragement and

Unconditional love

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Nomenclature

ASE	**Annual Sunlight Exposure**
BDTF	**Bidirectional Transmission Distribution Function**
BREEAM	**Building research establishment’s environment Assessment Method**
CGI	**CIE glare index**
CIE	**Commission International de l'Eclairage**
CASBEE	**Comprehensive assessment system for building environment efficiency**
CAD	**computer aided design**
DAcon	**Continuous Daylight Autonomy**
DA	**Daylight Autonomy**
DF	**Daylight Factor**
SC	**Direct Sky Component**
DSF	**Double Skin Facades**
EMA	**Egyptian Meteorological Authority**
EPW	**EnergyPlus Weather files**
EAs	**Evolutionary algorithms**
EP	**Evolutionary Programing**
ERC	**Externally Reflected Component**
GAs	**Genetic Algorithms**
GP	**Genetic Programing**
GH	**Grasshopper**
IES	**Illuminating Engineering Society**
IRC	**Internally Reflected Component**
LEED	**Leadership in Energy and Environmental Design**
DAmax	**Maximum Daylight Autonomy**
PMV	**Predicted Mean Vote**
PPD	**Predicted Percentage of Dissatisfied**
SHGC	**Solar heat gain coefficient**

RAD	**Solar Radiation**
sDA	**Spatial Daylight Autonomy**
CGI	**The CIE glare index**
USGBC	**The U.S. Green Building Council**
UDI	**Useful Daylight Illuminance**
UDI	**Useful Daylight Illuminances**
Tvis or VT	**Visible transmittance**
WWR	**Window-to wall ratio**

Abstract

Architects used to be the chief builder that controls the whole design process starting from early design phases till the final end-product construction. By the time specialization and the use of mass-produced building components spread widely and dominate all industrial fields and architects became more separated from many key aspects of a building’s production. New technologies, including digital generative design and digital fabrication systems can narrow the gap between architectural designs, associative engineering aspects and buildings construction and reintegrate them into a digitally collaborative cycle process where architects is the “chief builder” again. In this regard, parametric generative systems as well as optimization algorithms, have made a major shift in the design process from designing an ‘object’ to design the ‘logic’ of the object, considering parametric optimization approach as a generative-explorative tool.

On the other, hand building façade plays a significant role in architecture; it is not only a mean to express the design concepts but it is the main moderator between interior spaces and exterior environment. The increasing reliance of office buildings on air conditioning and artificial lighting systems indicates the failing role of the building facade to perform its function as a moderator. Within this context, ecological facades have proved their potentials for enhancing buildings’ environmental performance.

The main aim of this research is to define the effectiveness of both parametric design and Genetic Algorithms approaches for assessing various solar screens’ parameters and to optimize screen configurations that improve both indoor daylight quality and thermal performance while providing minimum energy consumption.

The research will discuss the issue through two main parts;

Firstly, a theoretical study, based on a comprehensive literature review, was addressed to; firstly, explore daylight and thermal performance fundamentals for office buildings as the main aspects affecting office building current energy raising demands, as well as presenting the building performance metrics, rating systems and simulation tools to establish the basic knowledge for this study. Secondly, investigate the ecological façade strategies and their effects on daylight, thermal and energy performance. This concludes with the integrated methodology that combines daylight and thermal performance for office buildings. Thirdly, investigate the parametric design and optimization algorithms approaches for optimizing building designs to conclude with the parametric design and Genetic Algorithms (GAs) integrated methodologies as generative-analytical design methods for optimizing building designs.

Secondly, an empirical study, based on computer simulation, was conducted using combination between the two previous methodologies. Thus, the methodology integrated daylight and thermal simulation tools with paramedic modeling and GAs technique using DIVA, Grasshopper and Galapagos respectively. It was used to generate, evaluate and optimize a non-conventional daigrid-based solar screen different parameters; size, rotation angle, scale ratios and protrusion value, to balance indoor daylight and thermal performance within the minimum possible energy consumption. The simulation was conducted for a south-oriented side lit office space in Cairo, Egypt to optimize a diagrid-based solar screen various parameters; size, rotation angle, scale ratio, and protrusion value.

Thus, the thesis presented a comprehensive analysis for the effect of the proposed solar screen different parameters on both daylight and thermal performance for office buildings. It addressed evaluation criteria that could give an indication about cooling loads based on daylight simulation and hence daylighting optimum cases can be sorted regarding thermal and energy performance without calculating them. This research also conducted an analytical comparison between the GAs optimization and parametric simulation approach testing each approach's effectiveness and limitations in balancing daylight and thermal performance for the proposed solar screen. Finally, two parametric-based optimization method; Modified GAs and Adapted Parametric Algorithm, were suggested to overcome the previous limitations. They could help architects to efficiently optimize any non-conventional solar screen regarding specific performance target.

Keyword: Parametric design, Optimization algorithms, Solar screen, Office spaces, Daylighting, Thermal Performance, Energy consumption

Chapter 1 : Introduction and research overview

1.1. Introduction

The current cycle of global warming is changing the rhythms of climate that all living things and built environment have come to rely upon. The cycling interaction between global warming and buildings and the impact of global warming on building energy use are becoming a vital issue. Such a warming climate will affect both the performance of existing building and the design of new buildings. Therefore, the need for energy-conscious design starting from early design phases is becoming imposition to avoid aggravation of the energy problem and global warming danger.

Egyptian cities are facing dramatic impacts of climate changes and have been experiencing energy shortage, with the problem being made worse after the revolution of 2011. Ongoing political and social unrest in Egypt has slowed the government's plans to expand power generation capacity by 30 GW by 2020. As a result, Egyptian electricity consumption is increasing much faster than capacity expansions.

Rising power demand, natural gas supply shortages, ageing infrastructure, and inadequate generation and transmission capacity have led to frequent blackouts in different places Egypt. Electricity shortages are now a problem in almost all Egyptian governorates and as energy cost increase, the need for buildings with high energy efficiency and low environmental impact has become even more critical issue.

In the world of architecture, the energy performance issues have been solved at the system level by providing high efficiency systems, high performance equipment, building materials and renewable energy technologies. As a result of this architects may have assumed that no matter what they design, engineering counterparts and other consultants will be able to make their ideas work at the building systems level.

1.2. Research Problem

In Egypt, over 60% of Egyptian total electricity consumption is ascribed to the built environment. Air conditioning and lighting were found to be accounted for over two thirds of electricity consumption in commercial buildings sector in Egypt. Attributing to this rising energy demand is the office building facades. In hot arid climates like Egypt, the facade's configuration is responsible for up to 45% of the cooling loads. Consequently, the need for more efficient office buildings facades' design that aim to reduce solar heat gain and encourage daylighting has become a vital issue.

Considering architectural field, performance simulation tools have been widely used to analyze design alternatives through the design process. However, current simulation tools failed to address novel shading systems and façade designs due to its limitation in modelling and exploring wide range of solutions. Thus, integrating new digital generative systems such as parametric design systems as well as optimization algorithms with these simulation tools could be considered as generative-analytical design methods that could overcome this limitation.

1.3. Research questions

The previous view of the problem generated the following research question:

How can parametric design approaches and Genetic Algorithms optimization help architects in exploring ecological building facades while achieving the optimal balance between daylight and thermal performance, hence reducing the energy consumption?

As this question includes several fields of application, it is divided into more elaborated questions:

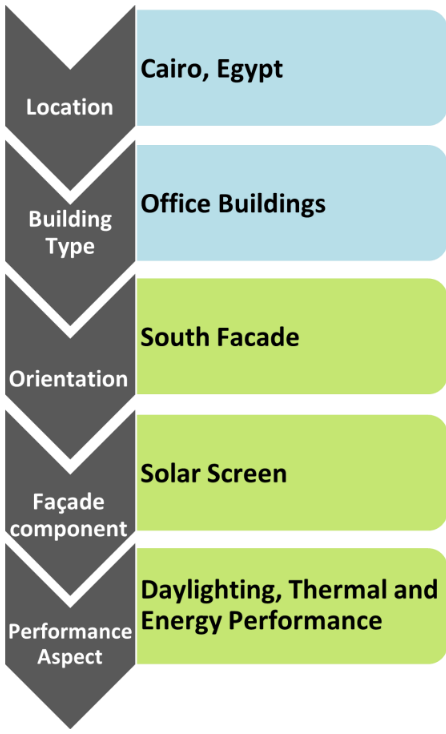
1. **How** does office building facade affect the energy efficiency and the whole performance of the built environment?
2. **How** can designing ecological building facades enhance daylight and thermal performance in buildings?
3. **How** can parametric design systems help architects to generate, explore and evaluate different design alternatives for specific target performance?
4. **Which** parametric modelling tools and optimization algorithms methods are the most appropriate for architectural performance-based-design approach?
5. **How** can architects integrate parametric design approaches and optimization algorithms with performance simulation tools to study and evaluate the impact of the daylight and thermal performance on designing solar screens?
6. **What** are the effective strategies and workflow that can be followed to enhance day lighting and thermal performance for office spaces in Egypt?

1.4. Research Hypothesis

Integrating parametric design approaches and Genetic Algorithms optimization with performance simulation tools provide architects with a generative-performative approach to explore evaluate and optimize novel ecological solar screen designs for balancing daylight and thermal performance within the minimum possible energy consumption.

1.5. Research Scope and Limitation

- Cairo, Egypt.
- Office Buildings.
- South facade
- Solar screen
- Daylighting, Thermal, and Energy Performance.



In this research; daylighting, thermal and energy performance will be the key performance criteria to designing solar screens using parametric optimization approaches for office spaces.

This thesis will focus on optimizing solar screen parameter; size, rotation angle, scale ratio and protrusion value, by integrating simulation techniques with parametric design system and optimization algorithms at early design stages to enhance natural daylight uniformity as well as thermal performance, by means of cooling and heating loads, while reducing the total energy consumption.

The case studies will be carried out for a typical side-lit office space facing the south orientation in Cairo, Egypt.

This thesis is intended to be useful to: Architects (Professional and students), academic researchers in architecture and building technology, researchers in sustainability and energy conservation fields. But especially architectural designers - involved in the environmental studies using new technologies.

1.6. Research Aim & Objectives

The main aim of this research is to integrate parametric design systems and Genetic Algorithms with simulation tools for assessing various solar screens' parameters and to optimize screen configurations that improve both indoor daylight quality and thermal performance while providing minimum energy consumption.

In addition this thesis aims to propose a parametric-based optimization method that could help architects to find the optimal configurations for any solar screens with respect to particular performance objectives.

In order to achieve the overall aim of the research, group of objectives had to be achieved too as:

- **Determining** the specifications and requirements of daylighting and thermal performance focusing on office spaces in Egypt.
- **Specifying** the building performance metrics, rating systems as well as the current simulation tools that integrate both daylight and thermal analysis.
- **Understanding** the ecological facade components and their effects on, daylighting, thermal and energy performance for office buildings.
- **Identifying** thermal and daylight performance integration methodology, its tools and process showing its potential and limitation.
- **Investigating** the effectiveness of parametric design systems and optimization algorithms approaches for exploring and optimizing architectural designs that correspond to specific performance goals.
- **Integrating** parametric design systems and Genetic Algorithms with performance simulation tools for generating, evaluating and optimizing solar screens to balance daylight and thermal performance within the minimum possible energy consumption.
- **Investigating** the effect of different solar screen parameters on daylight and thermal performance for south-oriented office buildings' facade.
- **Proposing** new approaches that could be used to find the optimal configurations for any solar screens with respect to particular performance goals.

1.7. Research Methodology

In order to achieve the mentioned aim and objectives, the methodology of the study confines;

- **Theoretical study based on an inductive analytical methodology;**
  - **Exploring** daylight and thermal performance fundamentals, outcomes, requirements and problems for office buildings.
  - **Analyzing** recent literature reviews that integrated daylight and thermal performance for optimizing ecological office buildings' façades
  - **Investigating** parametric design systems as well as optimization algorithms approaches in architecture and for addressing ecological designs.
  - **Analyzing** recent literature reviews for parametric design systems and Genetic Algorithms optimization applications that addressed ecological designs.
- **Practical study based on an empirical methodology;**
  - **Developing** an integrated methodology for optimizing a proposed ecological solar screen by integrating simulation tools with parametric design system and Genetic Algorithms for daylight, thermal and energy.
  - **Conducting** parallel parametric simulations as well as Genetic Algorithms process for assessing and optimizing the solar screen parameters.
  - **Exploring** the effect of solar screen parameters on daylight, thermal and energy performance.
  - **Comparing** parametric simulation approach with Genetic Algorithms approach as a tool to explore and optimize ecological solar screens.
  - **Suggesting** new design methods for optimizing ecological solar screens that could make a worthwhile investment from the previous exploration with the minimum possible limitations.

1.8. Research Structure

The overall structure of the study takes the form of six chapters, including this introductory chapter;

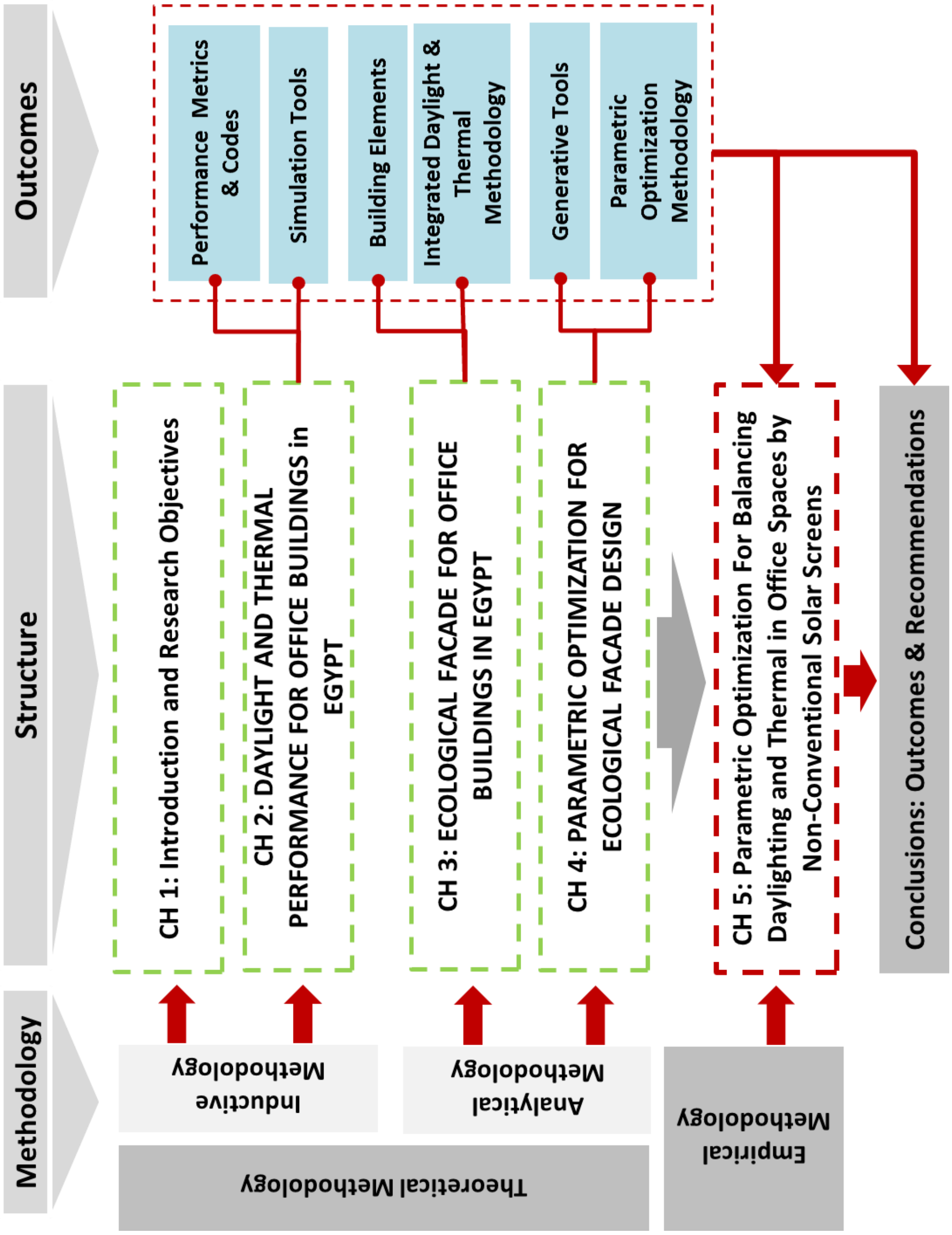
Chapter two discussed the specifications and requirements of daylighting and thermal performance focusing on the specific requirements for office spaces in Egypt. It also defined their potentials and limitations and addressed the current building performance metrics, rating systems and simulation tools.

Chapter three began with a brief overview for office buildings' facades design evolution in Egypt from the 18th century till the current days, showing their effect on the overall ecological performance. However, this chapter was concerned with the ecological facade approaches and their potentials for enhancing daylight, thermal and energy performance in buildings. It concluded with the integration methodology that could combine both daylight and thermal performance in the design process, showing its potential and limitation for optimizing ecological facades.

Chapter four addressed the potential enhancement of the digital practice to the design process in addressing the previous discussed limitations. Consequently, digital fabrication and generative systems were discussed in brief. Focusing on the scope of this research, the generative parametric design systems and tools were investigated showing their potentials, limitation and misconceptions for addressing ecological aspects in architecture. After that, optimization algorithms potentials as evaluation searching method that could overcome parametric systems' limitations were discussed. The study in this chapter focused on Genetic Algorithms optimization approach as a worldwide known optimization technique for sufficient searching complicated solution spaces showing its process, tools as well as addressing its limitations and drawback and how to overcome them. Finally the methodology of using parametric design systems as well as Genetic Algorithms for optimizing solar screens were conducted form analyzing recent literature reviews in the field.

Chapter five investigated a non-conventional solar screen that can be morphed to balance daylight and thermal performance within the minimum energy consumption for a south-oriented office building's facade in Cairo, Egypt. This chapter focusing on understanding the effect of the screen parameters; size, rotation angle, scale ratio and protrusion value, on the indoor daylight and thermal performance. Two main approaches; parallel parametric simulation and Genetic Algorithms were investigated and their results were compared. Finally two design methods; Modified Genetic Algorithms and Adapted Algorithm that could help architects to efficiently optimize solar screens for specific target performance were suggested.

Chapter six - Conclusion and Recommendations: gives a brief summary and critique of the findings. At the end of the research, recommendations and suggested further researches are identified.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Chapter 2 : INTEGRATED DAYLIGHT AND THERMAL PERFORMANCE FOR OFFICE BUILDINGS

2.1. Introduction

Egypt’s built environment is facing dramatic impacts of climate changes and has been experiencing energy shortage, with the problem being made worse after the revolution of 2011. Egypt depends mostly on oil as the primary sources of energy. By the obvious drop in Egypt's oil production accompanied by increasing electricity demand make, the need for buildings with high energy efficiency and low environmental impact has become even more critical issue. The current situation of energy and electricity consumptions pattern for office building in Egypt will be addressed so as to focus on the main problem determination.

Office buildings are typically occupied during daylighted hours. On the other hand, daylighting strategies strongly influence the thermal performance and energy load of office buildings as daylight has two noticeable effects, light and heat. Thus, the well-designed use of daylight in office buildings has become an important strategy to improve energy efficiency. Moreover, the benefits of daylighting extend from reducing energy consumption for electric lighting and cooling loads to improving occupant comfort and health, a view to the outside and enhanced design aesthetics.

This Chapter will be divided into three main parts; first part will address the general energy situation in Egypt, focusing on the main problems facing office buildings, increasing lighting and cooling loads. Thus, the second part will address the fundamentals of daylight and thermal performance in office buildings, showing their impacts not only on the energy consumption but also on the occupant’s health and productivity. Finally, the current building rating systems and code that encourage enhancing daylight and thermal performance in buildings will be addressed. As most of building rating systems encourage using simulation tools for achieving their performance metrics, the simulation tools that could integrate both daylight and thermal analysis will also be discussed.

It is expected that by this chapter all the necessary information on which the analysis of next chapters’ literature review (*chapter 3 & chapter 4*) as well as the simulations of the case studies (in *chapters 5*) are based would be discussed.

2.2. Office building Energy consumption In Egypt

Awareness of the expanding dependency on generated power in buildings started in the late 1960s by writings of Olgyay (Olgyay and Olgyay 1953) and Banham (Banham 1969). But, it was not till the 1970's after the energy crises that the issue of controlling energy in buildings was addressed worldwide.

The energy Crisis provoked a fundamental change in architectural design. In the past 40 years, the environmental agenda in architecture, in both practice and research, has undergone an observed radical transformation. This transformation supported mainly by changes to building regulations that would drive the architectural profession into environmental and energy consumption consciousness.

Egypt set a National Environmental Law in 1994 which is increasingly concerned with the protection of the environment and conservation of energy (Hamza 2004). The government is also preparing a national climate change action plan and a national strategy for improving energy efficiency in Egypt. Three building energy codes were published for new residential (HBRC 2005), commercial (HBRC 2009) and Governmental (HBRC 2010) buildings. These codes estimate to improve the efficiency by about 20% of total Electricity consumed (Hanna 2013).

Production of electricity in Egypt depends mostly on fossil fuel amounting to 76% while only 24% of electricity is produced from renewable sources (hydro and wind), no other sources are available (EIA 2015). Oil accounts for 92% of Egypt's primary sources of energy, besides being a mainstay of national economy as a source of foreign exchange revenue through its export to other countries. Egypt's oil production faced an obvious drop from more than a decade ago after reaching more than 900,000 b/d (barrels per day) in the mid of 1990s to only 708,000 b/d in 2014. Meanwhile, according to statistics by International Energy Agency (IEA 2015), investigation of total energy consumption in Egypt over 24 years in TeraWatt-hours = 10^{12} Wh indicates that electricity demand has increased 8 times from1980 to 2012 from 17.00 to 145.66 TWh as shown in Figure 2.1 with an expected continuous increase by a growth rate of 6.8% in the next few years (Hanna 2013).

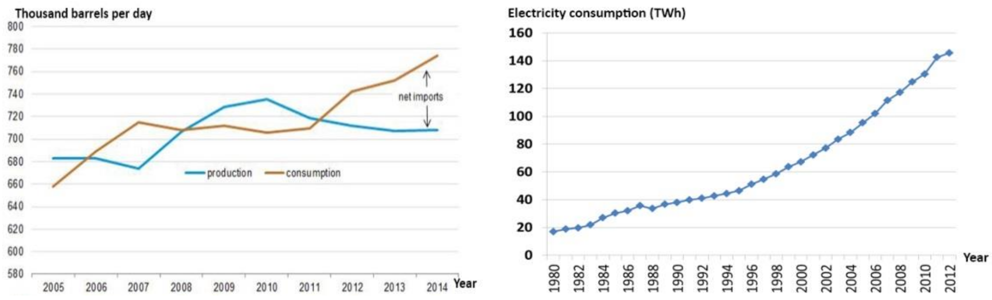


Figure 2.1 On the left, Egypt's oil production and consumption (2005-2014). On the right, Egypt Electricity consumption (1980-2012) (TWh)

Source: U.S Energy Information Administration (EIA)
http://www.eia.gov/beta/international/analysis.cfm?iso=EGY

In Egypt, Over 60%of Egyptian total electricity consumption is ascribed to the built environment combining residential, commercial and governmental buildings with 71%, 20% and 9% respectively of the total built environment electricity consumption (AFDB 2010) as shown in Figure 2.2.

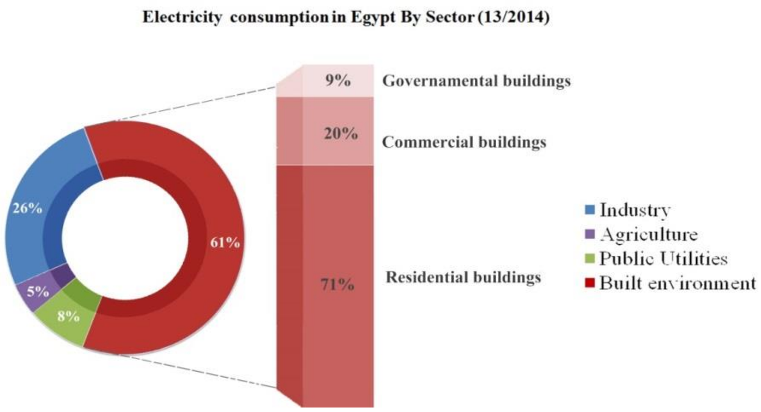


Figure 2.2 Energy consumption in Egypt by sector 2013/2014

Source: by the researcher based on African Development Bank Group (AFDB 2010)

According to A. Abdin and K. Elfarra (Abdin and Elfarra 2006), air conditioning and lighting account for 38% and 33%, respectively, of the total annual energy consumed in the commercial building sector making them account for over two thirds of electricity consumption in commercial buildings sector in Egypt as illustrated in Figure 2.3.

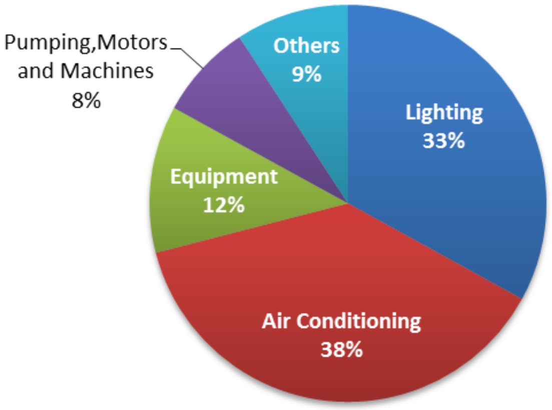


Figure 2.3 Energy Consumption Pattern for Commercial Buildings in Egypt

Source: (Abdin and Elfarra 2006)

It is important to note that the increase in electricity consumption in office buildings is also attributed to the increasing use of office equipment, and the aging of their cooling systems that depend solely on electricity for operation. This phenomenon deserves analysis for its cause and possible ameliorations to decrease the building energy consumption and provide more sustainable buildings.

Consequently, the need for more energy-efficient office buildings that aim to reduce solar heat gain and encourage daylighting has become a vital issue. Next sections will discuss the specifications for daylighting and thermal performance requirements, providing essential fundamental knowledge for the purpose of this research.

2.3. Thermal performance in office buildings

The thermal performance of buildings is considered one of the most important criteria for successful building design. It deals with the heat flow between buildings and outdoor environment. Building's components such as walls, windows and their materials affect this heat flow. It aims to provide a thermally comfortable environment for occupants while minimizing the energy demand for cooling and heating. Its importance increased in conjunction with the energy crisis, the environmental pollution and the climate change which caused by the overuse of energy in buildings.

J. Nayak and J. Prajapati (Nayak and Prajapati 2006) defined the thermal performance of a building as, “the process of modeling the energy transfer between a building and its surroundings”. The difference of temperature between the building and the outdoor environment is the main engine for energy flow throughout a building.

This section will overview the factors affect the thermal performance. Then it will explain the mechanism of heat transfer between the building and the environment. In addition, it will discuss the thermal comfort as a measure of thermal performance. Finally, it will display a general review of thermal performance impact on energy consumption.

2.3.1. Factors Affecting Thermal Performance of Buildings

The main factors affecting office buildings thermal performance are; heat gains or losses through structural components, internal heat loads generated by occupants as well as their activities and heat flow carried along with air by ventilation. Thus, the building thermal performance depends on a large number of factors, summarized as; design variables, material properties, weather data and building’s usage data as showed in Figure 2.4.

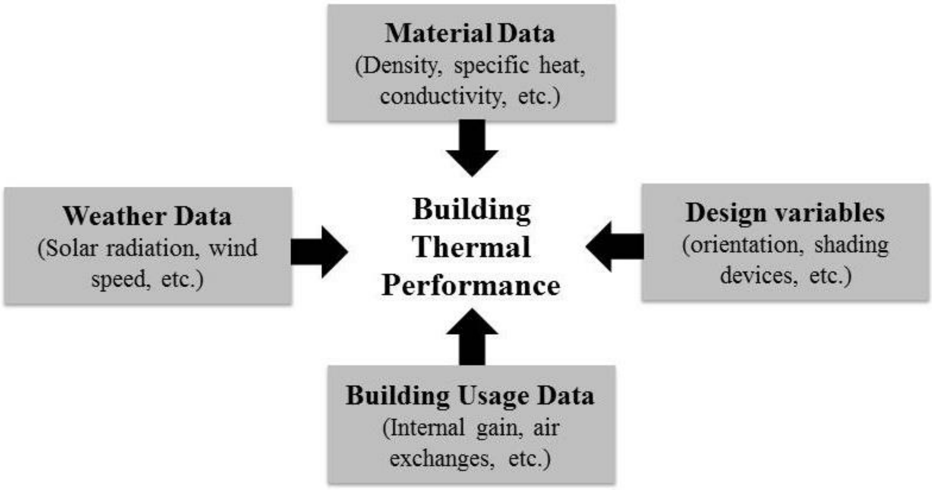


Figure 2.4 Factors affecting thermal performance

2.3.2. Heat transfer in office buildings

Heat transfer in buildings is an important factor for designing the building envelope as well as the passive and active systems to obtain the required thermal conditions with minimum energy consumption.

Typically, the heat transfer mechanisms between a building and the external environment are mainly categorized into; conduction, convection and radiation as shown in Figure 2.5. Hence, the thermal behavior of a system is a function of the dynamic relationship between these mechanisms.

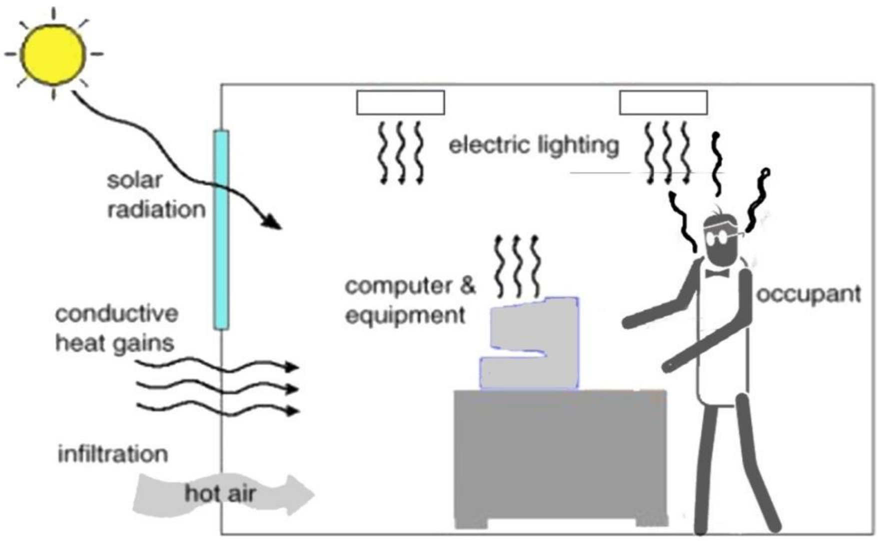


Figure 2.5 Heat exchange processes between office buildings and the external environment

It can be summarized that in buildings, conduction is primarily carried out through solid elements, convection is usually depended on ventilation or air movement rates, and radiation is mainly from the sun through external openings as shown in Figure 2.6. In some conditions one of these methods could dominates the other two but normally, two or all three process affect the heat transfer simultaneously. The indoor temperature and the occupants' thermal comfort are strongly affected by the resulted heat transfer.

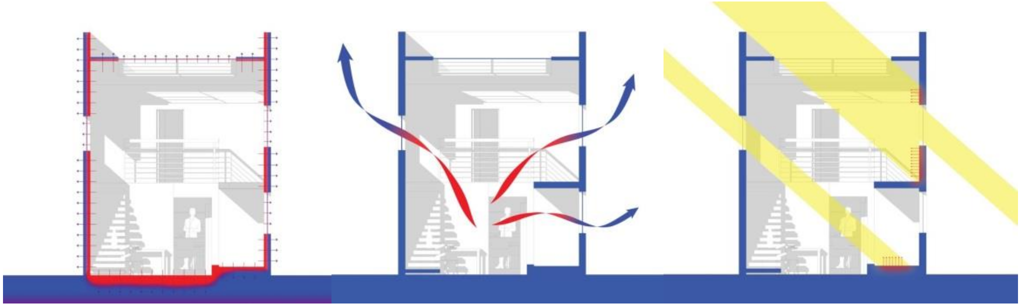


Figure 2.6 Conduction, convection and radiation heat transfer through building envelope.

Source: http://sustainabilityworkshop.autodesk.com/buildings/heat-energy-flows

2.3.2.1. Solar Radiation

Heat transfer in buildings depend mainly on two processes; firstly, the differences of temperature between indoor and outdoor, secondly, the radiant solar energy on both opaque and non-opaque surfaces. On any opaque surface, the radiant solar energy is partially reflected while the other is absorbed by the structure, bases on the material as well as the color of external finishing (Ascione, Bellia et al. 2010). Solar radiation accounts for most of the building envelope heat gain specially for office buildings with large glazed facades (Lam 2000)

Solar gain or solar heat gain indicates to the increase in space temperature that happens due to the solar radiation with its short-wave infrared radiation that passes through glazing and heat the building internal surfaces. The re-radiated long-wave infrared radiation by the heated surfaces doesn't have the ability to pass back out through the glazing. This result in heat accumulating in the interior, sometimes referred to as the 'greenhouse effect'(wiki 2014).

2.3.2.2. Internal heat gains

Internal heat gain described as the incensement in any indoor space temperature and/or humidity resulted from both sensible and latent heat emitted within the space. J.Ferdyn-Grygierek and A. Baranowski (Ferdyn-Grygierek and Baranowski 2011) studied the energy demand for office buildings considering several variants of internal heat gains, varying both the number of working persons and the power rating of the installed appliances. The results showed that by increasing the office's internal heat gains, the cooling loads needed to maintain the required indoor temperature also increases. P. Lubina and M. Nantka

(Lubina and Nantka 2009) as well as D. Jenkins (Jenkins 2009) also agreed with this results.

Internal heat gains main sources in buildings are as following (CIBSE 2006):

• **Occupants** (sensible and latent heat gain)
• **Lights** (sensible heat gain only)
• **Equipment**, office equipment, computers, etc. (sensible and latent heat gain)

For occupants; the body continuously produces heat due to metabolic activities by which part of it is used as work while others are released to the environment to balance the temperature of the occupant’s body. It can be released as sensible due to the skin higher temperature or latent by means of respiration and sweating. Thermal load due to occupants can be ranged from 70-80 watts to over 1,000 watts for a sleeping adult and an athlete engaging in intense exercise, respectively. It is about 100-130 watts for office spaces activities (Morton 1952, Starner and Paradiso 2004).

For both lights and equipment, the internal gains are generally equal to their energy use. However, for lights, heat gain only occurs after the surfaces of the space absorbed the energy emitted from the lamps. This process causes a time lag before the heat affects the cooling load.

2.3.3. Thermal Comfort in office buildings

From ancient history to present days, people have always striven to get thermally comfortable environment in their buildings. Nowadays, designers still consider thermal performance as one of the most significant parameters when designing buildings to achieve thermally comfortable environment for occupants (Straube 2006).

ASHRAE defined the following six factors shown in Figure 2.7, since the late 1920s, as those affecting thermal sensation (Goldman 1999).

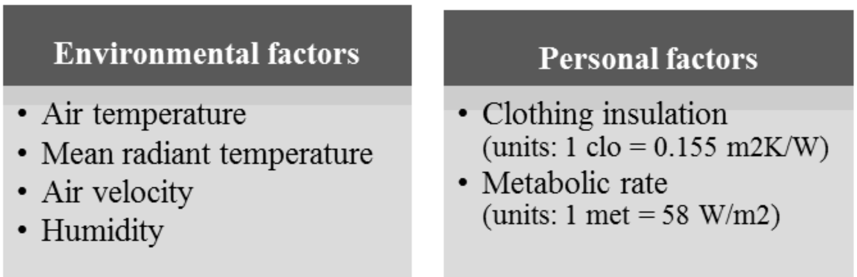


Figure 2.7 Factors affecting thermal sensation
Source: by the researcher

The level of subjective thermal comfort is widely measured by Fanger's PMV-PPD model. ‘‘Predicted Mean Vote’’ (PMV) is an index that defined as thermal scale which ranges from (-3) to (+3) indicating cold to hot respectively. The accepted PMV range for an interior space according to ASHRAE-55 is between -0.5 to +0.5. While ‘‘Predicted Percentage of Dissatisfied’’ (PPD) is an index that refers to the percentage of dissatisfied occupants at each PMV. The maximum percentage of dissatisfied people is 100% and the acceptable PPD range according to ASHRAE 55 is less than 10% as illustrated in (Figure 2.8) (Fanger 1970).

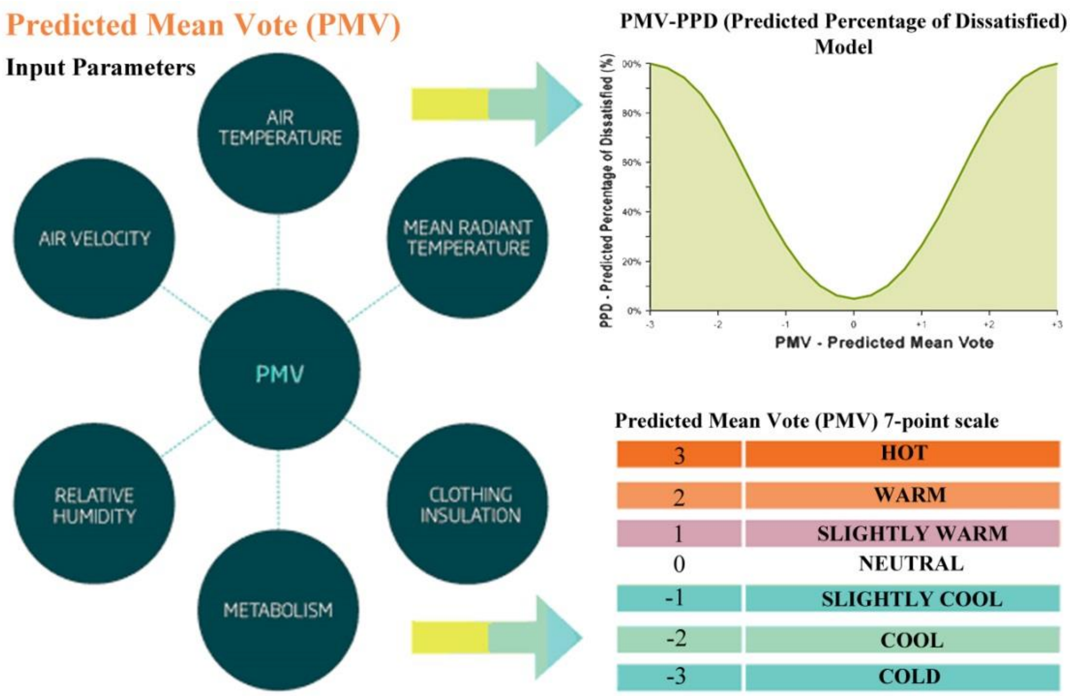


Figure 2.8 PMV-PPD model for thermal comfort

Source:https://continuingeducation.bnpmedia.com/concom/CE/CE_images/2011/

Human beings spend a significant amount of day at work. Thermal Comfort within these work spaces has a significant effect on occupants’ health and wellbeing which in turn affect performance and productivity. Many studies explored the relation between thermal comfort, health and productivity in office spaces. Seppanen et al. (Seppanen, Fisk et al. 2004) reported the results of multiple studies relating the performance in work and indoor temperature that affects thermal comfort and showed that if the indoor temperature is more than thermal comfort temperature range, occupants’ work performance decrease by around 2% per degree ^{o}C. Lan et al. (Lan, Wargocki et al. 2011) and A. Chen and V. Chang (Chen and Chang 2012) also discussed the relation between thermal comfort and human health for offices in different climates. The results showed that when occupants felt too hot or too cold, they reported many Sick Building Syndrome (SBS) symptoms, expressed more negative mood, and were less willing to exert effort.

2.3.4. Impact of Thermal Performance on Energy Consumption

Energy is considered one of the main factors affecting human life and it plays a huge role in development and civilization. The architectural buildings are important component of human civilization; however, they consume a large amount of energy due to technological development which contributes to achieve thermal comfort for occupants (Karasu 2010).

As mentioned discussed in *section 2.2,* the air conditioning for cooling/heating is the largest user of energy. It followed by lighting making air conditioning and lighting account for over two thirds of electricity consumption in commercial buildings sector in Egypt. Thus, the need for more energy-efficient buildings, that depend on reduction the energy demand by increasing thermal-performance level, has become a vital issue.

Heat flow must be controlled in order to make buildings more energy efficient. It is possible to slow the rate of energy exchange through conduction, convection and radiation by increasing the thermal performance of building envelopes (BuildingScience 2015). R. Venancio and A. Pedrini (Venancio and Pedrini 2009) indicated a major influence of solar gains on energy consumption and thermal performance in office buildings. The heat transfer through the building components, such as walls, windows and floors, in a mean of heat gains or losses adding to the internal heat gains are considered the most important factors affecting the thermal performance. In turn, this thermal response defines the required heating and cooling energy in order to maintain thermal comfort conditions for occupants (Aye, Charters et al. 2005). Yu et al. (Yu, Xu et al. 2011) concluded that the most influential factor on both cooling and heating energy consumption is the heat transfer coefficient of wall, followed by the building shape coefficient.

2.4. Daylighting performance for office building

Given that any non-opaque element in a building envelope 'daylights' the building's interior, the concept of daylighting is as old as architecture itself. The role of daylight as the primary daytime lighting source for building interiors remained mostly unchallenged until the widespread deployment of affordable fluorescent light from the early 1940s onwards. The introduction of affordable electric lighting and mechanical ventilation allowed floor plan depths to grow and windows – being freed from having to provide light and fresh air. Daylight became dispensable until the oil crisis of the 1970s, when daylighting enjoyed renewed attention from governments, researchers and designers who promoted a more efficient use of energy in buildings. During this period daylighting tended to be mainly viewed as an energy efficiency measure, a means to replace electric lighting and to reduce cooling loads. With the beginning of the new millennium, the daylighting concepts turned once again with the appearance of environmental green building technologies.

2.4.1. Factors that impact daylight performance through

Daylight is only to the solar radiation's part, with a wavelength between 380nm and 780nm, that responsible for humans' visual reaction (CIE, 1987). Generally, for the indoor spaces, daylight consists of a combination of direct sunlight, the primary source, diffuse skylight as well as their reflection from indoor and outdoor surfaces they face while entering the indoor spaces. On clear-sky days, direct sunlight luminance could reach up to 100,000lux, whereas on overcast days, sky luminance could reach up to 10,000lux (Baker, Fanchiotti et al. 1993, Wyckmans 2005).The main factors that impact daylight performance in a building can by summarized as shown in Figure 2.9.

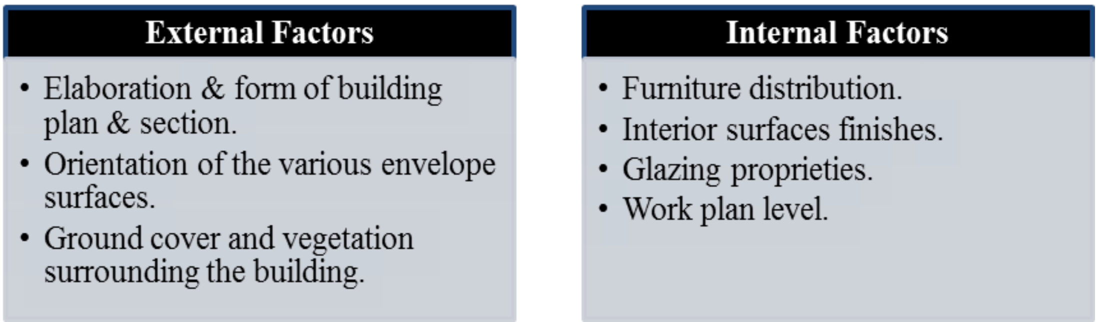


Figure 2.9 Factors that impact daylight performance

2.4.2. Importance of daylighting for office buildings

Daylighting performance design could positively affect several aspect related to office building design. Two main aspects are; employees' human health and productivity and energy-saving potential will be addressed in this section.

2.4.2.1. Human health and productivity

Artificial lighting can provide almost the same spectrum of daylight however; it can't provide the dynamic effect of daylight that occurs due to; changing in time, seasons, sites and weather conditions. Consequently, people still appreciate the natural gift of daylight and its role in maintain a healthy and productive environment.

Lovell mentioned that "Daylighting – the illumination of a space by sunlight – is not purely a matter of quantity and measurement. Decades of research have shown that access to natural light increases our well-being, comfort, and productivity – we are visual-centric beings."

C. Cuttle (Cuttle 1983, Hee, Alghoul et al. 2015)discussed that people prefer working in daylight rather than in electric light and that they feel less stress under sunlight environment while working in electric lighting could negatively affect occupants' health. Many other researches addressed the biological benefits of natural lighting and on the employees (Caudill, Peña et al. 1978, Chang and Chen 2005, Sop Shin 2007). Moreover, many other studies demonstrated that depending on daylight for lighting office buildings can increase occupants' productivity and subsequently affect the organizations' finances positively

(Edwards and Torcellini 2002, Heschong 2003). According to a research at Carnegie Mellon a 20% increase in employee productivity could equalize the construction cost of a single office in the first year (Loveland 2004, Tzempelikos 2005). The technical report of Heschong Mahone Group (Heschong 2003) also showed that daylight glare could in fact decrease productivity. Thus, there has to be a well-incorporated connection between office architecture and daylighting design which has an extensive impact on its occupants.

2.4.2.2. Energy-saving potential

Conscious architectural designs that integrate daylight strategies could achieve significant energy consumption directly by reducing the artificial lighting loads and indirectly by changing the cooling and heating loads of the buildings.

N.C. Ruck (Ruck 2006) reported that using advanced daylighting systems could highly increase the energy saving potentials as compared to conventional buildings systems. Moreover, P.E. Kristensen (Kristensen 1994) demonstrated that electricity for lighting can be cut by 50-75% in office buildings using daylighting design techniques in combination with efficient artificial lighting. However, Coyne and Cowling (Coyne and Cowling 1994, Leung 2011) argued that this percentage is too high comparing to the real suggesting 30% to 40%, depending on different locations and weather conditions, to be more accurate and realistic percentage of energy saving's potentials. Furthermore, the highest electric consumption in office buildings is mainly during daytime, which considers wasteful and thus the possibilities for energy savings using daylighting are significant (Wyckmans 2005).

2.4.3. Problems associated with daylighting

Using daylight in buildings has many advantages as mentioned above but in some conditions daylight could also cause several problems. The most critical problems are; visual discomfort and thermal discomfort.

2.4.3.1. Visual discomfort

Visual discomfort can occur due to glare or due to too great contrast of two surfaces. Many researches stated that excessive amount of daylight transmitted in a room could be a disadvantage for the optimal visual conditions (Nazzal 2005); (Bellia, Cesarano et al. 2008).

In office buildings, glare has been a major concern according to the Illumination Engineering Society of North America (IES). Glare was showed to negatively affect productivity as reported in a study by Horgen et al. (Horgen, Helland et al. 2007) and M. Boubekri and L. Boyer (Boubekri and Boyer 1992) examined the effect of window size on glare in a private office room based on occupants' appraisal (perceived glare) and glare prediction algorithms (calculated glare). The results indicated that window's size could affect glare and that becomes more critical if occupants face the window directly. Arabi et al. (Arabi, Husini et al. 2012) also conducted a research on the occupant's perception toward visual comfort in office buildings by a qualitative field survey and a quantitative DAYSIM simulation. Finding showed that the majority of the respondents were disturbed from the glare and that internal shading reduced this discomfort glare.

Often occupants will resort to shutting the blinds or shades to avoid this visual discomfort. The space then becomes too dark and users turn on the electric lighting, thus negating the expected energy savings of using daylight. Usually, shutting the blinds or shades is the suitable solutions for the occupants to overcome this visual discomfort which in turn, resulting into dark spaces that need more electric lighting causing more energy consumption and ignoring any daylight energy savings' potentials.

2.4.3.2. Thermal discomfort and Increasing thermal loads

Office buildings commonly use large surfaces of glass on their façades in order to reflect a luxurious appearance. This maximizes the daylight penetration into the space but daylight is only the visible portion of solar radiation, about 46%, and when it transmitted in a space, undesirable parts of solar radiation may also be transmitted. This often results in high and risky solar heat gains and highly thermal loads throughout the year. Thus, the amount of energy needed to maintain indoor thermal comfort increases.

Hence, the appropriate office building design isn't achieved simply by opening up the building envelope and flooding the indoor environment with daylight but by the efficient using of the available daylight sources. Thus, a balanced solution could be achieved, where acceptable daylighting performance would be attained with appropriate thermal performance at minimum energy consumption.

2.5. Daylight performance metrics and rating systems for office buildings

Building performance metrics are supposed to be "quality measures" for buildings with respect to their energy efficiency, lighting performance and any other required performance. It can be used by building designers for comparative studies to guide and support effective decision making for different proposed architectural solutions especially at early design phases.

2.5.1. Static Daylight metrics

Presently, there are many static-quantitative performance metrics for daylighting in office spaces. Daylight factor (DF) is one of the most common quantitative static metric that commonly used to analyze the daylight performance as it is a quantity metric. DF can be measured or calculated based on calculation tables or more refined simulation methods. It is defined as the ratio of the internal illuminance at a point in a building to the unshaded, external illuminance under a standard uniform sky. The calculation of DF depends on split-flux method that depends only on indirect sunlight. As shown in Figure 2.10 the DF in any space could be calculated deepening on three sources as followings; Direct Sky Component, Externally Reflected Component and Internally Reflected Component. Building geometry, surrounding context, as well as surface properties has an impact on the daylight factor and accordingly the ability to influence design choices (Reinhart, Mardaljevic et al. 2006).

But on the other hand, the orientation of the investigated building does not influence the DF since the CIE reference sky is rotationally constant and independent of the geographical location of the building. Another common drawback is that the reference overcast sky is the worst case sky condition and therefore any other sky will lead to more daylight in the space as shown in Figure 2.11 (Reinhart, Mardaljevic et al. 2006).

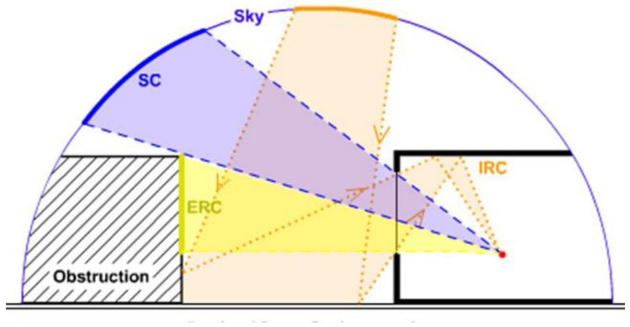


Figure 2.10 Different components of (DF)

Source: http://www.green-modeling.com/ecotect-natural-daylight-analysis.html

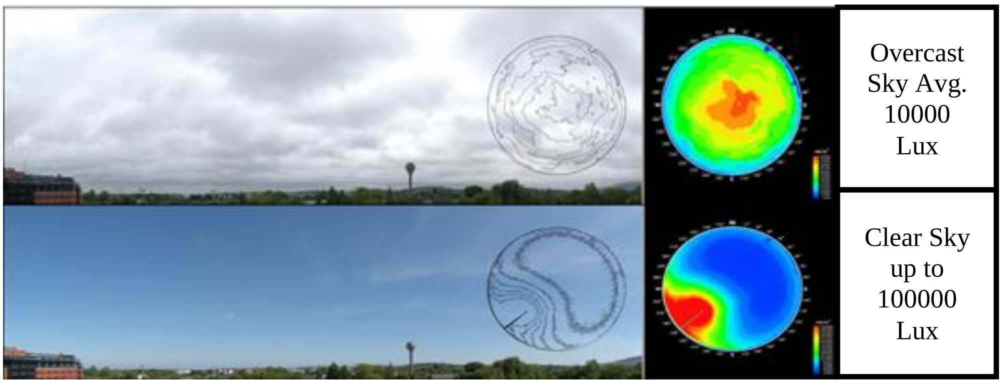


Figure 2.11 Overcast Sky and Clear Sky illuminance levels

Source: http://www.pro-lite.co.uk/File/case_study_illumination_design.php

Fortunately, many design teams are aware of the above mentioned limitations of the daylight factor and consider the avoidance of direct sunlight in parallel with daylight factor calculations known as “combined approach” (weighting daylight factor against unwanted solar gains). However, although the combined approach considers building orientation and latitude it doesn’t consider the actual climate in which the building is placed. This approach also ignores building type and occupant requirements of the building completely. These main barriers motivated researchers to investigate alternative metrics.

2.5.2. Dynamic Daylight metrics

The main advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together. Dynamic daylight performance metrics are based on time series of illumination within a building, usually extend over the whole year, and are based on external, annual solar radiation data for the building site.

CHPS Daylighting Committee (2006) gave some recommendations for variables that need to be addressed to standardize the calculation of any dynamic metric as:

- **Time:** It is important to specify the time of the year that will be considered during the calculations. Generally, two main criteria could be used; the daylit hours during the year or the annual occupied hours. Both approaches have their pros and cons. For office buildings, it is more accurate to use the occupied hours for the calculations.

- **Testing points and analysis grid:** Depending only on a specific point in a daylit space to use it for the calculating can't guarantee accurate results. Thus, new approaches have replaced the testing points by the analysis grid that extends throughout a lighting zone to offer more accurate calculations. Thus, Standard LM-83-12. Approved Method by IES specified no greater that (60cm x 60cm) grid size as smaller grid size will result in more accurate analysis.

- **Target illuminance:** There was diversity between different committees and researchers about the daylight illuminance range to be considered in calculations. Commonly illuminance range differs according to different space types but it can be based on reference documents such as the IESNA Lighting Handbook (IESNA 2000). For office workstations, it is ranged between 300-500 lux but according to IESNA it is better to use 300 lux for calculations.

For office spaces, IESNA and ASHRAE/IESNA Standard 90.1 recommended design illuminance levels between 300-500 lux (IESNA 2000) (ASHRAE 2004), while the French Institute for Care and Health as well as LEED rating system recommend illuminance level of 300 lux for an office spaces (David, Donn et al. 2011, USGBC 2013).

- **Location and Climate:** A more accurate approach would be to use the most representative climate data available for a given projects site. Climate based metric is the prediction of various radiant or luminous quantities using sun and sky conditions derived from standard meteorological datasets; the results are dependent both on the locale and the building orientation, in addition to the building's composition and configuration (Mardaljevic 2008). There are 70 typical climate data stations providing hour-by-hour climate data all around Egypt according to the official statistic by the Egyptian Meteorological Authority (EMA).

Once the previous considerations have been established, the next step is to choose criteria that determine whether the daylight situation is adequate at a particular point in time. Next, Table 2.1 concluded five main popularly used dynamic daylight metrics. More details about dynamic daylight metrics could be found in Appendix A.

Table 2.1 Dynamic daylight metrics different criteria

No.	Dynamic Daylight Metric	Description
1	**Daylight Autonomy (DA)**	Percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone.
2	**Spatial Daylight Autonomy (sDA)**	Percentage of an analysis area that meets a minimum daylight illuminance level for a specified percentage of the annual occupied hours.
3	**Useful Daylight Illuminances (UDI)**	• UDI is achieved (100–2000 lx) • Fall short of the UDI range (<100 lx) • Exceed UDI range (>2000 lx)
4	**Daylight Availability**	• **Daylit**: >=50% of hours reach minimum threshold • **Partially daylit**: <50% of hours less than minimum threshold • **Over lit**: <5% of hours exceed maximum threshold.
5	**Annual Sunlight Exposure (ASE)**	Percentage of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year.

2.5.3. The building rating systems and codes

The building performance metrics was originally promoted by the building rating systems which provide a framework for assessing a building's performance strategies.

The national Green Pyramid Rating System (GPRS) developed by the Egyption Green building council (GBC), as a national Green Building Rating System as well as many other international building rating systems has evolved over the years. The most popular international ones are shown in Figure 2.12 including:

a) **BREEAM** (Building research establishment's environment Assessment Method, country of origin: United Kingdom)
b) **CASBEE** (Comprehensive assessment system for building environment efficiency, country of origin: Japan)
c) **Green Building Index** (country of origin: Malaysia)
d) **Green Globes** (country of origin: Canada)
e) **Green Mark** (country of origin: Singapore)
f) **Green Star** (country of origin: Australia)

g) **LEED** (Leadership in Energy and Environmental Design country of origin: United States)

Figure 2.12 Current major global building rating systems

The Daylight Approved Method by IES (IES 2012) as well as the U.S. Green Building Council (USGBC) codified two of the mentioned dynamic daylighting metrics in the newest version of LEED, LEED v4, which allow a daylit space to be evaluated for a one year period using two different performance criteria: sufficiency of daylight illuminance and the potential risk of excessive sunlight penetration (IES 2012). These two metrics are: Spatial Daylight Autonomy (sDA $_{300,50\%}$) and Annual Sun Exposure (ASE$_{1000,250h}$) metrics that together form a clear picture of daylight performance and that can help architects to make good design decisions.

sDA describes how much of a space receives sufficient daylight, which is for commercial office spaces must achieve iIlluminance level (300 lux) for at least 50% of the total occupied hours from 8 am-6pm over the year. According to LEED v4, the percentage of sDA$_{300,50\%}$ should be at least 55% or 75% to achieve 2 to 3 LEED credits (USGBC 2013). While in IES approved method, sDA$_{300,50\%}$ must meet or exceed 75% of the analysis area (IES 2012). sDA has no upper limit on luminance levels, therefore, ASE provides the balance by describing how much of space receives too much direct sunlight, which can cause visual discomfort or increase the cooling loads. (ASE$_{1000,250h}$) calculates the percentage of the analysis points that exceeds a specified illuminance level, 1000 lux, for at least 250 hours of the occupied hours without any contribution from the sky. In LEED v4 (ASE$_{1000,250h}$) of occupied hours per year must not exceed 10% of floor area (USGBC 2013). While IES approved method (IES 2012) the supporting research, spaces with more than 10% ASE1000,250h were judged to have unsatisfactory visual comfort, space with less than 7% ASE$_{1000,250h}$ were neutral, while spaces with less than 3% ASE1000,250h were clearly acceptable. LEED v4 daylight requirements and IES Approved daylight method criteria are concluded in Table 2.2.

Table 2.2 LEED v4 and IES Approved daylight method criteria
Source: by the research based on (USGBC 2013)&(IES 2012)

Daylighting Criteria	
Target Illuminance	300lux
$sDA_{300,50\%}$	**>75%** – 3 points on LEED v4 & IES **>55 %** – 2 points on LEED v4
$ASE_{1000,250h}$	• Must be: < 10 % – LEED v4 & IES • preferred ratio: < 07 % – IES • the best case: < 03 % – IES

2.6. Daylighting and thermal performance simulation methods

The terminology 'simulation' originally comes from the Latin word 'simulat' meaning 'copied, represented' (Oxford English Dictionary: Web Version). Currently 'building simulation' generally means to produce a computer model imitating the appearance or physical performance of a building for design, evaluation or analysis purpose. The essential objective of simulation is to generate observable output data for analysis appropriate performance indicators. It enables the designer to consider the performance of their designs and alternative schemes with an accuracy and depth beyond that of the traditional manual and intuitive methods, as well as deliver required information faster than the specialist consultants.

Building energy simulation is also playing an increasingly important role in building energy codes. Many countries have developed or upgraded their building energy codes in the past decade to promote energy conservation and control building design performance. An important trend for modern building energy codes, such as that in the US Green Building Council's (USGBC) LEED system, is to encourage and move towards a greater use of building energy simulation and modelling techniques as shown in the previous chapter (Galasiu and Reinhart 2008, Elghazi, Wagdy et al. 2015).

2.6.1. Integrating thermal and daylight performance simulation tools

Generally, performance simulation tools consist of two components: the simulation engine and a graphical user interface (Figure 2.13). The graphical interface facilities the use of the simulation tools to input the data and represent the output in a more friendly-users platform while the actual analysis process occurred in the hidden simulation engine. The simulation engine is usually developed by one or more academic institutions or research organizations, the user interfaces are usually implemented by private software vendors.

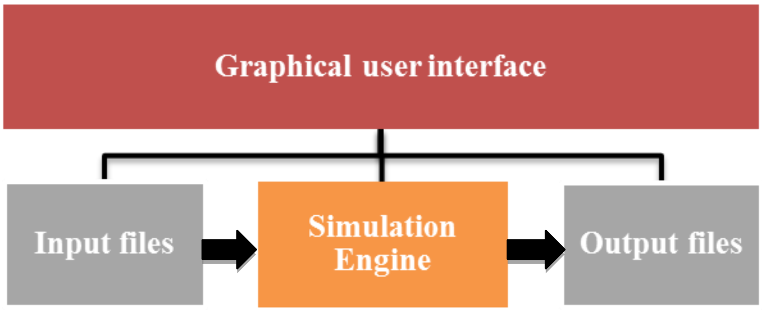


Figure 2.13 General structure of simulation program
Source: by the researcher

2.6.1.1. Daylight Simulation engine

Many simulation engines have been developed to carry out validated daylight analysis though the past years. Radiance and DAYSIM are two of the most validated and popular engines that have been integrated within many current simulation tools.

a. RADIANCE

Radiance is an advanced lighting simulation program for analyzing color and illuminance of building. Radiance was first released by Gregory J. Ward in 1989 at the Lawrence Berkeley Laboratories (LBL) in California with main support from U.S. Department of Energy and Swiss Federal Government as the first standalone daylight analysis tool.

Radiance is a simulation engine meaning that it consists of a series of command line programs that carry out the different simulation steps. It uses the light-backwards ray tracing method to analyze inter-reflections between both diffuse and specular surfaces. A Monte Carlo method (i.e., a numerical method) also was used in Radiance to estimate indirect illuminance and the CIE glare index (CGI) to analyze visual comfort.

Radiance can calculate spectral radiance, irradiance and glare indexes. Simulation results can be presented using rendered images, mathematical values or contour plots (Radiance). Rendered images generated from Radiance are significantly beneficial to evaluate lighting distribution and aesthetics.

b. DAYSIM

DAYSIM is validated RADIANCE-based daylighting analysis software. It was proposed in 2000 by C.F Reinhart and S. Herkel (Reinhart and Herkel 2000) as a new method for predicting annual daylight illuminance distribution in a space. In another paper, Reinhart and Walkenhorst presented the validation results of the method in comparison to the measured data for a simple model office building.

DAYSIM is a simulation engine and its users may choose from a variety of Graphical User Interfaces which call DAYSIM such as Rhinoceros, SketchUp and Ecotect. DAYSIM can model annual illuminance calculations, dynamic shading systems and glare analysis. It includes many innovative simulation capabilities. It can model annual illuminance calculations, dynamic shading systems and glare analysis. It includes many innovative simulation capabilities. DAYSIM calculate the annual illuminance calculations by combining daylight coefficient with Perez all weather sky models and Radiance backward ray-tracer. The results then can be used to calculate annual electric lighting and drive Daylight Autonomy and Useful Daylight Illuminance daylighting metrics. DAYSIM also generates hourly schedules for occupancy and shading device status which can be directly coupled with thermal simulation engines such as EnergyPlus.

2.6.1.2. Thermal Simulation engine

Starting from 1970s, paralleled to the energy crisis and oil embargo, the need for emerging computers in building energy and performance modelling began to arise. In 1971, many corporation and institutions started to develop building energy simulation engines. In the late 1970s, BLAST, TRNSYS, ESP-r and DOE-2 energy based engines been released and slightly used. Since then many improvements have been applied to those engines while other new energy engines have been developed.

c. DOE-2

The DOE-2 energy and thermal simulation engine uses the daylighting results from ADELINE software, following a sequential-type approach. Nevertheless, this has an effect on the integration with HVAC system operation (link consistency and data exchange). Moreover, this software uses the concept of the split-flux method, carrying all the resulting disadvantages.

d. EnergyPlus

EnergyPlus is primarily a simulation engine developed based on features of BLAST and DOE-2. It was released in April 2001 by the U.S. Department of Energy (DOE) (Crawley, Lawrie et al. 2004). EnergyPlus solves the sequential shortage of DOE-2 by using integrated techniques at all simulation levels and supports fully integrated simulation for buildings loads and systems. It uses WINDOW 5.0 software (Arasteh, Finlayson et al. 1994) to handle angular-dependent optical and thermal properties and uses the Perez model (Perez, Ineichen et al. 1990) for calculation of irradiance and illuminance values.

EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use. It includes many innovative simulation capabilities: time-steps less than an hour, multi zone air flow, thermal comfort and photovoltaic systems. The daylighting module can simulate controllable shading devices and produces interior illuminance values, glare indices, and reduced electric lighting operation to be used by the heat balance module.

Despite all these improvements, the daylighting engine of DOE-2 is still used and split-flux inter-reflection module calculations are not simulated accurately.

Furthermore, the program does not yet have an interface. It reads input and writes output as text files only. However, some available Graphical interfaces such as; Design Builder, Open Studio and Sefaira use EnrgyPlus as their simulation engine for calculations (EERE 2014).

2.6.2. Simulation tools interfaces

Many simulation tools are now integrate both daylight as well as thermal simulation engine within the same user interface to facilitate a whole comprehensive analysis for the building performance from early design phases. Some of the currently used simulation tools will be discussed in brief showing the integration process.

2.6.2.1. Design Builder

DesignBuilder is a user-friendly modelling environment that enables design teams to use the same tool for creating energy-efficient buildings. The latest version, version 4, adds a substantial set of new features including the latest certification software for UK, a new Multi Objective Optimization tool and a LEED module. DesignBuilder includes many simulation capabilities and can model energy and thermal comfort analyses, HVAC systems, daylight factors and illuminance, Computational Fluid Dynamics (CFD) as well as provides early stage building cost estimation. DesignBuilder also enables users to import existing BIM and CAD data and generate impressive rendered images and movies (Figure 2.14).

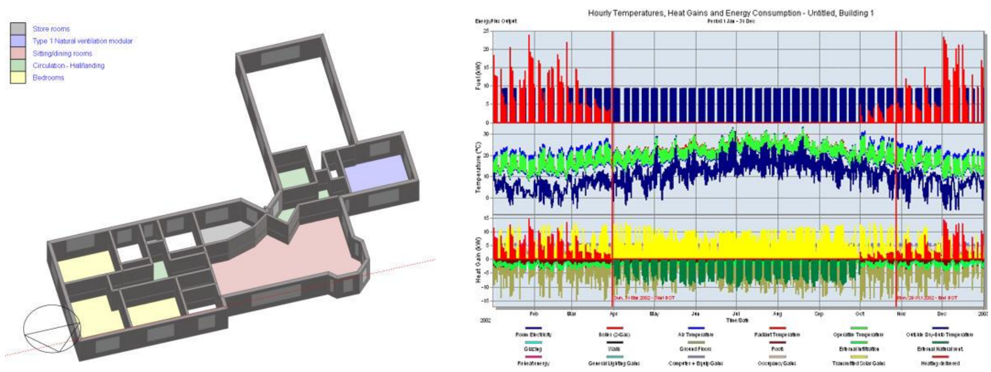


Figure 2.14 Design Builder interface and energy results sample

2.6.2.2. DIVA-for-Rhino

J Alstan Jakubiec, & Christoph Reinhart automated the process of coupling daylight and thermal simulations using DIVA, which stands for Design Iterate Validate Adapt (Jakubiec and Reinhart 2011). It is an environmental analysis plugin for the Rhinoceros 3D NURBS modeling program which integrates detailed daylighting analysis using Radiance / DAYSIM with thermal load simulations using EnergyPlus. These models are automatically linked, through the software interface, with detailed lighting and schedules generated by DIVA/DAYSIM.

DIVA allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes including radiation maps, photorealistic renderings, climate-based daylighting metrics, annual and individual time step glare analysis, LEED and CHPS daylighting compliance, electric lighting and single thermal zone energy and load calculations.

DIVA 3.0, last version which released on 4 September 2014, now supports the new LEED v4 daylighting calculations via IES-LM-83's Spatial Daylight Autonomy and Annual Solar Exposure metrics (Figure 2.15).

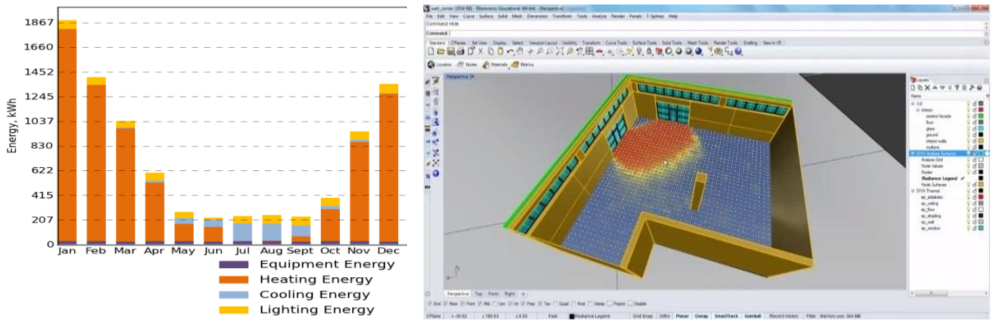


Figure 2.15 On the left, DIVA monthly energy consumption output and on the right, DIVA annual Daylight simulation result

Source: http://diva4rhino.com/user-guide/simulation-types/thermal-analysis

2.6.2.3. Open Studio

Open Studio is developed by the National Renewable Energy Laboratory, and it supports whole building energy modelling through integrating thermal and energy analysis engines by EnergyPlus and advanced daylight analysis using Radiance.

OpenStudio includes graphical interfaces such as the RunManager, ResultsViewer and Trimble SketchUp, which allows users to build geometry, space types and thermal and lighting zones in a 3D modeling construct which is very familiar to general architects. RunManager manages simulations and workflows and gives users access to the output files through a graphical interface. Results Viewer enables browsing, plotting, and comparing EnergyPlus output data (Figure 2.16).

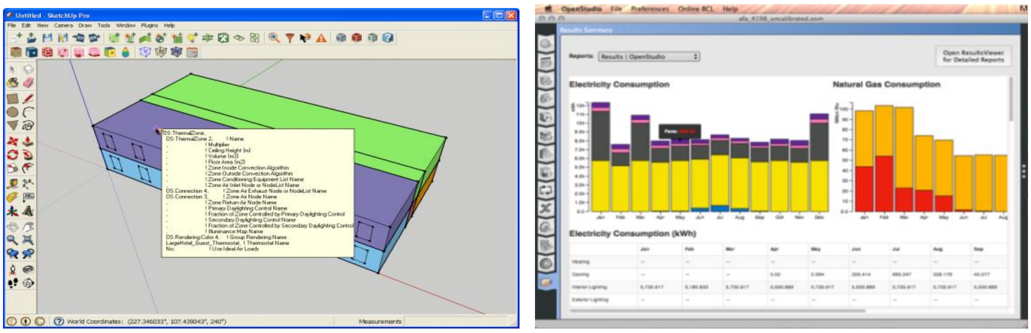


Figure 2.16 on the left; OpenStudio with SketchUp-Screenshot and on the right; a screenshot shows and example of the standard OpenStudio results

Besides of those tools, (Janak 1998) introduced a dynamic coupling between the widely used and validated tools ESP-r (Clarke 1997) and RADIANCE (Larson 1993) that links daylighting, electric lighting and thermal/airflow simulation. The simulation process is controlled by ESP-r and the lighting engine of RADIANCE is called when required, to perform a detailed raytracing-based lighting analysis at each simulation time-step. The whole process is computationally demanding and requires extensive knowledge of both simulation programs. (Bueno, Guidolin et al. 2014) also proposed a new Radiance-based building energy model called Fener to perform detailed analyses of complex fenestration systems. Fener has been evaluated against EnergyPlus and Radiance showing satisfactorily results.

2.7. Conclusion

Commercial office buildings in Egypt consumed 8.2% of primary energy and about 18% of the nation's electricity in 2011. Air conditioning and lighting account for 38% and 33%, respectively, of the total annual energy consumed in the commercial building sector. Consequently, the need for balancing thermal and daylight performance in office buildings so as to contribute in reducing the total energy consumption while enhance occupant comfort in an environmentally sustainable manner, has become a vital issue.

Despite the various advantages of the dependence on daylight for lighting office buildings on occupants' health and productivity as well as energy-saving, in some conditions daylight could also cause several problems that should be carefully addressed. The most critical problem caused by the risky solar heat gains and highly thermal loads of excessive daylight penetration into the space. Thus, the amount of energy needed to maintain indoor thermal comfort increases.

Hence, the appropriate office building design isn't achieved simply by opening up the building envelope and flooding the indoor environment with daylight but by the efficient using of the daylight sources. Thus, a balanced solution could be achieved, where acceptable daylighting performance would be attained with appropriate thermal performance at minimum possibly energy consumption.

Building rating systems and codes were briefly addressed focusing on LEED v4 daylighting performance metrics and requirements that will be used later for evaluating the case study in chapter 5. The current simulation tools was also explored showing the main daylighting and thermal engines that control almost all of the nowadays used simulation interface such as , Radiance and DAYSIM for daylight and EnergyPlus for thermal analysis.

Next chapter will focus more on the scope of this thesis, ecological facades and especially solar screen, addressing their roles in enhancing daylight and thermal performance for office buildings.

Chapter 3 Ecological Solar Screen for Office Buildings in Egypt

3.1. Introduction

Attributing to commercial office buildings' rising energy demand is the building facades. The building envelope plays a critical role in the conception of energy and climate optimized buildings. It is the building facade that functions as an interface between interior and exterior space. It provides thermal insulation and guides the entrance of daylight into the building. In this chapter, the ecological facade, in terms of overall transparency, the design of windows, and solar shading, will be the key element to enhance office buildings performance.

This chapter will be divided into three main parts; the first part wills overview the evolution in office buildings facades design in Egypt through the years. This aims to show how facades design affect the overall ecological performance and energy use. The second part introduced the ecological facade components and their effect on thermal, daylighting and energy performance for office buildings through investigating various related literature review. While the third part conduct a comprehensive analysis for literature review that integrated daylight and thermal performance using ecological facade approach in order to conclude with the main methodology needed for the aim of this thesis.

3.2. Office building facades in Egypt

Attributing to commercial office buildings' rising energy demand is the building facades. Building facade plays the role of moderating the outdoor environmental and climatic conditions guiding daylight into the building and providing thermal insulation through the building spaces. Thus it has a major impact on reducing/increasing the building's energy demand. In hot arid climates like Egypt, the facade's configuration is responsible for up to 45% of the cooling loads (Hamza, Dudek et al. 2001, Hamza 2008).

In Egypt, and specially Cairo, till the end of 18th century, concurrent with the introduction of Neo-classicism architectural style, the general trend was the straight lines of the Western architecture such as Bank Misr. After that, in the mid 1950's, the international style was introduced in Cairo. The European model of shading building was utilized and vertical and horizontal concrete louvers were a popular design solution (brise-soliel). Facades were designed with few straight and perpendicular lines reflecting mechanically the structural grid and a rhythmic monotonous order of simplistic notion of functionalism as shown in Ouzonian Building. Till the 1980s, office buildings in Cairo were designed for natural ventilation, with shaded openings. Although these buildings weren't rely on high electrical consumption for cooling system, there is no evidence of whether these buildings provided thermal comfort to its occupants or not.

In the 1980's with building materials and techniques being exported, fully glazed office buildings appeared, with their dependence on electric consuming HVAC systems such as Aboul Fetouh building in Mohandsien, Cairo. Over the following decade till nowadays the illusion with the fashionable architecture style is dominant trend while few trials are strived to follow these artistic trends while concerning the climatic solutions such as the example of Faisal Islamic Bank in Dokki, Cairo. However most of the current office buildings give the priority to the form over the performance (Hamza 2004). Figure 3.1 showed the façade timeline in Egypt from the 18^{th} century till the present time. The increasing reliance of office buildings in the Middle East, the Arabian Gulf countries and other arid regions in the world on air conditioning systems indicates the failure of the building facade to perform its function as a climatic moderator.

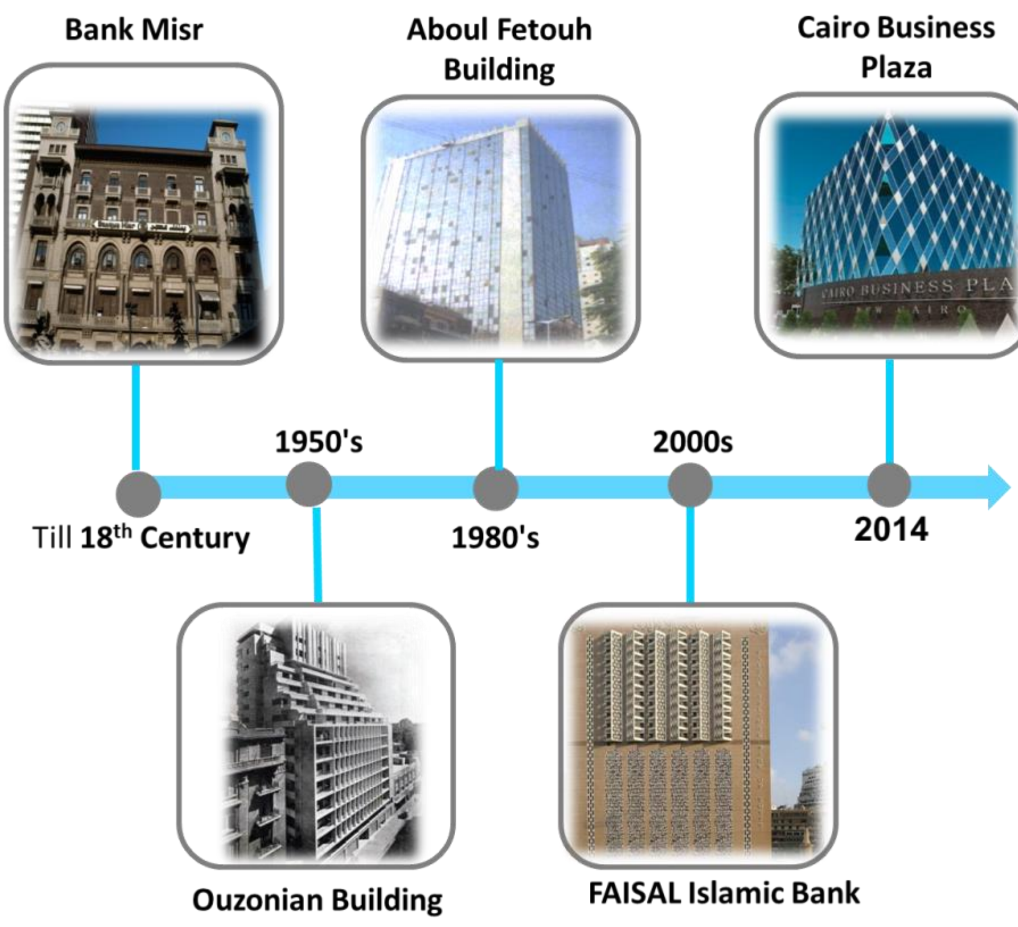


Figure 3.1 Office building façades timeline in Egypt from the 18th century till the present time.

Source: by the researcher

3.3. Ecological façade components

Focusing on the scope of this thesis, the ecological facade, in terms of overall transparency, the design of windows, and solar shading, will be the key element to balance daylight and thermal performance with the optimal possible energy saving. Moreover, this thesis focuses on the initial stages of design, where the façade is conceptually designed but has significant influences on the whole architectural design progress.

Generally, ecology is one branch of environmental science which is more concerned about the available natural resources scattered throughout an environment. Ecological impacts together with economic and social impacts of buildings on their surroundings are the main three principles of sustainable building design. Thus, ecological façade could be defined as the building facade that relates to climate conditions and surrounding environment resources while responding to conflicting needs for heating, cooling, daylight and ventilation. When designing ecological facades, the building function, occupants, internal loads, zoning within the building must be considered, as they shift the appropriate design strategies as shown in Figure 3.2. Since lighting, cooling and heating are office buildings' main sources energy-consumption as shown in the chapter 2, this thesis will focus on the ecological façade role in enhancing thermal and daylighting performance and thus reducing the total energy consumption (InnovateUs. 2013).

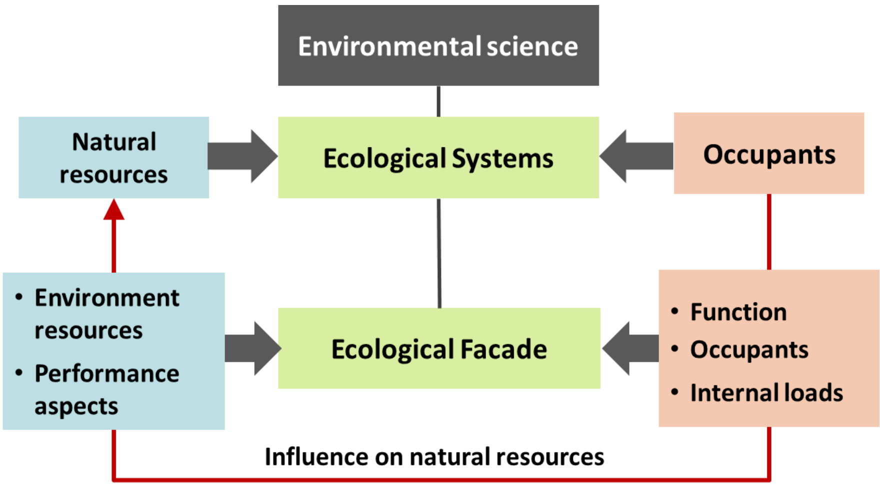


Figure 3.2 Ecological Facade as a subcategory of ecological systems and environmental science
Source: by the researcher

As shown in Figure 3.3, ecological facade could be divided into three main components; walls, windows and solar shading systems. The first two components are essential for any building façade. However, they could be combined with several ecological strategies to enhance their performance when ecological façade is considered. The third component, solar shading system, is an additional effective component to the facade when ecological aspects are taken in consideration; moreover it has many strategies that will be discussed later in this chapter.

The first component involves the exterior walls with its various material and properties, The second component consists of windows' various sizes and dimensions ,window-to wall ratio (WWR), window's or façade's layers and finally, glazing systems. The third component is divided into solar shading devices and solar screens with their different systems. Following, a comprehensive review of the recent literature in the area will be discussed.

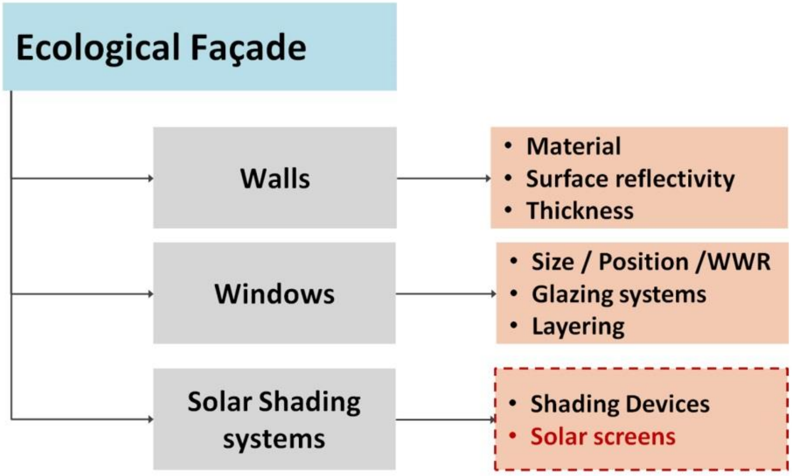


Figure 3.3 Ecological Facade components
Source: by the researcher

3.3.1. Window design

Façade window design through its various parameters; window size, glazing properties as well as number of façade layers installed and the relationship between them play critical roles in how the ecological façade system will affect energy consumption, thermal indoor environment and daylighting in office buildings.

Next section will study and investigate the available researches for all the various window parameters focusing on their daylight, thermal and energy use analysis.

3.3.1.1. Window size, position and Window-to-Wall Ratio (WWR)

Balancing between opaque and transparent elements could be considered as one of the essential methods that could affect daylight and thermal performance as well as the energy efficiency of the building. Large windows allow more daylight to the space but on the same time large glazed area could increase heat gain or loss. Thus, Window size, expressed as glass ratio of a façade or window-to-wall ratio (WWR), is one of the main windows' design parameters when ecological aspects are considered.

Studying WWR effects on the thermal aspects by means of heating and cooling loads as well as the total energy consumption with or without shading components was obtained by many researches. Studies by Susorova et al. (Susorova, Tabibzadeh et al. 2013) as well as Ghisi and Tinkar (Ghisi and Tinker 2005) who studied the effect of room's geometry, window dimensions and orientation on energy loads for office spaces in various climatic conditions.

Results showed that for hot climate, 14% total energy savings and 20.6% to 86.2% lighting energy saving can be achieved using the larger window area on the orientations whose energy consumption is lower due to the smaller solar thermal loads reaching the façade. Similarly, Motuziene and Juodis (Motuziene and Juodis 2010) investigated the effect of WWR, window orientation and glazing type on the total building energy consumption for an office building in the cool climate zone of Lithuania. The results showed that the most energy efficient WWR for south, east and west façade are 20% and 20–40% for the north facade. However, such WWR values might not be satisfied for day lighting performance. Thus, some other research activities focused only on potential savings due to a better use of daylighting. In a study by (Ibrahim and Zain-Ahmed (2007)) the effect of WWR with three glazing types on daylight performance of office buildings was conducted. The optimum WWR to achieve the maximum percentage of daylit floor area for 4.5m deep office area were 40%, 55%, and 65% for clear, tinted and reflective glass, respectively. While Mahdavinejad et al. (Mahdavinejad, Matoor et al. 2012) aimed to define the optimal WWR for office buildings in a semi-arid climate of Tehran, Iran to make benefits from daylight abundance concerning the climatic features without making the designers involved with the complicated calculations. It was found that the most appropriate options are %30, %35 and %40 WWR.

3.3.1.2. Glazing systems

Window glazing selection is one of the crucial issues when designing windows. Various window glazing types are shown in Figure 3.4. The following literature research reveals their ecological impact including daylighting, thermal and energy performance in the building.

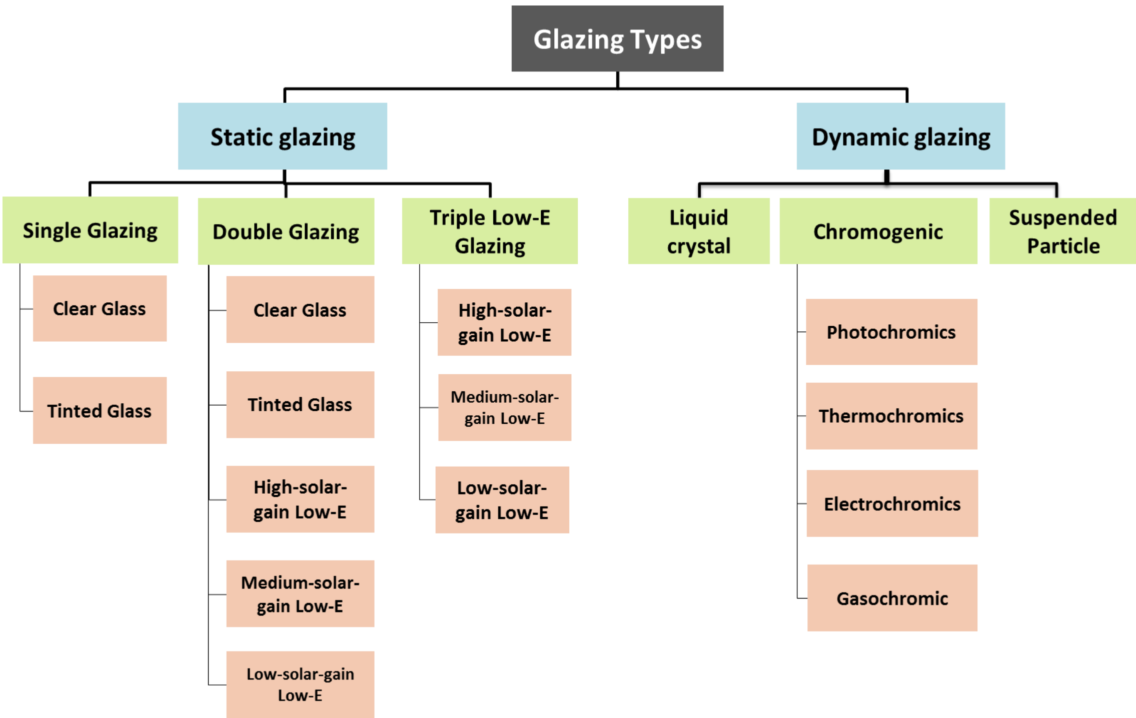


Figure 3.4 Glazing systems for ecological facade design

Arasteh (Arasteh 1994) addressed literature review about the developments in window technologies from 1973 to 1993 focusing on their role in reducing heat losses through windows. Recently, Hee, Alghoul (Hee, Alghoul et al. 2015) also conducted a comprehensive literature review on the influences of window glazing types but on energy and daylight performance of building. Moreover, the optimization techniques used by various researchers in choosing a glazing were highlighted.

a. Static glazing

Static glazing refer to glazing that possesses single fixed optical and thermal properties, such as U-value, visible transmittance (Tvis), or solar heat gain coefficient (SHGC). This section will review the impact of static window glazing on the thermal, daylighting and energy performance in buildings.

Sadrzadehrafiei et al. (Sadrzadehrafiei, Sopian et al. 2012) addressed the differences in cooling loads savings by comparing single clear glass to two triple glazing with different air gap sizes for the tropical climates of Malaysia. The results showed that triple-glazing achieved 6.3%, cooling electricity savings, compared to a single clear glass. Tahmasebi et al. (Tahmasebi, Banihashemi et al. 2011) agreed with this results showing that as the glazed layer applied increase, the cooling energy consumption decrease due to the reduced solar heat gain decreases. Many other studies addressed the effect of different types and proprieties of glazing on building thermal performance and energy consumptions such as the work findind in (Hassouneh, Alshboul et al. 2010, Jaber and Ajib 2011, Sadrzadehrafiei, Mat et al. 2011).

On the other hand, the effect of static glazing properties on daylighting performance was addressed by many researchers such as (Ibrahim and Zain-Ahmed 2007, Taylor, Duponchel et al. 2009, Husin and Harith 2012, Husin and Harith 2012). Generally, the daylight penetration heavily depends on the Visible Transmittance (VT or Tvis) of the static glazing. In (Ibrahim and Zain-Ahmed 2007) Ibrahim & Zain-Ahmed investigated the daylight availability in Malaysia's office spaces by varying type of window glazing; clear glass, tinted green glass, and reflective glass Tvis value of 88%, 75% and 30%, respectively. The results showed that clear glass allow more usable daylight than tinted green glass while reflective glass provide a very small chance of daylighting the space. This study had shown that as the Tvis value decreases, the opportunity for the space to utilize daylight decreases as well.

b. Dynamic glazing

Autonomous responsive dimming glazing was evaluated physically and by simulation tools in Tokyo. The case study was a window facing south in an office building. It was found that an appropriate configuration of Thermochromics glass, float glass and low-e coating etc., provides large energy saving and reduce thermal loads by 20% compared to using solar shaded window with low-e static glass. Despite being relatively simple system, large energy savings was obtained by shading the direct solar radiation and use the daylight efficiently (Inoue 2003, Arafa 2012).

3.3.1.3. Facade Layering

The main concept of the façade layers is how to apply various solutions according to the number of building skins incorporated in the design, the terms used are single skin facades and multiple skin facades.

a. Single skin façade

Single skin facades is the default case of windows that consist of single layer which is usually glazing with various types as discussed earlier in *section 3.3.1*.2 and could be integrated with exterior or interior shading as will be discussed later in this chapter.

b. Double Skin Facades (DSF)

The concept of Double Skin Facades (DSF) was first introduced in early 1900s, but little progress was made until the 1990s where it was used to create a more comfortable and ecologically office environments (Ahmed, Abel-Rahman et al. 2016). Recently it has received much attention as opposed to the more typically glazed curtain wall. DSF is an envelope construction which combines two glazing surfaces separated by a cavity (Oesterle, Lieb et al. 2001, Zhou and Chen 2010). The outer surface is usually single-glazed while the inner one is an insulating double-glazed unit. It is a common practice to assign shading elements within the cavity between the two DSF's layers (Wong and Istiadji 2004, Kim and Song 2007, Wong 2008, Kim and Kim 2010). The air cavity between the two layers can be naturally or mechanically ventilated with various width ranging from 0.20 m to larger than 2m (Chan, Chow et al. 2009).

The DSF system classifications are varied depending on construction type, the origin, destination and the air cavity arrangements, etc. One of the more general classifications of DSF was the one introduced by S. Kim and Song (Kim and Song 2007, Wong 2008). They classified it, according to the geometry and the type of air cavity and the way of air flow within it, into four types; Box Window facade, Shaft-box facade, Corridor facade and Multi-story façade as shown in Figure 3.5.

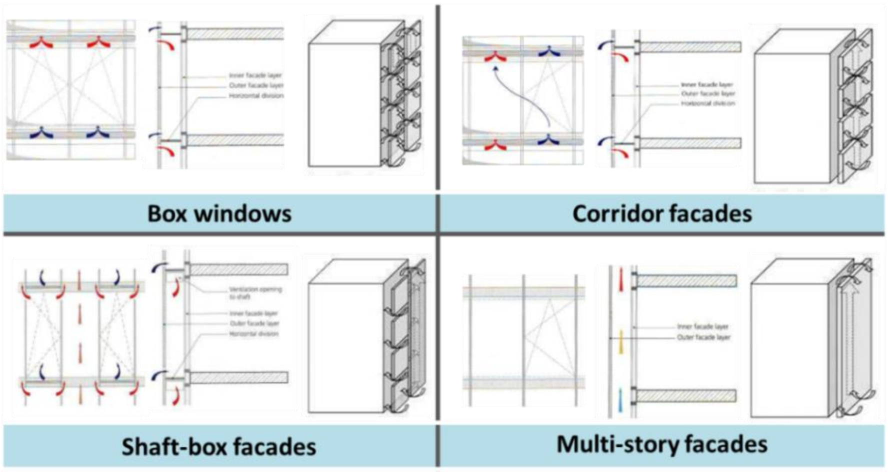


Figure 3.5 Double skin facade (DSF) classification
Source: by the researcher based on (Kim and Song 2007, Wong 2008)

Many studies recommend the application of DSF for reducing the heat gains and increasing the energy saving in building (Chou, Chua et al. 2009, Shameri, Alghoul et al. 2011). According to Arons and Glicksman (2001), energy savings attributed to DSF are achieved by minimizing solar loading at the perimeter of buildings and providing low solar factor and low U-Value that minimize cooling load of adjacent spaces. Furthermore, Gratia and De Herde (Gratia and De Herde 2004) explored DSF system for a south-face office building in a temperate climatic condition. Thermal analysis of different seasons of a year was conducted with and without DSF. It was found that significant energy saving is possible if natural ventilation could be exploited through the use of double- skin façade.

On the other hand, few studies had been interested on investigating daylight performance of DSF. Viljoen et al. (Viljoen, Dubiel et al. 1997) Viljoen, Dubiel et al. (1997) investigated daylighting performance of DSF for an office building in Belgium, considering the position of a maintenance walkway within the air cavity or a similar horizontal projection. Different size, color and perforation of the walkway have been investigated. The results show that using the walkway options increased the daylight area up to 23%. However, none of the options were able to produce a daylight area for greater than 53% of the total floor area. In addition, Hien et al. (Hien, Liping et al. 2005) and E. Gratia and A. De Herde (Gratia and De Herde 2007) showed that using DSF can reduce the lighting energy consumption by making full use of day lighting. On the other hand, Høseggen et al. claimed that the additional glass layer reduces the indoor daylight illumination levels (Høseggen, Wachenfeldt et al. 2008).

In conclusion, DSF has been proven to be significant useful in addressing ecological aspects in office buildings. But, it has some drawbacks when compared to normal single facades such as; the high cost, lack of fire safety information, reduction of available space for offices, and less room-to-room sound insulation (Selkowitz 2001, Butera 2005, Shameri, Alghoul et al. 2013).

3.3.2. Solar Shading Devices

Generally, solar shading systems can be considered as an essential integral part of ecological facade systems. They can be used to improve building thermal and lighting performances (Bellia, Marino et al. 2014). McCluney and Chandra (McCluney and Chandra 1984) examined the effect of various shading systems including window tinting, screens, awnings, and overhangs on reducing heat gain in various cities in Florida. All these shading systems proved their effectiveness in saving energy.

Shading devices can be multi-purpose by; blocking direct sunlight while contributing to indoor illumination from daylight, reducing solar gains and glare, and , improving thermal comfort. However, this blocks the view out and generally may affect the aesthetics of the building negatively (Freewan 2014).

There are various types of solar shading devices depending mainly on their position to the façade such as; horizontal overhang, louvers or light shelf as well as vertical fins or louvers and finally the egg crate that combine horizontal and vertical shading devices (Figure 3.6).

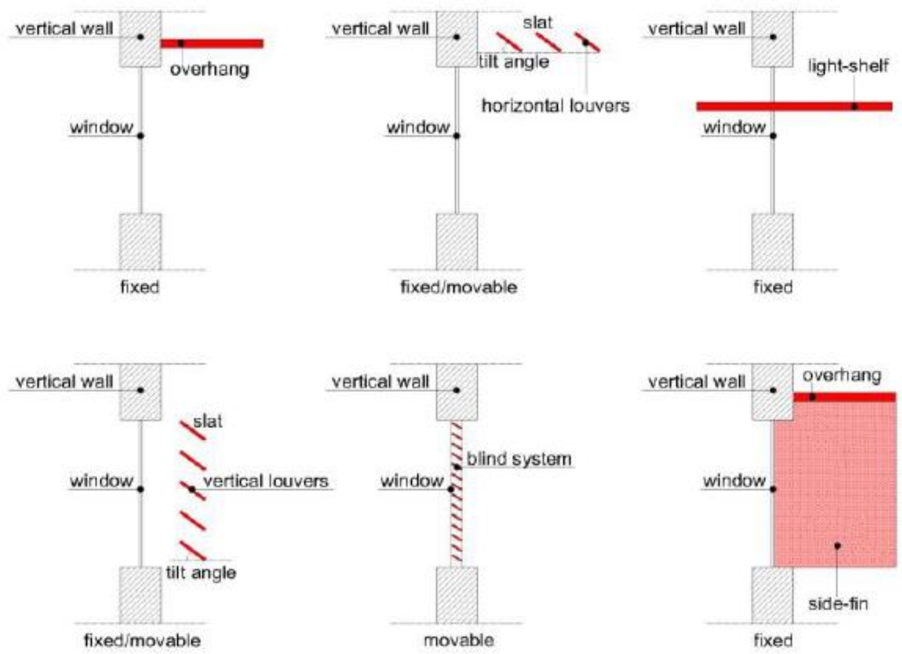


Figure 3.6 Main shading devices types

Source: (Bellia, Marino et al. 2014)

Shading devices can be **exterior, interior or intermediate,** in case of DSF, and for each case shading devices could be **fixed or movable**. Internal shading systems are quite effective in controlling glare but they do not block solar heat gain. Many studies such as (Kim and Kim 2010, Kim, Lim et al. 2012, Bellia, Marino et al. 2014) proved that external shading devices are much more efficient than the internal ones, providing better performance daylight and thermal aspects as they block radiation before it reaches the window or enter the space.

3.3.2.1. Fixed External shading devices

Shading elements enrich facades' architectural vocabulary, create variable shading effects in the space that vary throughout the day and seasons, reduce energy use and improve occupant comfort as discussed by (Carmody, Selkowitz et al. 2004, Carmody and Haglund 2006, Zelenay 2011, Baker and Steemers 2014) and many others.

In a study by Palmero-Marrero and Oliveira, the impact of horizontal overhangs and vertical louver on building thermal performance was studied for different cities. The cooling and heating energy consumption were evaluated with respect to louver tilt angle and window area. Results showed that louvers decreased energy consumption significantly and achieved thermal comfort especially in cities with high intensity solar radiation such as Cairo, Madrid and Lisbon. For east and west facades, 20° tilt angle louvers achieved annual energy saving by 60% for Cairo, 50% for Lisbon and 9% for Madrid (Palmero-Marrero and Oliveira 2010). Similar results were achieved in a study by Datta (Datta 2001) but in this study the horizontal shading devices effect on cooling load through different seasons was considered for four cities in Italy. For example, for Milan it was found that 70% of gain is cut off in summer, while only 40% is cut off in winter by using optimum shading.

On the other side, many other studies focused on the effect of fixed shading devices on daylight distribution. M.C. Dubois studied the impact of seven types of shading devices on daylight quality. It was found that some shading devices could provide the offices with acceptable illuminance level suitable for traditional office work such as; white awning, overhang and horizontal venetian blind. While other devices could be more suitable for computer-based work such as; 45° venetian blind, white screen and blue awning (Dubois 2003).

Another study by Claros and Soler reported the effects of overhang and light shelves on daylight performance for a south office façade in Madrid. The results showed that light shelves achieved better daylight performance than the overhang as light shelves brought more light to the back part of the model (Claros and Soler 2001). Conversely, N.H Wong and A.D. Istiadji reported that the shading devices did not always enhance the daylight performance as it could increase the glare effects. A light shelf, overhangs with different depths and combinations of overhang and two side fins were all examined and the results showed that illuminances were higher than the recommended ones for all of them except with the combination of overhang and side fins (Wong and Istiadji 2004).

3.3.2.2. Movable shading devices

As mentioned before shading devices could be fixed and movable. In light of the solar dynamic characteristic, movable shading devices have been appeared and are used to achieve optimal daylight and thermal performance. Movable shading devices may include any type of the fixed ones but with the advantages of being manually operated by users or automatically by intelligent control systems.

E. S. Lee et al. estimated thermal and daylighting performance of an automated venetian blind system for an exciting office in Oakland, California (Lee, Dibartolomeo et al. 1998). Significant energy savings and peak demand reductions were attained with the automated venetian blind compared to a static one with the same dimmable electric lighting system. Another study by Tzempelikos and Athienitis (Tzempelikos and Athienitis 2007) aimed to evaluate the impact of moveable shading device control on thermal and daylight performance of office spaces in Montreal, Canada considering an exterior roller shade. Two different types of shading control were considered: passive control (roller shade is closed during working hours) and automatic on-off control (roller shade is open when beam solar radiation incident on the window was minor than 20 W/m^2). The passive control type determined poor daylight availability, whereas the on-off control type increased annual daylight availability by 20%. The on-off electric lighting control determined a 16% increase in annual heating demand, 16% reduction in cooling demand, 76% decrease in lighting demand and 22% reduction in total energy.

Despite the fact that automated and moveable shading controls provide a way to control facade systems., they provide their own set of challenges, added operational complexity and cost, and the need for maintaining additional controls and components (Lee, Selkowitz et al. 2002, Lee and Selkowitz 2006, Zelenay 2011, Zelenay, Perepelitza et al. 2011). In contrast, fixed exterior shading, may offer less opportunity for selective control of daylighting and solar heat gain, but on the other hand the risk of faulty system operation, experienced with automated systems that are improperly installed or maintained, is eliminated.

3.3.3. Solar Screens

Solar screens have traditionally evolved to control solar penetration in the buildings of the middle-east such as the Mashrabeya, Indian Rawshan and Japanese Goshi. Other solar control systems were also found in Spain, South-East Asia and South America. There is no difference between these kinds of screens in terms of function (Spencer 1990, Arafa 2012). These panels were typically fixed externally in front of windows and other building openings. By the time, new geometric forms and pattern configurations have been used as solar screens in line to contemporary architecture. Figure 3.7 illustrate some of those screens and their type while, Figure 3. 8 showed conventional solar screens and Figure 3.9 showed non-conventional examples. However, some of these non-conventional contemporary examples only deigned forms neglecting its ecological role.

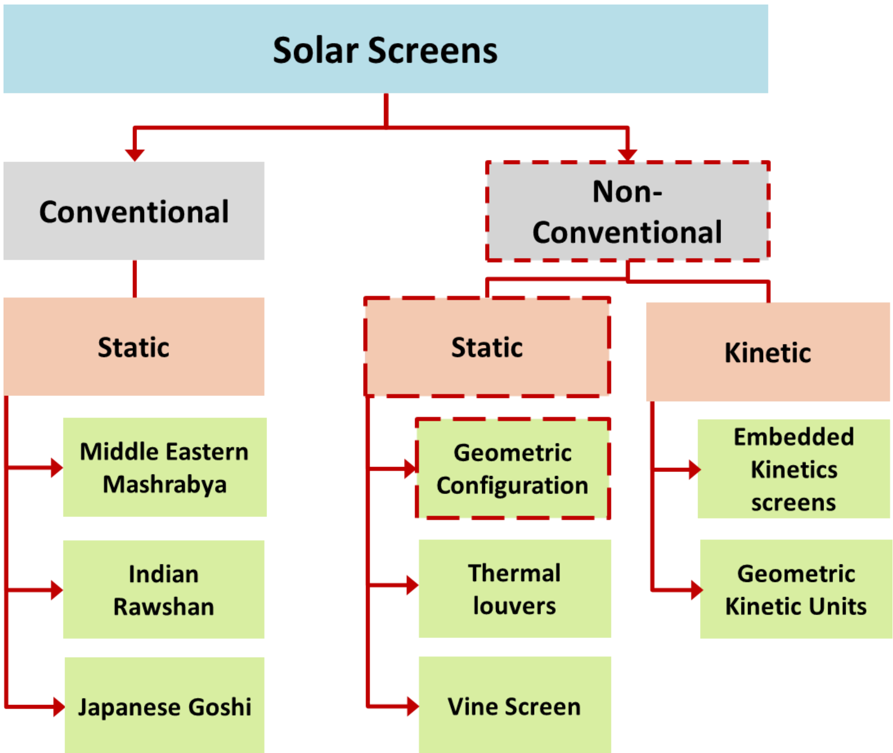


Figure 3.7 Solar screens classifications

Source: by the researcher

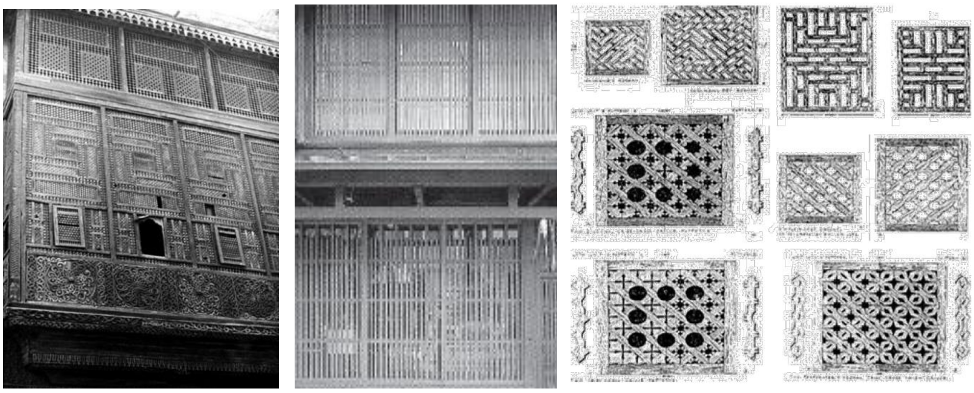


Figure 3. 8 Conventional solar screens

Figure 3.9 Non-Conventional solar screens

The various ecological performance aspects of solar screens are affected by many parameters. These include screen perforation, depth, reflectivity and color, aspect ratio of openings, shape, tilt angle and rotation. They showed their effectiveness in improving both daylight and thermal performances in hot arid climates which are endowed with abundance of clear skies. Next, number of publications addressed the parameters of solar screens and their influence on daylighting and thermal performance will be discussed.

The effect of solar screen configurations on thermal performance and energy loads was studied in small number of recent publications. This included The influence of changing the perforation percentage of external perforated solar screens of desert buildings by (Sherif, Faggal et al. (2010)). It was found that thermal loads dropped rapidly when screens with high perforation ratios were used. Screens with an 85% perforation rate provided significant energy savings. Reduction of perforation below this rate reduced thermal loads insignificantly. Reduction of the cooling energy was attributed to the substantial decrease in the transmitted solar energy and window heat gain energy.

Developing modern types of the perforated wooden solar screens systems can enhance building thermal performance and lead to significant energy savings. (Sherif, El Zafarany et al. 2011) studied the effect of using these screens on Window-to-Wall Ratios. It was found that optimum WWR for un-screened windows in the desert environment of Kharga Oasis in Egypt was 4% for orientations of South, west, and east, while in north the optimum was a range between 4%-8%. The energy consumption of the 4% unshaded window was achieved with a medium sized window of 22%WWR when screens were used.

Another similar paper by the same authors in (Sherif, El-Zafarany et al. 2012) addressed the influence of changing the perforation percentage and depth of these screens on the annual energy loads to define the optimum depth/perforation configurations for different window orientations. The results proved that in West and South orientations, deep perforated solar screens could achieve energy savings up to 30% of the total energy consumption. The optimum percentages of depths and perforation were 80–90% perforation rate and 1:1 depth/opening width ratio. These lighter and deeper solar screen configurations were found to be more efficient in energy consumption in comparison with the traditional ones.

On the other hand many studies focused on the effect of sola screen in enhancing the indoor daylight quality. The daylighting aspects of solar screens were analyzed in several publications. The effect of size of the solar screen perforation openings on reflected sunlight through screens was studied by E. Aljofi (Aljofi 2005). Daylighting was found to be lower in rounded screens having larger cell diameters. This was attributed to the ratio of openings to solid parts of the screen panels. Screen reflectance was also investigated and it was found that light colored screens increase the average daylighting efficacy by 17% compared to the dark colored screens. Sherif, Sabry et al. (2011) also studied solar screen perforation openings aspect ratio, where the illuminance levels in the clear sky of El Sadat City, Egypt was demonstrated. It was found that for all orientations, 1:6 and 1:5 proportions can provide a satisfactory balance between energy efficiency and daylighting. Another paper by Sherif, Sabry et al. (2012) examined the minimum perforation rate of solar screens that provides adequate daylighting performance in different orientations in the desert.

The effectiveness of solar screens axial rotation on daylighting performance was studied by Sabry, Sherif et al. (2011). It was found that for all orientations, as the rotation angle increased, the daylighting increased linearly. Screens rotation angle varied according to the change of orientation, season and time especially in the south and north orientations, where rotation angle from 0° to 30° influence was found to be significant in summer. However, for East orientation, the rotation angle influence was found to be significant in winter. Similar study by Sherif, Sabry et al. (2012) also investigated the impact of changing solar screen axial rotation but with screen opening aspect ratio on daylighting performance. The study was conducted under the desert sunny clear-sky of Jeddah, Saudi Arabia and for the main four orientations. Solar screens with openings having horizontal aspect ratios (H) were found to be the most effective, while those with vertical aspect ratios (V) were achieved the lowest performance. For the South orientation, there the 3:1 (H: V) screen aspect ratio was recommended as it reduced the annual transmitted solar radiation by 60% while achieving acceptable daylighting performance.

3.4. Integrated daylight and thermal analysis for office building

As shown in the mentioned literature review, ecological façade with its various strategies have an effective role in the daylighting and thermal performance as well as energy use in buildings. Therefore conscious designing that balance daylight and thermal performance by appropriate integration methodologies and tools starting form early design stages is becoming a vital demand. Thus, this section will address a comprehensive analysis for the recent studies that integrate daylight, thermal and energy performance analysis using ecological façade different components.

Even though most of the analyses carried until now focused on either thermal or lighting aspect, a global energy approach was already adopted in some of the first investigations by (Johnson, Arasteh et al. 1985). The most important results were the relevant role of the WWR: optimum WWR resulted in significant energy saving, more than 50%, for heating, cooling and lighting. Moreover, (Goia, Haase et al. 2013) recently presented a methodology and the results of the search for the optimal WWR in a façade module for low energy office buildings. The study was carried out in a temperate oceanic climate, on the four main orientations, on three versions of the office building and with different HVAC. The results showed that, regardless of the orientations, the optimal balanced configuration is achieved when the WWR is between 35% and 45%.

Similarly, a study by (Sweitzer, Arasteh et al. 1987) were conducted but in this case by addressing glazing types with different WWR. The energy use effects of low-E glazing in comparison to the conventional glazing at various window-to-wall ratios were studied considering the cooling, lighting and energy conservation in office buildings. Savings in lighting, cooling and energy were obtained in both hot and cold climates using the insulated glazing with low-E coatings. Where (Clarke, Janak et al. 1998) described in detail the integrated approach of advanced glazing taken for office buildings within IMAGE (IMplementation of Advanced Glazing) big projects in Europe combining ESP-r with RADIANCE engine for thermal and daylighting respectively. The results showed that advanced glazing could significantly reduce total energy consumption but insignificantly decrease the daylight availability however; it will not change its characteristic distribution. In the same year (Sullivan, Beltran et al. 1998) investigated the thermal load and daylight performance of anisotropic angular selective glazing. They also used RADIANCE lighting engine but in this case with DOE-2.1E energy simulation tool for an office building module in Blythe, California. They defined a theoretical solar-optical distribution of the glazing, which resulted in a reduction in annual energy use and peak electric demand with more uniform illuminance levels when compared to a conventional case.

On the other hand, there are few studies that performed a full scale analysis of the impact of fixed shading systems, including thermal, energy and daylight. The research by (Alzoubi and Al-Zoubi (2010)) examined the effect of vertical and horizontal shading devices on the quality of daylight and the associated energy saving for southern exposure facades. It concluded that there is an optimal position for shading devices that keeps the internal illuminance level within an acceptable range while maintaining the amount of solar heat gain to the minimum. Where in a study by (Mazzichi and Manzan 2013), an integrated thermal and daylighting simulation was performed also for a south-facing window but with 5 different shading devices in an office building. The obtained results showed good balance between daylighting distribution and energy consumption for the fixed venetian blinds with angle inclination control as well as for the overhang and deployable devices. M. David et al. (David, Donn et al. 2011) proposed simple indexes to compare the thermal and daylight efficacy of different types of overhangs for a typical office building. These indexes included; solar shading coefficient, cooling energy demand Daylight Autonomy and UDI. The best type was the overhang with an infinite width and a relative length equal to 1 (the length of the solar shading is equal to the height of the window).

Also in (Mazzichi and Manzan 2013) an integrated thermal and daylighting simulation was performed but for a south-facing window with 5 different shading devices in an office building. The total energy consumption and daylight distribution using UDI metric were evaluated by coupling two simulation tools; DAYSIM for daylight analysis and ESP-r for energy analysis. The cases for fixed venetian blinds with angle inclination control as well as the overhang and deployable devices showed good daylighting distribution with lower energy consumption. Similar study by (Yun, Yoon et al. 2014) also evaluated the shading control strategies for visual comfort and building energy savings of a cell type office with venetian blinds in Seoul, Korea. In this research, DIVA-for-Rhino program was used to evaluate the annual glare (DGP) and EnergyPlus program was used to evaluate the annual energy consumption. They found that a blind slat angle of 0◦ is better in winter and a blind slat angle of 30◦ is suitable in summer for energy efficient and anti-glare control strategy. They also reported that if the shading is controlled to minimize the cooling load, it can affect an increase of the lighting energy. Therefore, the control strategy can differ by priority, or by season. While Freewan examined the effect of using shading devices on air temperature, visual environment and users' interaction in offices facing south-west facade at Jordan University of Science and Technology (JUST). Three fixed shading devices (vertical fins, diagonal fins and egg crate) were installed in three identical offices. The results showed that offices with diagonal fins and egg crate shading devices performed better than the office with vertical fins and the base case (Freewan 2014).

A more comprehensive analysis was conducted by (Pino, Bustamante et al. 2012) who simulated thermal and daylighting performance of an office building in Santiago, Chile. Various types of solar shading systems with different glazing types and WWRs and for different orientations were analyzed using EDSL TAS thermal simulation tool and DAYSIM lighting simulation tool. Energy demand for heating/cooling was calculated, and daylight quality was assessed by Daylight availably and UDI. The resulted showed that 20% WWR could achieve the best performance with overhang for North orientation and blinds for East/West.

A more related studies to the aim of this research defining solar screen designs to enhance daylighting performance, while maintain the energy consumption at a minimum for desert environments was studied in a paper by Sabry, Sherif et al. (2014). The study focused on the effect of solar screen axial rotation and the aspect ratio of its openings. The results showed that a non-rotated solar screen that has wide horizontal openings (aspect ratio of 18:1) was successful in the north and south orientations. In contrast, the screen that was rotated along its vertical axis while having small size openings (aspect ratio of 1:1) proved to be successful in the east/west orientations. They provided 66–97% “daylit” areas in the tested spaces. In addition, use of solar screens reduced energy consumption by up to 25% in comparison with a non-screened window. This study confirmed the results of previous publications on the usefulness of using solar screens in desert environments.

Solar screen colours and their effect on daylighting and buildings thermal performance should also be taken into consideration. This issue was investigated in a study by El-Zafarany, Sherif et al. (2013) for hot arid climates. A range of solar screen colours ranging from white screens having a visible reflectance of one, to black screens with a visible reflectance of zero were examined for a case study in the Kharga Oasis, in the Egyptian desert. It was found that the lighter the colored screens the less the lighting and heating energy but with significantly increasing in the cooling energy, and thus overall energy consumption. Results scientifically confirm the effectiveness of the traditionally colors of the “Mashrabeya”, which were typically dark. Conclusions prove that energy savings up to 14% could be achieved using appropriate screens visible reflectance.

R. Arafa (Arafa 2012) conducted her master thesis on the investigation of the impact of changing various screen configurations on the energy loads. It was concluded with a proposal of non-conventional solar screen forms that defined the most efficient configuration range for various window sizes and orientations.

3.5. Methodology for the integrated approach

From the above literature review it could be deduced that the key issue for integrating daylighting and thermal performance is to determine a set of linking parameters that affect both the thermal and lighting performance of the space. The dynamic interaction between lighting and thermal simulation can then be described by investigating the relationship between these linking parameters and the simultaneous impact on the two domains during the actual simulation process.

The linking parameters can be divided into direct and secondary links. Direct links have an immediate impact on both daylighting and thermal performance; e.g. amount of transmitted daylight and solar radiation, such as the different ecological façade components that had been addressed and specifically;

- Glazing type and properties (Thickness / U-value / SHGC)
- Window position and size (window-to-wall ratio WWR)
- Shading systems

Secondary links transfer the dynamic effect of direct links from one domain to the other domain. A secondary dynamic link is the electric lighting control as, for a given set of direct links; it operates by reading data from the daylighting module and dynamically transfers the effect to the thermal module in the form of resulting internal gains as shown in Figure 3.10.

From the literature review it could also be reported that for the integration between daylight and thermal performance in building designs, daylight is often evaluated using performance metrics while the approach followed for thermal performance evaluation was to estimate solar gains and internal gains or heating loads and comparing them to a selected base case.

On the other hand, Some researches indicated for energy consumption as a measure for lighting loads with cooling loads only while other researches such as the study by (David, Donn et al. 2011) indicated to daylight visual discomfort indices as a prediction for cooling loads. However; the two methodologies ignored some effective performance analysis and thus presented inaccurate results comparing to the real states. This were shown in the above literature review that integrated both thermal and daylight simulation to measure thermal loads (cooling and heating), daylight performance based on daylight metrics as well as the total energy consumption so as to present more accurate results and closer to reality.

Thus a more dynamic and comprehensive methodology depending on an integrated approach between thermal and daylight simulation such that of (Tagliabue, Buzzetti et al. 2012) which would provide designer with precise performance-based measures that help them taking more efficient decisions from early design stages. This integrated methodology would consist of the followings;

- Calculation of daylighting dynamic performance metrics;
- Identification of electrical consumption integrating daylighting;
- Calculation of heating and cooling demands;
- Estimation of total energy consumption considering a possible thermal system for the office space.

Moreover, the above literature reviews showed that the approach followed for most of the studies was to use separate simulation tools for daylight and thermal analysis and estimate internal gains from lights, contribute to cooling load. However, with significant architectural developments and the re-identified of the potentials of coupling daylighting and thermal analysis the need for developing integrated thermal and daylighting simulation programs in one model have widely arisen Selkowitz (Sweitzer, Arasteh et al. 1987). This approach aims to allow designers to test the relative effect of different daylighting the thermal performance from early design phase, where there are multiple design variants, without manually exporting to multiple software. It is supposed that this integrated methodology would result in a more accurate where the thermal results depends on daylight simulation results so as to define the electric lighting control based on the indoor daylight performance.

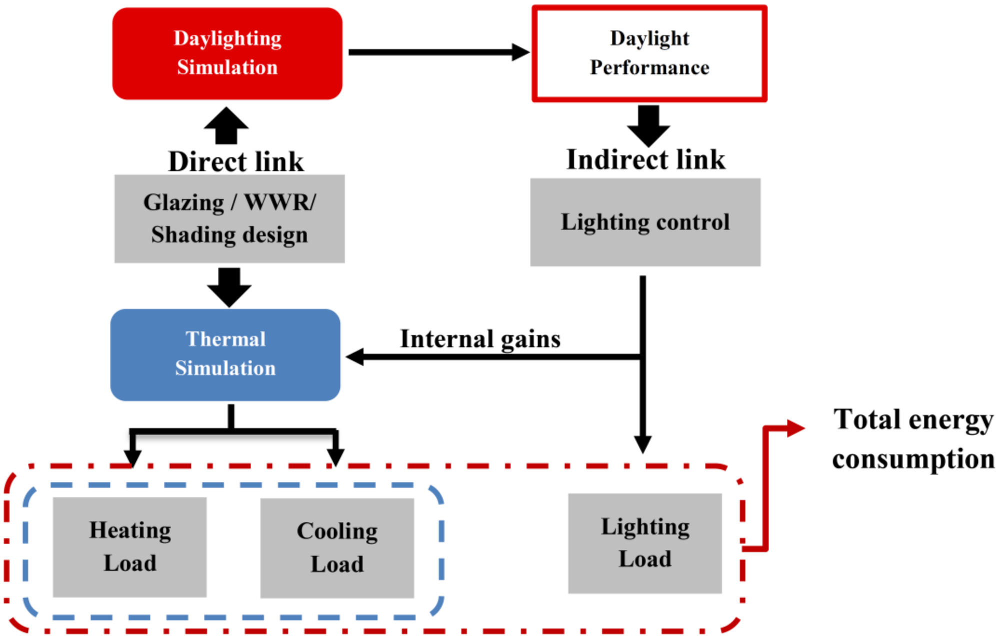


Figure 3.10 Integrated daylight and thermal simulation methodology

3.6. Limitations with current methodology and tools

Simulation tools had proven to be powerful tools for studying the environmental performance of the building with the ability to engage daylight with thermal analysis through the design process. However, current simulations are based on the scenario-by-scenario approach where limited alternatives are modeled and evaluated to make design decisions. This is mainly due to effort and time consuming limitations of modeling large number of alternatives. Thus, this method is inaccurate because the designers are only able to choose number of scenarios to simulate and evaluate.

Next chapter therefore, will introduce new methods that could determine different design alternatives and evaluate them efficiently.

3.7. Conclusion

The building envelope plays a critical role in the conception of energy and climate optimized buildings. In hot arid climates like Egypt, the facade's configuration is responsible for up to 45% of the cooling loads.

In Egypt, from the 1980's, fully glazed office buildings appeared widely, with their dependence on electric consuming HVAC systems. Over the following decade till nowadays the illusion with the fashionable architecture style is the dominant trend giving the priority to the form over the performance.

Ecological facade could be divided into three main components; walls, windows and solar shading systems. The main strategies of each component were discussed showing their role in enhancing daylight and thermal performances in building by analyzing various related studies. Thus, in this thesis, the ecological façade, and specially the ecological solar screens, will be the key element to balance daylight and thermal performance with the optimal possible energy saving.

A comprehensive analysis was conducted for recent studies that integrated daylight and thermal performance for office buildings using ecological facades components. The results showed the linking parameters, tools, evaluation methods and criteria for the integration approach. Thus, the overall integration methodology of daylight and thermal performance for office building, that will be used for the empirical study later in chapter 5, were conducted showing their limitations in evaluating wide range of alternatives. This was mainly due to their scenario-by-scenario based approach where the designers can only choose from limited number of alternatives.

Next chapter therefore, will introduce new methods that could determine different design alternatives and evaluate them efficiently.

Chapter 4 PARAMETRIC OPTIMIZATION PROCESS FOR ECO-LOGICAL FAÇADE DESIGN

4.1. Introduction

In the previous chapters the current computational systems including performance and energy simulations tools have been discussed showing their various potentials which make them a major keystone in architectural design during the last decades. However, some limitations, due to their scienario-by-scienario based approach were also highlighted and need to be concerned.

In this regard, this chapter emphasizes the potential enhancement of the new digital practice to the design process in addressing the previous mentioned limitations. The main aim of this chapter is to identify the parametric design and Genetic Algoritms optimization methodologies as generative-analytical design methods for optimizing architectural designs that correspond to specific performance goals showing the potential and limitations of each approach.

This chapter will be divided into four main parts; first part will discuss in brief digital fabrication and generative systems application in architecture. Second part will focus in parametric design systems, as a sub-category of generative systems, showing their main principles, potentials for performative design exploration, tools as well as their limitations and commonly misconceptions. Third part addressed the optimization algorithms approaches focusing in Genetic Algorithms (GAs) optimization. In this part GAs' process, tools, its potentials to be combined with parametric modellings through the design process as well as its limitations and drawbacks will be addressed. Fourth part will conduct a comprehensive analysis for recent academic studies that concerned with parametric design and/or optimization algorithms applications for ecological designs. Consequently, the parametric design and Genetic optimization methodologies as generative-analytical design methods for optimizing ecological facades will be defined.

4.2. Digital fabrication Design

Architects used to be the chief builder or the main craftsman that controls the whole design process starting from early design phases till the final end-product construction. By the time specialization and the use of mass-produced building components spread widely and dominate all industrial fields, including building industry and architectural designs. However, in spite of their undeniable benefits to the building industry in terms of lowered costs, higher predictability, and greater accuracy, one main shortcoming is that architects have become more and more separated from many key aspects of a building's production, most notably in the area of component or assembly design and fabrication.

On the other hand, the integration of digital design and fabrication in the architectural design process affords a hypothetically seamless connection between designs and making that narrows the gap between architects conceptual designs and final products construction. In another saying, by integrating digital technologies in the design process, architects can return back to be the “chief builder” narrowing the gap between architectural design, associative engineering aspects and buildings construction by reintegrate them into digitally collaborative cycle process.

4.2.1. Digital fabrication techniques and tools

Digital fabrication could be defined simply as a manufacturing process where the used machine is controlled by digital data. Nowadays many available digital fabrication techniques and cutting technologies are attainable to use as shown in Figure 4.1. Computer numerically controlled (CNC) cutting technique, or 2D fabrication, is one of the most commonly used fabrication technique. Additional common used techniques are; subtractive fabrication technique using CNC milling machines, and Additive fabrication technique, a process converse of milling, using 3D printing machines. Digital technology can also facilitate the construction and the assembly of the fabricated building components on site using digital methods such as robotic arms, laser positioning and electronic surveying. These technologies have been widely used around the world to accurately control the location of building components.

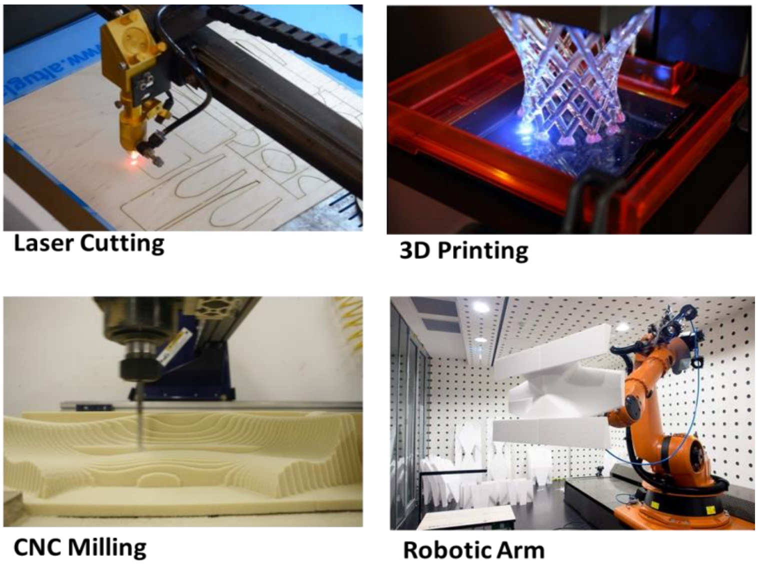


Figure 4.1 Digital fabrication techniques

4.2.2. Digital fabrication and Mass Customization

Using digital fabrication facilitates the mass production of any customized building component with the same efficient as standard components and thus, introduces the concept of ‘mass customization’ into building design and production. The digital fabrication ability to mass produce special customized building components with the same efficiency as standards components introduced the concept of mass customization into building design and production. The digital fabrication ability to mass produce special customized building components with the same efficiency as standards components introduced the concept of mass customization into building design and production. Kolarevic stated that, “it is just as easy and cost-effective for a CNC milling machine to produce 1000 unique objects as to produce 1000 identical ones.” (Kolarevic 2001). Mass customization using digital techniques can be seen as mass production of individually customized design components, thus offering a remarkable increase in the creation and customization of unique designs without any increasing in costs.

Digital fabrication has encouraged a design revolution, causing a leap in architectural invention and innovation as it makes it possible for the complexity of the building geometries to be customized for construction. As Iwamoto stated in his book Digital Fabrications: Architectural and Material Techniques, “Digital fabrications sparked the imagination of a new generation of designers.”

4.2.3. Digital fabrication and performative design

Digital fabrication are increasingly being used for both design prototyping during the design process starting from early design phases, as they are useful for testing constructability, material properties, geometric properties and aesthetic qualities, as well as for full-scale constructions. As shown in the previous chapter, building performance simulations help in investigating design alternatives and the overall building performance. Thus, by combining digital generative design approaches and building performance simulations tools with the rapid prototyping techniques of digital fabrication in a design feedback loop process, architects have real-time capabilities to generate various design alternatives, improve targeted performance and end with scaled artifacts to study, review and evaluate the design solutions as illustrated in Figure 4.2. However the details of the digital fabrication approach are out of the scope of this thesis meanwhile, it will focus on the generative design systems and techniques that would be discussed in next sections.

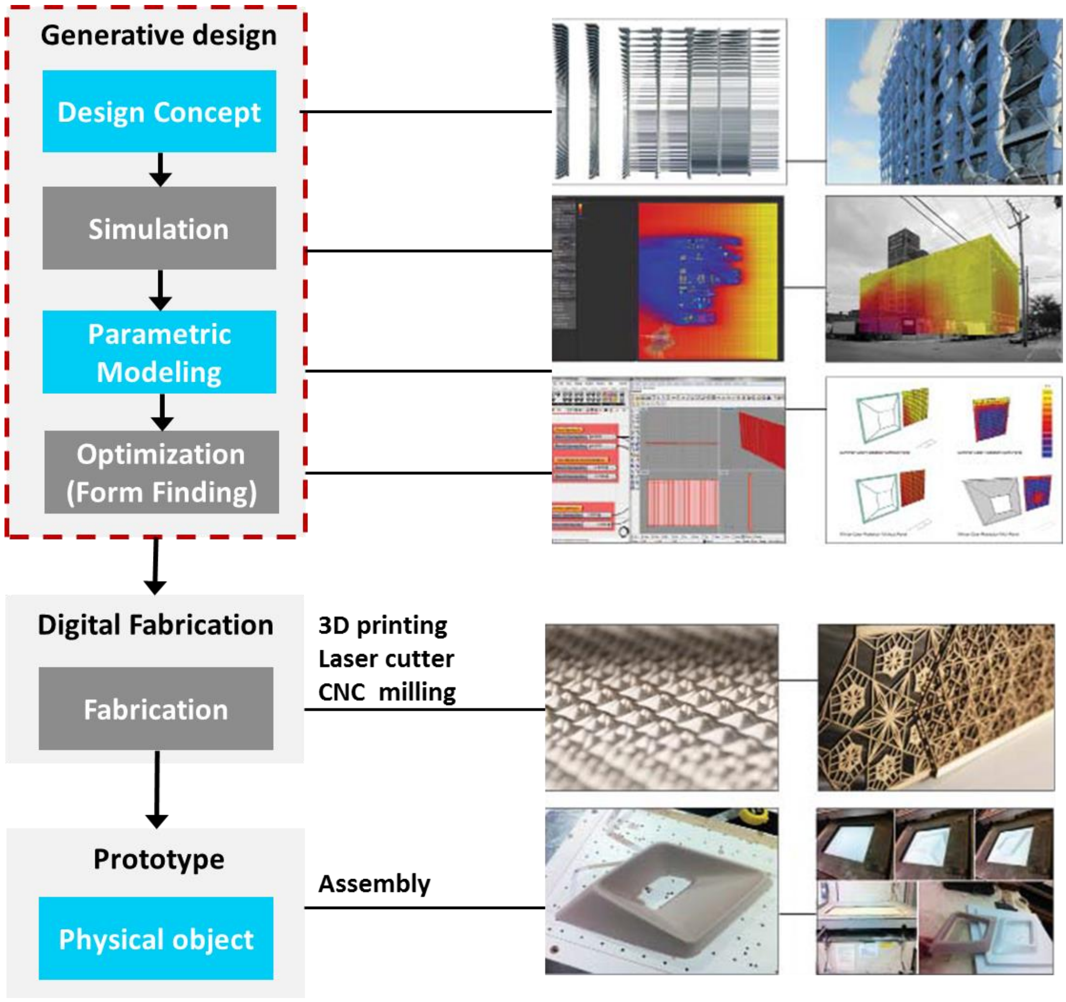


Figure 4.2 An integrated generative design/performance/fabrication design feedback loop process
Source: by the researcher based on (Aksamija, AP BD et al. 2012)

4.3. Generative systems in architectural design

Design as a word involves a double meaning; firstly, design as a process that prepares the basic sketches, plans, forms, etc. and secondly, design as an artefact that includes the end product of the previous design process. This difference is essential in generative systems approaches where formations are preceded over form. "Generative design is not about designing a building," as Lars Hesselgren explained, "It's about designing the system that designs a building." Thus, Generative systems made a major shift in the concept of design modeling from the modelling of a pre-designed “object” to the modelling of the design “logic” (Leach 2009).

From the perspective of computer aided design (CAD) development; two main categories were enlisted by Gero (Gero 1994); “the representation and production of the geometry and topology of designed objects” and “the representation and use of knowledge to support or carry the synthesis of designs”. The first one refers to the common CAD tools which are used to rapid and automate design drafting and representation while the second while the second concerns about the process of the design itself, opening the ways to generative systems to be integrated from early design phases as an explorative tool that assist architects' decisions. Generative design approach allows the formation of complex configurations through the implementation of a simple set of parameters with special operations.

The main challenge in this case is to consider the computation methods in the contemporary architectural agenda as a tool that complements the designer's abilities from the early deign phases till the end production of the design artifacts (Menges and Ahlquist 2011, Dino 2012).

Generative design logic isn't new to architecture; Mitchell traces its roots in architecture to Leonardo daVinci (Mitchell 1977). R.Hanna and T.Barber, showed that Jean Nicolas Louis Durand used a special generative system based on applying various elements' combinations in designing neo-classical architecture (Hanna and Barber 2001).

Many other pioneers had used the concept of the generative systems in their designs from a long time ago before the appears of computational tools in architecture such as; Le Corbusier with his formalized style based on his Five Points of Architecture as well as Louis Sullivan with his series of plates that describe his methodology in the design. Another recently example is Peter Eisenman, who used a set of transformational rules in his design process as shown in his series of houses designs, House I – X. According to him, "the house is not an object in the traditional sense - that is the end result of a process – but more accurately a record of a process"(El-Khaldi 2007).

Generally, the generative systems' process is based on four main components: the input parameters, the controlled rule, the output generations and the selection of the optimal solution as shown in Figure 4.3. The design artifact could only be obtained by the fourth phase.

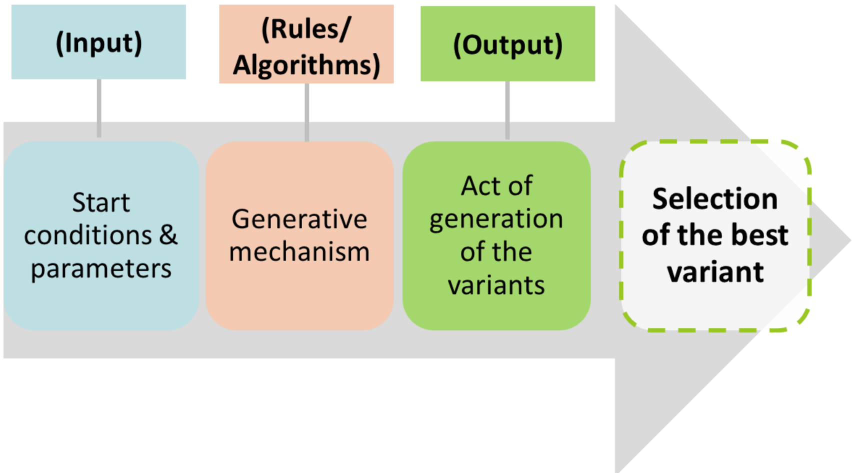


Figure 4.3 Generative system process
Source: by the researcher

Parametric-generative design system is one of the main categories of the generative systems, as it depends mainly on algorithmic fundamentals to generate and explore a wide range of design alternatives. Next section will discuss discus this approach in details.

4.4. Parametric design systems

Parametric design approach is one of the main categories of the generative systems that depend mainly on algorithmic fundamentals to generate and explore a wide range of design alternatives. Thus, the basic knowledge of the algorithms role in design will be firstly discussed in brief.

The algorithm is generally a definite set of instructions follow specific procedures to achieve certain targeted criteria. Any Algorithmic process, similarly to generative systems, starts with a set of input values or parameters which are then subjected to specific mathematical operations in order to get a set of outputs. Terzidis discussed that the algorithms' inductive methodology could be regarded as another human mind not only its digital mirror (Terzidis 2011). The computational application to the algorithmic concept allow designers to effectively control all the complexities of the design process starting from exploring geometric forms till evaluating and respond to specific performance or condition.

Parametric design is considered as a subcategory of algorithmic designs which depends entirely on algorithms structure. Considering computational systems' point of view; parametric and algorithmic systems are the same as the main element of parametric systems is the algorithm process and the algorithm itself depends mainly on parameters. However, the main difference between both systems is appears obviously during the design process where parametric design systems mainly based on changing the parameter values within the same algorithm, which often called schema or definition, to get different results or alternatives, often called instance (Dino 2012).

In parametric design systems, the algorithm in which the design parameters are relied on to manipulate the changes in the whole deigned object, could be as simple as changing in forms or dimensions or more complex by representing aesthetic, functional, performance-based approach or even more complicated by integrating more than criteria, and sometimes conflicting ones, such as environmental performance, ex. lighting or thermal performance, with engineering or structural aspects (Aksamija, AP BD et al. 2012). The latter case is in the focus of this thesis where parametric design systems is investigated as performative, ecological-based, and form- generative methodology.

4.4.1. Performative design exploration based on parametric aspects

Usually in early design phases, architect challenge a wide range of concepts and alternatives to obtain final design that could integrate many complex and in most times conflicting objectives in a way that ensure the most possible efficiency such as; designers' aesthetic intuition with the required ecological performance or structural considerations.

As investigated in the previous chapter, current CAD and simulation tools only used as a representational tools for the final design case. Conversely, parametric modelling approach allow the modelling of unlimited set of design variations depending on the parametric definition which in turn opens a wide range of possibilities to explore, evaluate and even regenerate the design model to comply with targeted aim as illustrated in Figure 4.4 (Dino 2012, Naboni, Zhang et al. 2013). Consequently, parametric design aspects and tools can assist architect or designers generally to overcome the previous complex limitations. This could be achieved by embedding all the required performance and concepts in one comprehensive platform where the designers could control, analysis and evaluate their combinations together at the same time and through all the design phases, considering parametric design as a generative-explorative tools.

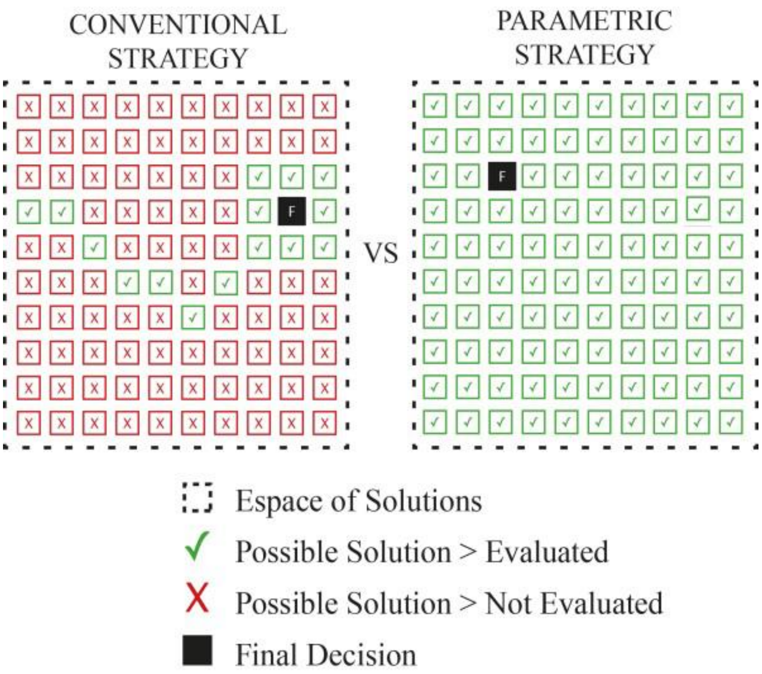


Figure 4.4 Conventional approach vs. parametric approach
Source: (Naboni, Zhang et al. 2013)

In this context, parametric modelling has the potential ability to address performative aspects in architecture by allowing the exploration of wide search space within specific performance metrics in consideration. This could be done by two approaches; the first is based on encoding values that indicates to the performance metrics with the parametric definition, while the second depends on combing an external simulation tools with the parametric model in specific ways that ensuring that the simulation process is evaluating the resulted parametric generations in a comprehensive cycle till reaching the optimal solutions. This thesis will focus on the latter case.

4.4.2. Parametric modelling tools

Parametric modeling has converted the default concept of CAD tools from a represtationl tool to a generation-simulation tools. Combing parametric systems with Computer Numerical Control (CNC) fabrication technologies and Computer Aided Engineering (CAE) tools opens new fully integrated design generations. Applying this approach in the design process not only provide architects with accurate and time consuming designs but also the ability to enhancement the performance behavior of the designs according to different aspects such as the various ecological ones that are considered within the scope of this research (Graham 2012).

Akin stated that; “Architecture is a representation saturated problem domain, mentioning two distinct modes of representation in design: analog and symbolic.”(Akin 2001, Dino 2012). Analog considers drawings and planning, sketches, 3D-physical or digital models, etc. which aims to represent a near realistic design while symbolic describe the algorithms that are beyond the design objects such as the performance aspects , such as daylight or energy performance, structural calculation, etc. With respect to those two modes, parametric design tools could be considered as a tool that combine them both in one platform that represent the technical and physical forms of the deign in one hand while embedding their performance and algorithms parameters that control the design.

Next sections will investigate the current parametric modelling tools that could be used for ecological-conscious architectural designs.

4.4.2.1. Grasshopper

Grasshopper (GH) was developed by David Rutten at Robert McNeel& Associates in 2007 as a parametric modelling plugin for Rhinoceros 3D modeling software. GH is a graphical-base tool which doesn’t require scripting knowledge to use it, and this feature is one of the main reasons that making GH preferable for architects. GH is also consider as the main parametric platform that could include many other plugins, such as environmental simulations plugins, to expand the parametric model ability to include performance aspects or any other targeted aim while quickly generate parametric forms (Figure 4.5 & Figure 4.6).

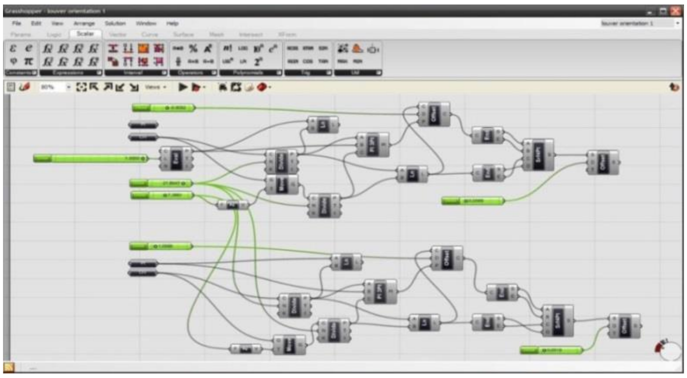


Figure 4.5 Grasshopper Script

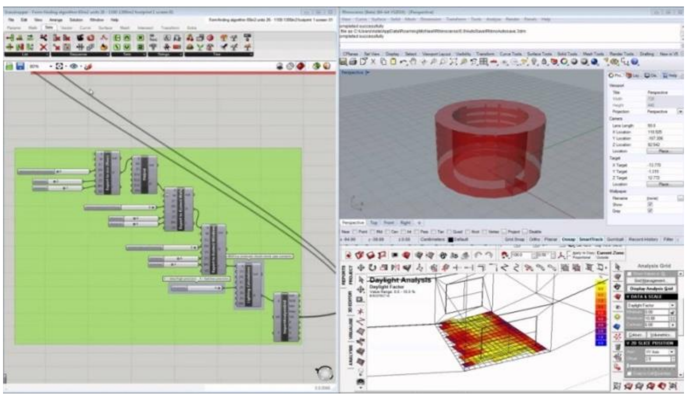
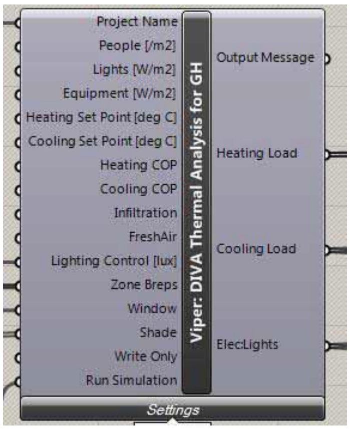


Figure 4.6 Diva and Geco for Grasshopper

4.4.2.1. DIVA-for-Grasshopper

DIVA-for-Grasshopper or, DIVA-for-Rhino plugin for Grasshopper, is a highly optimized daylighting and energy modeling plug-in for Grasshopper. The plug-in was initially developed at the Graduate School of Design at Harvard University and is now distributed and developed by Solemma LLC. DIVA-for-Rhino allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes. It works by the same way DIVA-for –Rhino does that had been described before *in section 2.6.2.2*but in this case by adding the parametric modeling potentials to the simulation runs. It could conduct climate-based daylight analysis based on dynamic daylight metrics using 'DIVA Daylight Analysis for GH' component that interface with Radiance/DAYSIM daylight engines. It also could link the daylight results with 'Viper: DIVA Thermal Analysis for GH' component within grasshopper to run thermal and energy simulation accurately by interfacing with EnergyPlus thermal engine (Figure 4.7)



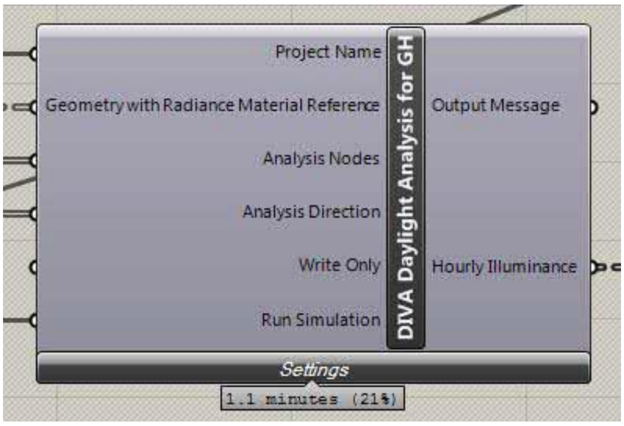


Figure 4.7 On the left, Interface of Viper Diva for Thermal Analysis. On the right, Interface of Diva Daylight for GH for Daylight Analysis.

4.4.2.1. GECO

GECO was developed by Otto and that could directly connect GH with Ecotect models. The Plugin provided users the ability to quickly export complicated geometries to evaluate their performance within Ecotect and then import feedback to GH platform. This can be done as a single operation or loop to improve performance and the design of a building in the context of their environment. Results can be saved and one of the process within a single century in the vertices of a network analysis of the data storage for later use within the different design approach (Graham 2012).

4.4.2.1. Kangaroo

Kangaroo is the add-on for Grasshopper / Rhino and Generative Components that ensures the physical behavior directly in the 3D modeling environment allows the user to interact with 'live' like simulation is running. It can be used for several of optimization methods and structural analysis.

4.4.2.2. Ladybug

Ladybug is an environmentally plugin for GH. It mainly considers the weather conditions analysis. It works mainly by importing EnergyPlus Weather files (.EPW) in GH. Ladybug supports architects with a variation of 2D/3D interactive modes so as to assist architects in taking more conscious-performance decisions through the design process and especially at early design phases. It also provides the evaluation of the radiation and sunlight analysis for the various designs (Roudsari, Pak et al. 2013) (Figure 4.8).

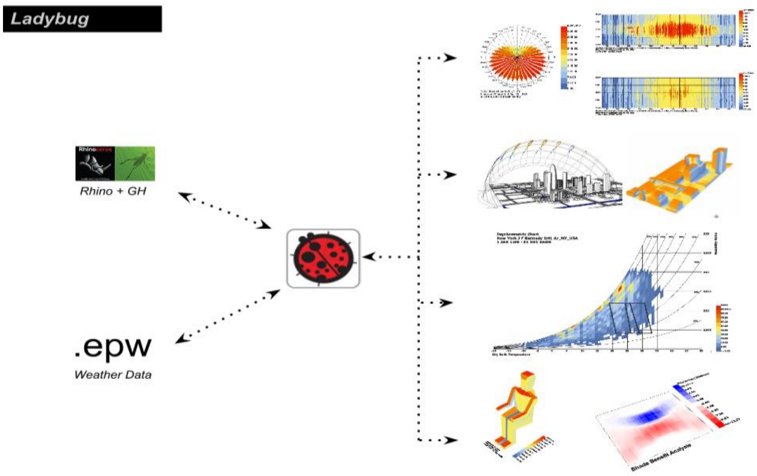


Figure 4.8 Workflow of Ladybug plugin for Grasshopper
Source: http://www.grasshopper3d.com/group/ladybug

4.4.2.1. Honeybee

Honeybee is the extension of Ladybug which extends users' ability to work directly with Radiance, Daysim, and EnergyPlus. Honeybees also connects Grasshopper 3D with OpenStudio to build energy and daylight project simulation. The honeybees offer many features of these tools to be available for simulations a parametric manner (Roudsari, Pak et al. 2013) (Figure 4. 9).

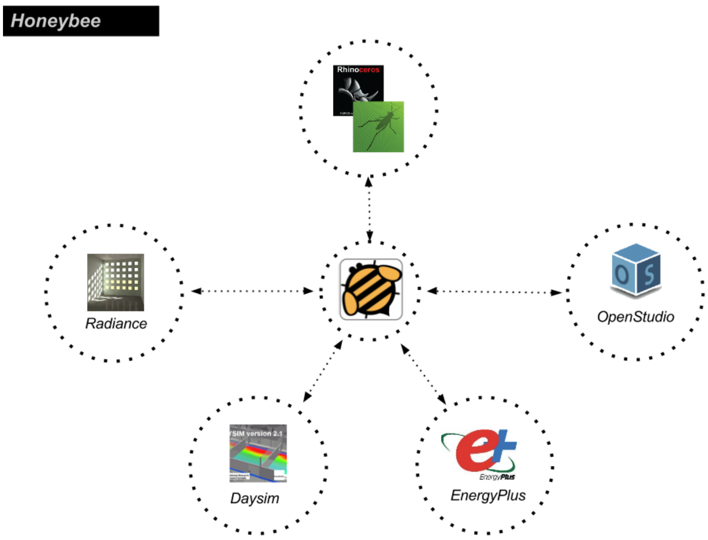


Figure 4. 9 Workflow of Honeybee plugin for Grasshopper
Source: http://www.grasshopper3d.com/group/ladybug

4.5. Some limitation and misconceptions of parametric systems

Recently, parametric systems have gained enormous attentions in architectural designs. This was mainly obvious after the appearance of user-friendly interfaces that don't require a previous experience on algorithmic scripting methods from the architects. But on the other side, this simplification constitutes a threat as many architects could easily use it in a superficial manner for new complex form generative tool which in real eliminates the parametric systems main aspects. Thus, next sections will discuss some of these misconceptions and limitations of parametric modelling so as to fully understand its potentials.

4.5.1. Parametric design is a design method not a style

Patrik Schumacher, the director of Zhaha Hadid firm, referred to parametric design in his famous essay as, "a profound style that has been maturing within the avant-garde segment of architecture", presenting the word "parametricism" as a new style in architecture that "offers a credible, sustainable answer to the drawn-out crisis of modernism that resulted in 25 years of stylistic searching" (Schumacher, 2009).

In spite of the common features that distinguish many parametric architecture designs through their potentials in generating complex and free-form designs, they aren't confined to specific approaches and certainly can't be considered as a style. Meredith indicated that the unconscious tendency to the aesthetic aspects and non-conventional or free-forms designs accompanying with parametric approaches in architecture, poses critical threats that need to be remedied (Meredith, 2008). Moussavi also states that considering parametric design as an architectural style, disposing it from any external restrictions related to the performance of the design, the context, etc. giving the priority mainly to the architectural form (Moussavi, 2011). Thus, considering parametric design as a new avant-garde style ascribes it false skin-deep character that overshadows its real values.

On the other side, the real potential of parametric modelling appears by considering it as method that control the complexity of any design process where exploring the design search space is encouraged. This potential could be exploited in performative-design where intricacy targeted performance; functional requirements, contextual aspects, etc. are addressed while exploring new geometric forms.

4.5.2. Parametric design as complicated free-forms

Another common misconception is that parametric design is currently the only used tool for designing and modelling complex architectural geometries and forms. But in fact, complex forms have already been exists in architectural field from long time ago even before computational applications in architecture have been appeared. These could be seen in the work of Felix Candela, Pier Luigi Nervi, Antoni Gaudí, Jorn Utzon and many others who followed specific procedure to deal with the complexity of free-forms. Such type of designs has the same concept of the current parametric-based designs where designs could respond to specific performance by controlling specific set of parameters. However, designing those examples was neither easily nor accurate and lacked the ability to explore wide range of solution as they mainly based on trial and error strategies or testing limited numbers of physical models. Thus, the main potential of using parametric modelling over the conventional design methods is that parametric modelling facilitates design exploration through its ability of generating enormous set of alternatives to be addressed for different design intentions or targeted.

4.5.3. Parametric design doesn't offer unlimited Flexibility

Parametric design exploration needs to be flexible enough so as to adapt to the changing parameters. However, the algorithms, that control the parametric generation and exploration process, need to be operated in a very specific and accurate way. This could be done by defining each step in the algorithm and the consequence action for each resulting alternative (Knuth, 1997).

In parametric modelling, the designer has to define and generate the algorithm definition clearly before starting parametric generation or exploration itself. And any change in the parametric models only occurred if it has been already defined within the current algorithm definition. Thus, parametric modelling isn't an easy flexible process; on the contrary Kilian reported on the threats that parametric modelling could by exposed to due to getting stuck in generating the parametric definition rather than supporting later parametric design explorations (Kilian, 2006). Burry also discussed that modifying some of the relations of the initial parametric definition is usually needed throughout the exploration process (Burry, 2007). On the other hand, this definition modifying is a very expensive and time consuming process and in some cases it becomes extremely complicated when dealing with complex data flow.

As a conclusion, parametric modelling flexibility is resulting from, and depending on, the proper input parameters and the algorithms that well defined the exploration search area.

4.5.4. The difficulties of exploring large solution spaces

Although one of the main potentials of a well-defined parametric modelling is that it offers a wide range of alternative to be explored and analyzed through the design process, it is still can't address performative explorations efficiently.

Generally, with the wide span of the search space and the size of resulting solutions, it becomes almost impossible for the designers to evaluate each solution systematically based on the targeted performance due to time consuming and other limitations. This forced the designer to evaluate and select the optimal solutions based on his own experience and intuition rather than being based on systematic evaluation. Thus, the performance evaluation criteria become the key-issue to search among different parameters configurations that are supposed to lead the designers in achieving optimal solutions. This isn't an easy process and become even more challenging when addressing complex and interdisciplinary performances.

In conclusion, using parametric design approach for addressing performance-based exploration showed its great potentials through the design process, but on the other hand, the limitations of exploring the parametrically-generated solutions systematically are still on of the main disadvantages that need to be overcome. Next sections will discuss some of the possible solutions.

4.6. Potentials of genetic algorithms combined with parametric modeling

Based on the previously addressed limitations of parametric design explorations, design exploration methodologies that are based on combining parametric design tools with computational search methods could assist architects in reaching the optimal cases that responds to the desired performance values and overcome the current limitations. Next, two scenarios of these methodologies, which will be used later in the case study in *chapter 5*, will be discussed.

The first scenario is based on integrating parametric modelling and performance simulation tools with a specific search algorithm within the same parametric definition in order to automate the whole parametric generation process in a continuous searching process that explores all the possible configurations and finds the optimal solutions between them, also known as an exhaustive search method (Daintith and Wright 2008). This method is very efficient when dealing with reasonably small number of parametric generated solutions but on the other hand, it can't deal with large set of solutions due to many restrictions such as; time and the effort needed to systematic analysis each solution related to its resulted performance. (Turrin, von Buelow et al. 2011)

Thus, optimization algorithms, as the second methodology, aims to guide the parametric generation to the optimal or near optimal solutions without the need to explore all of the alternatives. Optimization algorithms, in contrast with the exhaustive search method, could handle large set of solutions that are very important through the design process exploration.

4.6.1. Genetic Algorithms (GAs)

Generally, optimization methods can be divided into stochastic and deterministic. In the stochastic optimization method, the current generation does not completely determined next generation. This is mainly because the optimization is based on random selective process. Hence, the same optimization process will run repeatedly for the same conditions but without reaching to the same outcomes. On the other hand, in deterministic optimization method, there is no randomness and each value is assumed accurately. Thus, each generation determines exactly the next one. Hence, in this case the same optimization process with the same repeated values will have the same outcomes each time (Burry and Burry 2010, Chalabee 2013).

Results in design analysis come usually from a large number of parameters, where traditional or scenario-by-scenario methods do not offer the appropriate guarantees for achieving optimal results. Thus, stochastic optimization techniques can be the perfect solution to the problem, as they facilitate the search of a far greater range of solutions to a problem within reasonable time and complexity.

Evolutionary algorithms (EAs) is a well-known technique of stochastic optimization that has been widely applied in various architectural fields. EAs include many approaches such as; Genetic Algorithms (GAs), Genetic Programing (GP) and Evolutionary Programing (EP) as shown in the diagram in Figure 4.10.

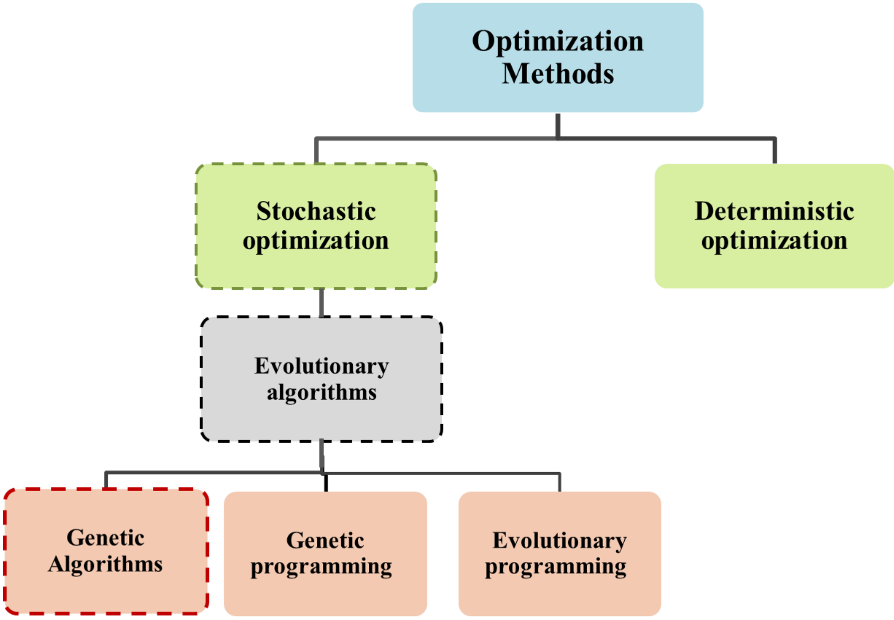


Figure 4.10 Different approaches of optimization methods

Source: by the researcher

The study in this thesis will focus on GAS optimization as it is the most popular type of EA that is worldwide known optimization technique for sufficient searching complicated solution spaces with local and global minima. Its main concept is based on the transformation of natural evolution theory into the optimization field. This approach was first introduced by John Holland's concept in 1975 (Holland 1975), as an artificial design system to solve problems that mimics the process of evolution and natural genetic reproduction of species (Marin, et al 2008). New generations in GAs use Darwinian principle of reproduction and survival of the fittest of natural occurring genetic operations (Chalabee 2013). The searching starts by randomly sampling within the solution space and then stochastic operators to direct a hill climbing process based on an objective function value (Golberg 1989).

Genetic algorithms and evolutionary systems provide a framework by which locally optimal solutions that meet certain criteria can be searched for within an infinite generative field of variation. Nathan Miller (Miller 2011) stated that "Using GAs and EA tools, the parametric system becomes the genome, the field of alternatives becomes the population, and the architect's design goal becomes the fitness criteria.” This methods does not necessarily find the optimal solution; it could find a local optimal solution instead (Singh and Kensek 2013)

In GAs terminology, we refer to design parameters as (genes) and for the design solution resulting from the combinations of these genes as (genomes). A genome is a specific value for each gene. A group of genomes in each generation called (population). These genomes will be evaluated based on the target evaluation criteria or performance which defined as (Fitness function). Generally, GAs considers various random genomes and drives them to reach the target optimization value (fitness value). If a particular genome improves the fitness value, the algorithm will favor this proximity of genes on the genetic landscape for the next generation. In other words, if the parameters are close to a good result, the optimization solver will focus on testing the range of parameters closer to that value (Portugal and Guedes 2012, LMNts 2013).

The subsequent generations is controlled and evaluated by the Genetic operators. There are three basic genetic operators, which are Reproduction, Crossover and Mutation which are defined as following (Portugal and Guedes 2012, Chalabee 2013);

- **Reproduction**: is depending on the individual performance of each
- **Crossover**: is the breeding between two randomly selected genomes from the fittest population to create a new genome.
- **Mutation**: is the searching for random new parameters outside the previously defined population to expand the search scope in order to find any lost optimums.

4.6.2. Genetic Algorithms (GAs) optimization process

The fitness landscape of a particular model could be presented as a 3-dimensions surface with different heights as illustrated in Figure 4. 11, where in this case only two parameters (genes) are allowed to be changed (A &B). By changing gene A the fitness of the whole model goes up or down referring to better or worse results depending on the predefined target. Meanwhile, for every value of gene A, gene B could have different value. Every combination of A and B results in a particular fitness referring to better or worse case. The main aim of the GAs optimization is to find the highest peak in this landscape.

However, it is important to mention that this fitness landscape represents a very simple case and that in real design practice a lot of cases are defined by more than two genes, in which it can’t be described by such a simple landscape. For example, a model with 6 genes would be a 6-dimensional fitness volume deformed in 7-dimensions instead of a two-dimensional fitness plane deformed in 3-dimensions. This would mean something terribly more complex than the below image shows. However, as this is impossible to visualize, the main process will be described for the two-dimensional model shown below in Figure 4. 11.

As the genetic optimization solver starts it has no idea about the actual shape of the fitness landscape and to find the optimal combinations of genes (or "genomes") it goes though the following steps, as shown in Figure 4. 11 (Rutten 2010);

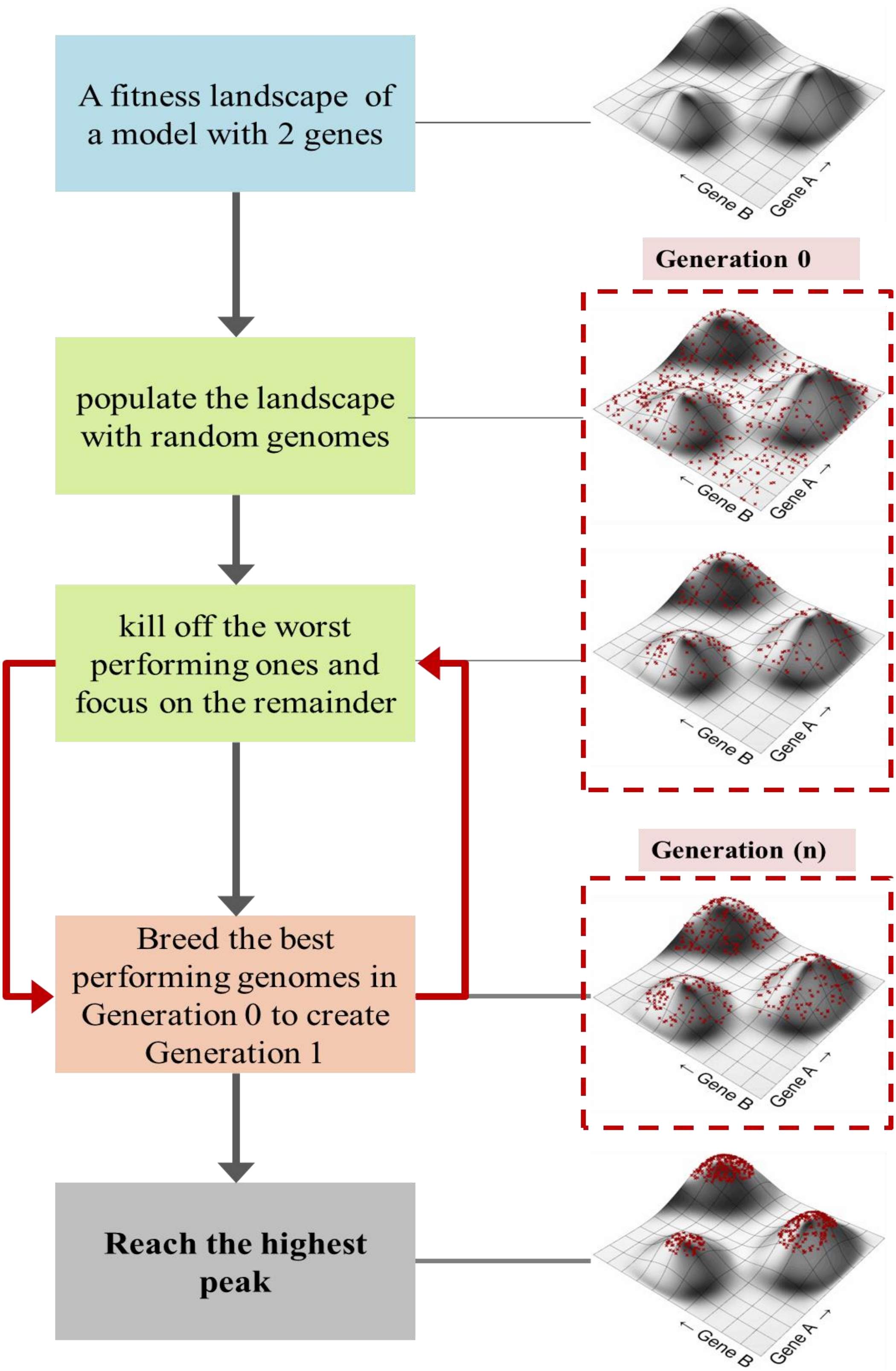


Figure 4. 11 Genetic Algorithms process workflow

Source: by the researcher based on http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles

4.6.3. Optimization algorithms tool

A parametric or generative model is an essential feature in the optimization process. The optimization process needs geometry or a building which is able to respond the obtained simulation feedbacks. In other words, optimization is an iterative process which starts with defined geometry, then the geometry will be simulated with a simulation process, after that based base on the obtained feedback for the simulation engine, the geometry has to capable to change its parameters to get better simulation results in the next generation of geometry or building.

Generally, there are two different type of optimization: Single and Multi-Objective Optimization. Single-Objective Optimization is used when the design problem optimizes a single objective, which mostly maximizes or minimizes. Therefore the optimization model in this case is scalar. While Multi-objective Optimization: when the problem has more than one objective to optimize, the optimization model will have vector objective instead of scalar. Optimization algorithms are also classified to global and local optimization solver. Some of the commonly used tools that will be addressed below showing their types related to the both mentioned categories, Single/Multi and global/local, application process and their potentials and limitations for optimizing ecological facades.

4.6.3.1. Galapagos for Grasshopper

Galapagos is the first application of evolutionary algorithms within Grasshopper. It is a generic component that was developed by Daivid Rotten who said "*It is my hope that Galapagos will provide a genetic platform for the application of Evolutionary Algorithms to be used on a wide variety of problems non-programmers*".

The optimization process does not occur, unless a clear problem has been defined and an answer has been addressed. Thus, defining a fitness function, which is capable to find different solutions with different variables, is required. Goat has the ability to control the input parameters using numeric sliders (single genes) and gene pool components (a collection of genes) within Grasshopper. Also the criteria which needed to be optimized should be defined as numerical numbers. These numbers will pass to Galapagos in order to solve the problem (Figure 4.12).

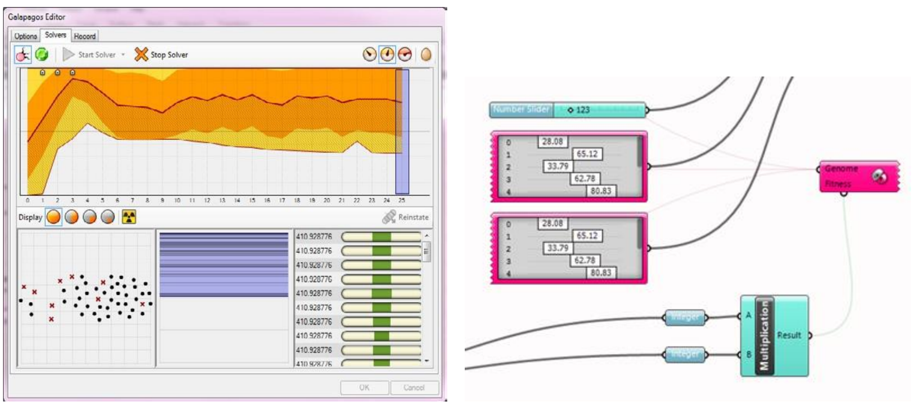


Figure 4.12 Galapagos component for GAs optimization with Grasshopper

Galapagos is a global single-objective optimization tool thus; the solution is based on maximizing or minimizing those numerical data in loops to see whether the results are going towards better or worth conditions. Consequently, the design outcomes will be optimized or a defined problem will be solved by using a numerical based fitness function in its highest/lowest achievable values (Khabazi 2010).

4.6.3.2. Goat for Grasshopper

Goat is an optimization solver component for Grasshopper which is perfectly complements Galapagos. Goat pursues a mathematical rigorous approach delivering fast and deterministic results. At every run, goat will yield the same optimal result. Goat is a single-objective optimization as Galapagos but one of the main features of goat rather over Galapagos is that it has the ability to apply both local and global solver. On the other hand, Goat could only deal with numeric sliders (single genes) component within Grasshopper to control the input parameters (Figure 4.13).

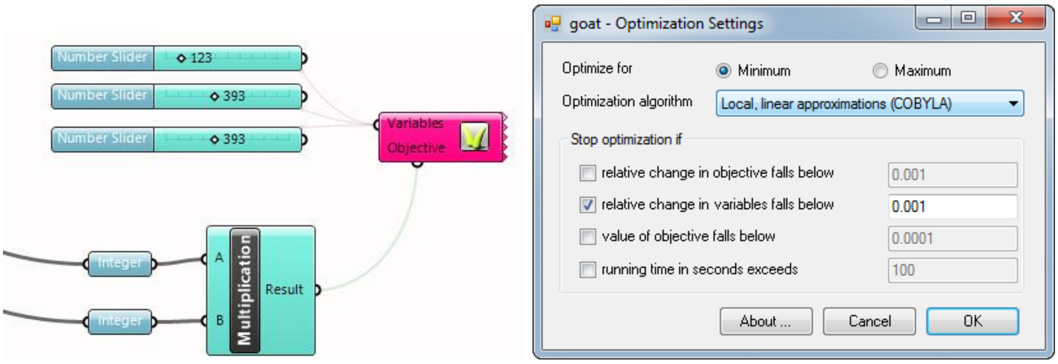


Figure 4.13 Goat plugin for Grasshopper

4.6.3.3. Octopus for Grasshopper

Octopus is a plug-in for Grasshopper that applies evolutionary principles to parametric design and problem solving. Octopus was developed by Robert Vierlinger at the University of Applied Arts Vienna as a multi-objective optimization solver which allows the search for many goals at once. It produces a range of optimized trade-off solutions between the extremes of each goal. One of its main feature is the ability to change objectives during a search process.

4.6.3.4. ParaGen GA

ParaGen is a parametric design tool using GAs for the exploration of form based on performance criteria. It was developed at the University of Michigan, Taubman College, where it has been used for structural form optimization. ParaGen is also extended for interdisciplinary optimization by a collaborations with Delft University of Technology (Turrin, von Buelow et al. 2011)

ParaGen could make use of a parallel network of PCs and web server to facilitate the process between the tools of parametric form generations, evaluation and optimization. The system is open to different parametric modeling tools such as; Grasshopper and Generative Components. ParaGen is considered as a single-objective genetic based optimization tools but it has the potential to combine different performance values as a weighted average, to produce an overall score that combine multi objectives within the same fitness function used by the GA (Von Buelow 2012).

4.6.4. Genetic Algorithms limitations and drawbacks

Despite the various advantages of the GAs optimization in architecture, it also has its drawbacks and limitations. Firstly, the main limitation of the evolutionary algorithms generally, including GAs, is that they are slow. A complicated design cases might require several days to solve a single problem. Secondly, GAs doesn't guarantee optimal solutions and the process could tend to run on indefinitely, never reaching the optimal solutions if the problem hasn't been well-defined earlier (Rutten 2010). This includes a pre well-defined fitness equation accompanied with appropriate parameters and search space, which isn't always an easy task especially at early design phases.

However these limitations could be overcome by using the interaction potentials of GAs with the users. As discussed by David Rutten (Rutten 2010), one of the main features of GAs applications is that the process running time is highly clear and browsable which offers many opportunity for a dialogue between the algorithm and the human. Thus, the optimization solver can be coached across barriers with the help of human intelligence, or it can be forced into exploring sub-optimal cases and superficially dead-ends.

4.7. Parametric design systems and optimization algorithms methodologies for ecological facade design

In order to focusing the scope of this study and realize the effectiveness of parametric design systems and optimization algorithms in exploring and optimizing ecological screen for balancing daylight, thermal as well as the used methodology and integrated tools, a comprehensive analysis of recent studies that addressed them will be conducted.

This section will be divided into three parts to address the recent academic experimentations and studies as; firstly, parametric simulation based studies, secondly parametric optimization studies and thirdly the experimentations of both approaches to address non-conventional solar screens and shading systems.

4.7.1. Parametric simulation applications for ecological facade

In a recent study by A.Wagdy and F.Fathy (Wagdy and Fathy 2015) a comprehensive parametric approach was carried out for optimizing daylight performance using solar screens. Five screen parameters with different predefined ranges including; window to wall ratio, louvers count, louvers tilt angle, screen depth ratio, and screen reflectivity were computed resulting in 1600 different cases. The screen was tested for a generic south-oriented classroom located in Cairo's desert in Egypt using DIVA-for- Rhino as the simulation tool and

Grasshopper as the parametric modelling tool. The general tendency of each parameter and the interaction between them was examined based on; the Illuminating Engineering Society (IES) metrics, Spatial Daylight Autonomy ($sDA_{300/50\%}$), Annual Sunlight Exposure ($ASE_{1000/250hr}$), Daylight Availability and Annual Daylight Glare Probability (DGP).

It could be said that this study stepped away from the conventional parametric method that has the ability to generate a case by case solution by representing an evolving attempt to explore all possible screen configurations in a daylighting parametric study. By using a parallel computing procedure, where multiple Radiance simulations can be run based on the available CPU cores, to find optimal solutions while solving the simulation running time problem. A more deep exploration for the potentials of this method will be investigated in Chapter 5.

The same authors also implemented a parametric approach for balancing daylight with energy efficiency using horizontal louvers (Wagdy and Fathy 2016). In this study, the louvers were tested to find its optimal configuration in terms of three parameters, WWR, louvers tilt angle, and depth ratio, for a generic south-oriented classroom in Cairo, Egypt. They integrated daylighting and thermal simulations by using DIVA-for-Rhino to interface with Radiance, Daysim and Energy Plus software. Daylighting analysis was performed in which the Illuminating Engineering Society (IES) metrics; Spatial Daylight Autonomy ($sDA_{300/50\%}$), Annual Sunlight Exposure ($ASE_{1000/250hr}$), besides Daylight Availability were examined; then total energy loads were calculated in terms of lighting, cooling, and heating loads. Results proved the effectiveness of these louvers in reaching the optimum daylighting performance (100%sDA, 0%ASE), while still maintaining low energy loads. This was achieved with the lowest total energy loads at 40%WWR, downward tilt angle (-20°), and depth ratio 1.5. Then, a correlation between 'overlit' area and increasing energy loads was deduced despite having the same ASE (0%). Therefore, calculating Daylight Availability gave an indication about energy loads and hence daylighting optimum cases can be sorted regarding energy without even being calculated. Similar studies that focused on n exploring the effectiveness of parametric simulation in exploring and optimizing different shading devices and designs for daylight and/or thermal analysis with various other performance aspects could be found in (Naboni, Zhang et al. 2013, Sherif, Sabry et al. 2016)

4.7.2. Integrating Genetic Algorithms with Parametric modeling tools for ecological facades

The above studies were focused mainly on the usage of parametric modeling with simulation tools for exploring and optimizing various facades components. However, many other studies addressed the effectiveness of using Genetic Algorithms optimization for optimizing various shading systems and façade components for specific performance criteria. Naboni et al. (Naboni, Maccarini et al. 2013) investigated how different computational methods can be integrated in the design process of comfort and energy efficient buildings. The main aim of this research was to facilitate the use of parametric energy studies among the Architecture, Engineering & Construction industry by developing an online service to rum parametric energy simulations using cloud computing. Three approaches were explored: a scenario-by-scenario conventional approach, a parametric approach and an evolutionary optimization approach using EnergyPlus, jEplus and jEplus+EA respectively. A prototype of a nearly zero-energy building was designed and built in Copenhagen to explore the potential and limitation of such methods. The authors of this study developed a user-friendly cloud-based workflow that is suitable for architects and familiar with various energy simulations. Results showed that following this approach significantly reduced computational time by 213 times faster than the parametric simulations and that it could reduce buildings energy consumption to a higher degree than in a conventional design process. More studies that focused on using Genetic Algorithms for optimizing various façade component for optimal daylight and/or thermal performance with different other performance aspects could be found in (Torres and Sakamoto 2007, Portugal and Guedes 2012, Chalabee 2013).

In a master thesis by R. Arafa (Arafa 2012) a comprehensive investigation of the impact of changing screen configurations; perforation percentage, depth, perforation openings aspect ratio and reflectivity, on energy loads was conducted. It also defined the most efficient configuration range for various window sizes and orientations. The study was implemented using EnergyPlus simulation software for a typical residential building in the Kharga Oasis, Egypt. Then a parametric optimization using 'GenOpt' was conducted to verify the parametric results. Results proved that implementing optimum perforation and depth range for solar screen shading system allowed for a larger WWR of 22% instead of 4% without the screen for the same energy consumption. However, the highest energy savings were achieved in screens with 1 depth ratio and 80% perforation percentage in the West and North orientations, and a 90% perforation percentage in the East and South orientations. It also showed that using solar screen with square perforation or horizontally stretched rectangles achieved significant energy savings. Moreover, the optimization results proved the accuracy of these results while generating different unusual innovative architectural solar screen configurations for each facade that could reduce energy loads considerably.

4.7.3. Parametric systems and Genetic Algorithms for non-conventional solar screens and shading systems.

In a more related work to the aim of this thesis, a study by Y. Elghazi et al., including the researcher, conducted an exploration for a non-conventional solar screen based on origami: kaleidocycle rings that can be morphed to enhance daylight performance in residential spaces, which complies with both LEED V4 and Daylight availability. Two screen parameters, size and rotation, were examined based on both a scenario-by- scenario approach and GAs optimization approach (Figure 4.14). The study aimed to find the optimal screen configuration that could comply with both LEED V4 and Daylight availability metrics requirements. Thus, Galapagos as the GAs tool and Diva as a daylight simulation tool were used all within Grasshopper parametric model tool. The simulation was carried out for a south-oriented façade of a living room in Cairo, Egypt. Results demonstrate that using the tradition simulation process showed promising results but the optimal Kaleidocycle rings configurations weren't reached until the second GAs optimization phase. It showed that Kaleidocycle rings of 30 cm size and 64 rotation's angle reached results that exceed LEED v4 requirements while passing Daylight availability standards (Elghazi, Wagdy et al. 2014). A. Wagdy et al. (Wagdy, Elghazi et al. 2015) continued to explore the potentials of the same Kaleidocycle rings, but in this case the study aimed to find the optimal configurations that could reduce total energy consumed for heating and cooling while enhancing daylight uniformity. The results determined that kaleidocycle rings of 26 cm size and 64◦ rotation angle exceed the LEED V4 daylighting requirements while achieving a remarkable energy saving of 23% in comparison to non-optimized configuration.

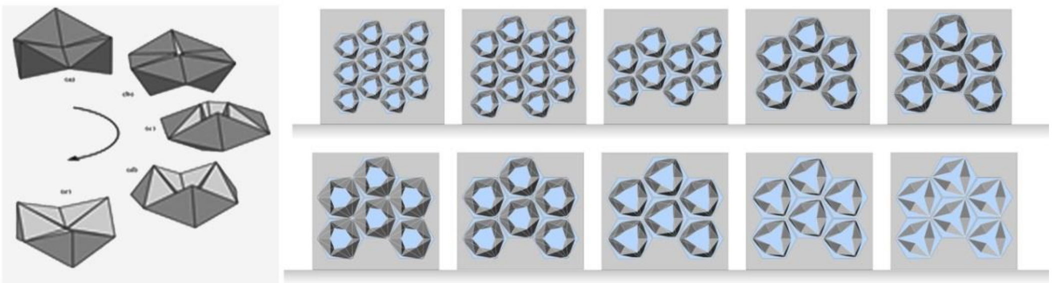


Figure 4.14 The kaleidocycle size and rotation angle various configurations Source: (Wagdy, Elghazi et al. 2015)

The study by N. Emami et al. (Emami, Khodadadi et al. 2014) conducted a multi-objective performance evaluation to explore the interaction of the variables and the geometrical parameters of a perforated screen wall on an office space daylighting performance as well as structural performance of the wall itself. The screen design was inspired by Persian geometric patterns as shown in Figure 4.15. The pattern has the potentials to change the perforation ratio, depth and curvature of the screen. DIVA-for-Rhino software was used to evaluate daylight performance of the screen based on the daylight autonomy and the daylight factor (DF) metrics. While the structural analysis were conducted using ANSYS software to evaluate the deformation, safety factor and weight of the screen. The two software were within Grasshopper to parametrically control the screen variables. The study was carried out through two phases. The first phase conducted parametric simulation and resulted in four possible configurations. While the second phase used GAs optimization by applying the ParaGen method resulting in pallets of possible design alternatives coupled with their relative performances.

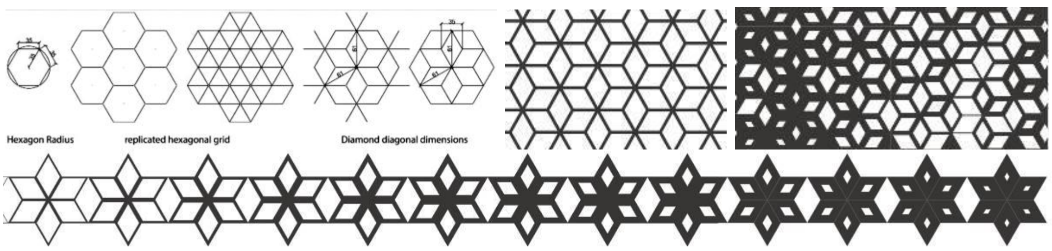


Figure 4.15 The basic pattern for the shading screen
Source: (Emami, Khodadadi et al. 2014)

Another important study that addressed the limitation of simulating complex geometric screens in energy simulation software such as Design Builder and EnergyPlus was (Omidfar 2011). As directly creating a complex surface geometry is infeasible using current simulation tools. This paper suggested that, in order to model the effect of a sun shading screen based on Sculptor Erwin Hauer's design (Figure 4.16), specific performance criteria of the screen had to be measured using DIVA, These should include the screen shading coefficient and a yearly electric lighting schedule based on daylight performance metrics, which was Daylight Autonomy (DA) in this case. The results were then synchronized with thermal analysis performed in Design Builder linked with Energy Plus. The screen was tested for a south facing open-plan office space in Boston, USA. Results are then compared to baseline spaces with 30% and 100% Window-to-Wall ratios (WWR) to understand the screen's relative performance gains. This analysis shows that the optimized screen manages to reduce annual energy use by 35% and 42% comparing to the two base cases while improving daylight by 30% more DA than the 30% WWR. This paper proved that, a building's shading device can be both a complex geometry that satisfies the aesthetics desires for ornament, while also fundamentally addressing building performance and user comfort.

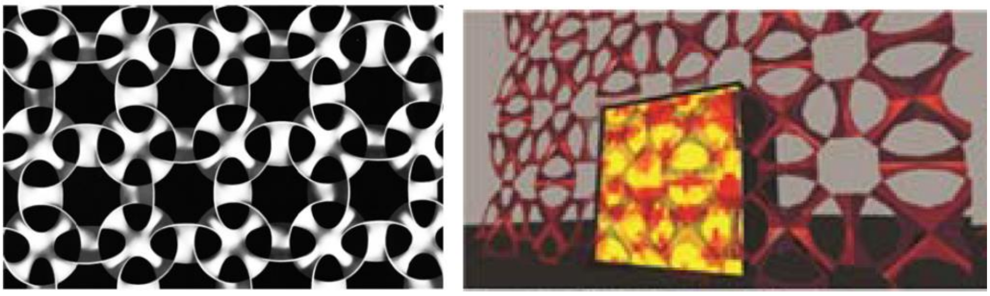


Figure 4.16 On the right, the screen intercircles designed by Erwin Hauer. On the right, the shading coefficient calculation for the screen Source: (Omidfar 2011)

Another study for the same author (Omidfar, Torghabehi et al. 2014), introduced an integrated methodology that allows designers to find solutions which yield good performance over a range of criteria to evaluate a design both aesthetically and performativity. For this study, daylight and structural analysis was conducted for self-standing skin warped around the South, East and West elevation of an office building in New York (Figure 4.17). The skin was applied by integrating daylight simulation, structural analysis tool with parametric optimization software using DIVA, STAAD.Pro, ParGen with Grasshopper respectively. The daylight was evaluated based on Dayligt Autonomy (DA)and one of the important considerations of this study was the calculation of Solar Radiation (RAD) penetration through the skin as it could give an indication about the cooling load of the space. RAD was calculated using a set of sensors or nodes located on the exterior walls directly behind the skin to measure Radiation penetration through the unit modules. Here, the RAD only measured the peak summer week from July 27th to August 2nd. RAD results showed 70% to 96% reduction in direct radiation which would ultimately reduce the overall cooling demand and therefore reduce the energy consumption during the summer months. Another study for the same skin was conducted by A. Omidfar (Omidfar 2015) but in this one she introduced using bidirectional transmission distribution function (BDTF) as a modeling technique for daylight simulation and showed how this method could provide detailed evaluation of different façade variables.

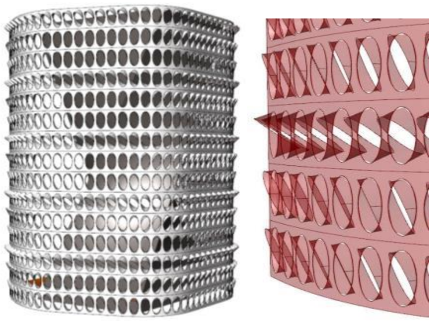


Figure 4.17 The proposed skin components and construction
Source: (Omidfar, Torghabehi et al. 2014)

Similar studies that addressed non-congenital shading devices using Genetic optimization for optimal daylight performance could be found in (Turrin, von Buelow et al. 2011, Hegazy and Wagdy 2016)

4.8. Effectiveness of parametric design systems and GAs optimization for ecological façade design

From the above literature review, some results could be concluded. Firstly, parametric bases simulations were conducting when the exploration of the design elements performance is preferred over just selecting the optimal case. This is due to the back-tracing potentials of the parametric results as shown in (Arafa 2012, Wagdy and Fathy 2015, Wagdy and Fathy 2016). On the other side, studies that concerned in finding the optimal configurations specially for non-conventional and complex geometric shading systems that can’t be analysis easily, depended more on Genetic algorithms and other optimization techniques such as the work of (Omidfar 2011, Elghazi, Wagdy et al. 2014, Emami, Khodadadi et al. 2014, Wagdy, Elghazi et al. 2015). However, both parametric simulation and Genetic optimizations showed their potentials in optimizing ecological façade elements to correspond to specific performance criteria including daylight, thermal and energy performance.

One of the main beneficial findings of analyzing the above literature review, was the methodology presented in (Wagdy and Fathy 2015) that made use of the Radiance potentials to run parallel simulation according to the available CPU cores of the used computer could make an significant time saving in the total running time. Thus, one of the main limitations of using parametric runs , over wasting running time, could almost be overcome.

Another important finding was the methodology presented by (Omidfar 2011) for analyzing thermal and energy performance for complex shading systems based on the calculation of shading coefficient as well as a yearly electric lighting schedule based on daylight performance metric. As current energy simulation tools can't recognize and analyze such complex geometries, this methodology allowed for overcoming this limitation.

In this paper, the shading performance of the screen was simulated using DIVA every hour over the year by placing a vertical test surface directly behind the screen. The simulation measured light falling on the test surface with and without the screen as a shading device. The ratio of both values resulted in an hourly shading coefficient of the Ornamental screen that was then connected to the thermal simulation.

Considering the used software and tools, Grasshopper was shown to be the most popular tool among architects due to its graphical interface that doesn't require a previous scripting knowledge to use it. Another reason for its popular use is the Availability of a large number of performance plugins that integrate with it to conduct various analyses. Galapagos was always accompanied with Grasshopper when Genetic Algorithms optimization is required as it is an efficient GAs component of Grasshopper that doesn't need an integrating with other optimization plugins. Finally, DIVA plugin for Grasshopper was also shown to be used widely when concerning daylight and/or thermal and energy performance, as it conduct all the required analysis within the same interface without shifting between different tools. Besides, it interfaces with validated daylight and thermal engines, Radiance/Daysim and EnergyPlus. With the ability of these tools, it was shown also that most of the studies relied on dynamic daylight performance metrics for analyzing daylight performance. A conclusion table for the addressed literature review is shown in Appendix C.

4.9. Conclusion

New combination of digital technologies including digital fabrication and generative design systems with building performance simulations tools introduced a continual design-feedback loop process that give architects the ability to generate various design alternatives, improve targeted performance and end with scaled artifacts to study, review and evaluate the design solutions.

Focusing on the scope of this research, the generative parametric design systems and tools were investigated showing their potentials, limitation and misconceptions for addressing ecological aspects in architecture. After that, optimization algorithms potentials as evaluating searching method that could overcome parametric systems' limitations were discussed. The study in this chapter focused on Genetic Algorithms optimization approach as a worldwide known optimization technique for sufficient searching complicated solution spaces showing its process, tools as well as addressing its limitations and drawback and how to overcome them. Finally the methodology of using parametric design systems as well as Genetic Algorithms for optimizing building components designs were conducted from analyzing recent literature reviews in the field.

Chapter 5 Parametric optimization algorithms for solar screen for office building façade (Empirical study)

5.1. Introduction

The literature review, discussed in previous chapters, demonstrated the usefulness of using solar screens in enhancing daylighting and thermal performance and reducing energy consumption especially under the clear desert sky. However, a limited number of studies addressed the balance between them using non-conventional screens with new inspired designs. On the other hand, parametric design approach and Genetic algorithms (GAs) have been proved their effectiveness in presenting new solutions to optimize shading devices with respect to various performance aspects.

Thus, this chapter will investigate non-conventional screens that can be morphed to balance daylight and thermal performance within the maximum possible energy savings. This will be carried out through a continual cyclic process between form generation, evaluation and optimization of the screen for a south-oriented façade for an office space in Cairo, Egypt.

The main objective of this study was to understand the effect of non-conventional solar screens on the indoor daylight, thermal performance and energy performance for south façades and to compare between parametric simulations and GAs as a tool to optimize these screens as illustrated in Figure 5.1. Finally, two design methods will be proposed to optimize south facing screens for specific performance goals.

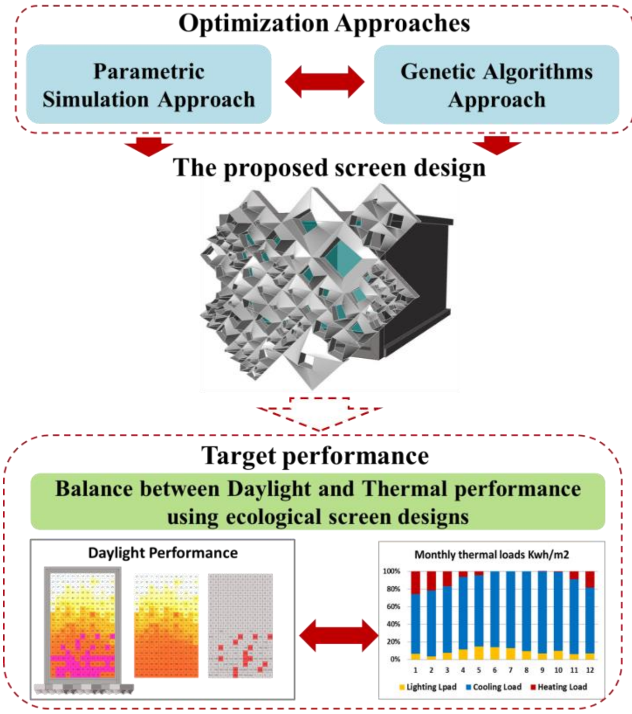


Figure 5.1 The main objectives of the study in this chapter

The study implemented in this chapter is a simulation-based study that integrates up-to-date simulation techniques with parametric approach and Genetic algorithms (GAs) optimization. Thus, the simulation process that was conducted here can be considered as a generative-evaluated methodology for balancing daylighting and thermal performance using ecological solar screens.

This chapter was divided into four successive parts; the first part showed the base case condition and properties, the proposed screen parameters; size, scale, rotation and extrude, and their values and configurations, the targeted performance evaluation criteria and simulation procedure. The second part dealt with the GAs optimization process to drive the screen parameters for optimizing daylight and thermal performance of the office space. The third part dealt with parametric simulation runs to evaluate the screen parameters effect on the daylight and thermal performance of the office space. Finally, a deductive comparison between parametric simulation and GAs optimization was conducted and concluded with two suggested solutions that aimed to combine the potentials of both parametric simulation and GAs optimization process.

5.2. Simulation framework

The initial exploration of the screen geometry was executed in the Rhinoceros 3D modelling environment. But the realization of various parameters that control the screen geometry required the geometry to be constructed in Grasshopper as a mean to control each variable parametrically. DIVA-for-Rhino, a highly optimized daylighting and energy modeling plug-in for Rhino and Grasshopper, was utilized to carry out the simulation runs. The simulation results were analyzed to understand and evaluate the daylight, thermal and energy performance behavior of the screen geometry.

The overall definition of solution was generated in Grasshopper and can be divided into three main sets as shown in Figure 5.2:

1) Parametric modeling which includes parametric office model and parametric screen model with its various variables; size, rotation, scale and extrude.
2) Performance simulations including daylight performance simulation and thermal performance simulation.
3) Performance evaluation through firstly collecting the data and exporting results to excel sheets and then analyzing them based on the target criteria.

Firstly two 3D models for a hypothetical office space with a south side-lit facade were modelled within Grasshopper, one with full details and real thicknesses to be used for the daylight simulations and another simplifying one to be used for the thermal simulations as thermal simulations tools could only deal with single surfaces models. Secondly the proposed screen was parametrically modelled and applied to this south façade. A wide range of screen configurations could be processed by changing parameters in Grasshopper as will be addressed later in details in section 5.2. After that each alternative was linked to DIVA Daylight Analysis component within Grasshopper to firstly, measure the daylight performance inside the office space. Secondly, generate the electric lighting schedule and to calculate the screen shading coefficient to be linked to the thermal simulation later. Then the thermal simulation was conducted using Viper Thermal Analysis component within Grasshopper. Finally the simulation results aligned with their specific configurations are collected and exported to a Microsoft Excel sheet using TT tool box plugin for Grasshopper that contains a fast Excel Writer which can transform results' numbers into excel to be analyzed and evaluated. Conclusion for the above main process workflow showing the used tools for each phase and main inputs data are illustrated in Figure 5.2.

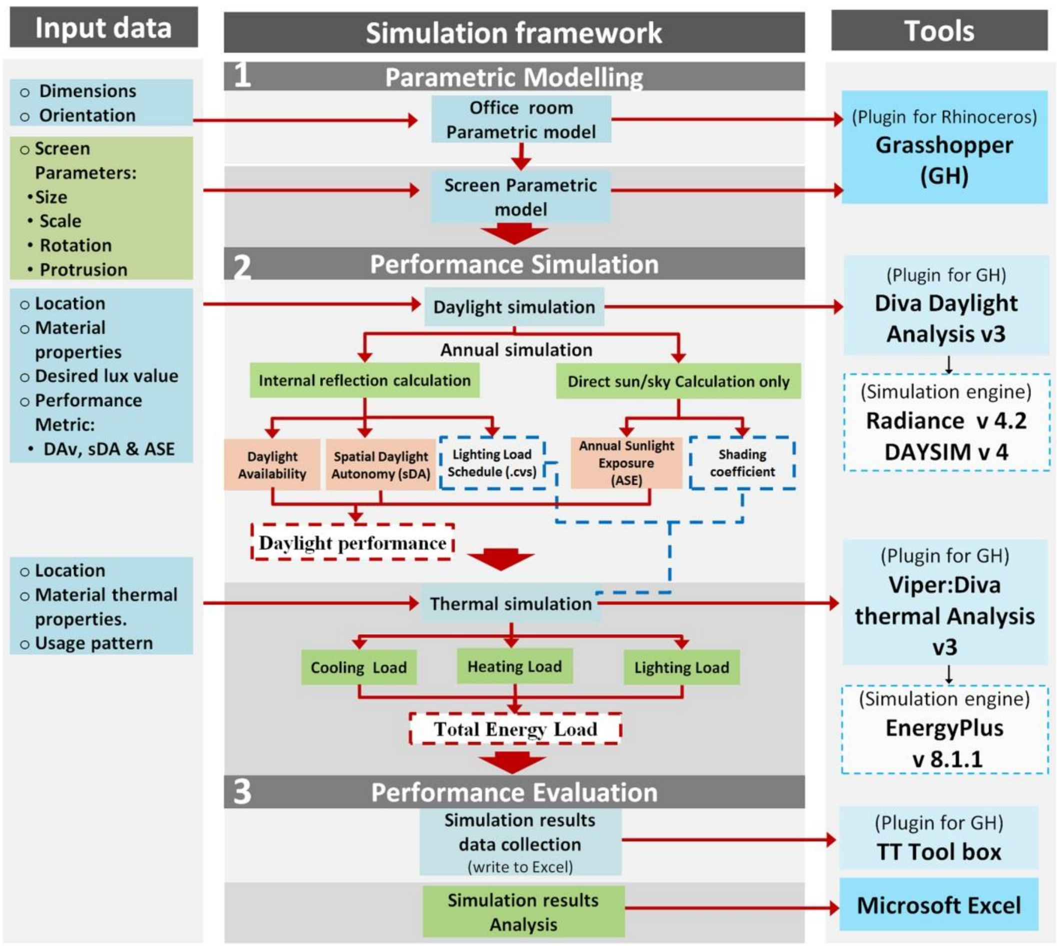


Figure 5.2 Main simulation process workflow and supported tools

Source: by the researcher

5.3. Base Case Parameters

The case study was chosen to be located in Cairo, Egypt (30°6′N, 31°24′E, alt. 75m). Cairo is the capital and major city of Egypt and considered as one of the world's 15 largest cities in urban and population growth and thus, contains large number of the offices and commercial buildings. On the other hand, it belongs to a subtropical desert arid hot climate according to Köppen's climate classification (Peel, Finlayson et al. 2007) which is characterized by high direct solar radiation and clear sky that demands special façade treatments to minimize solar heat gain while providing appropriate daylighting.

In this study, a side-lit space has been defined and constructed as a base model for a hypothetical office space of 24 m^2 area (4 m (width) x 6 m (length) x 3.2 m (height)) facing the south direction. It is assumed that the space is bordered on five sides by similar spaces with no external obstruction and that it is located at a mid-floor as shown in Figure 5.3. The external south façade has a window of 11.5 m^2 that represents a Window-to-Wall Ratio (WWR) of 90% as most of the curtain walls applied to the office buildings in Cairo. The proposed screen will be applied to this façade.

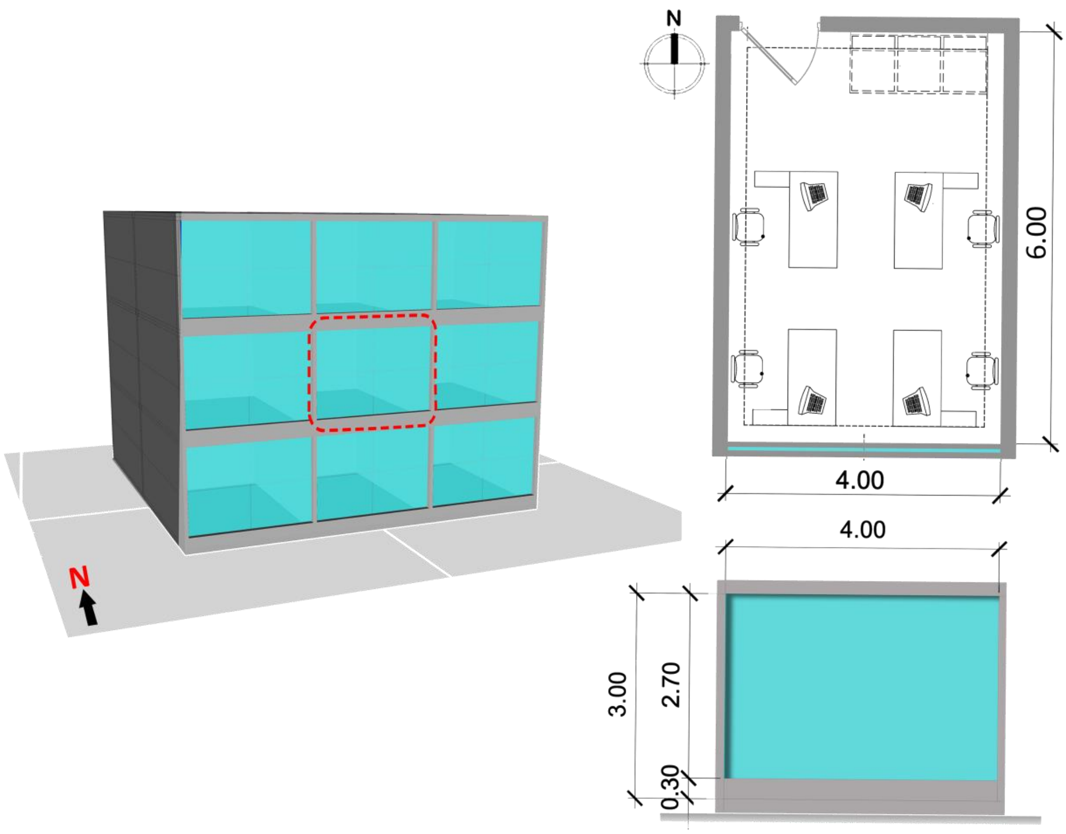


Figure 5.3 Base case 3D model showing its dimensions and location in the building.

The office space is considered to be occupied daily from 8AM to 6PM which is in agreement with the approved daylighting method by Illuminating Engineering Society (IES), IES LM-83-12, which promotes climate based daylighting metrics (IES 2012). During hours of occupation it is assumed that four workspaces shown in Figure 5.3are occupied and that occupants are performing regular office work including working on a computer.

For all the office building floors, recessed fluorescent luminaires were used to represent standard commercial installations lighting power density was set at 11.74 W/m^2 to meet the ASHRAE/IES standard for office buildings.

The thermal properties were assigned according to ASHRAE90.1-2007 which complies with the Egyptian codes while the optical properties and interior surface reflectance are set according to the IES's report number LM-83-12. Optical and thermal properties of all building components as well as the peak occupant and equipment load are listed in Table 5.1.

Table 5.1 Base case's parameters

Office room main parameters	
Location	Cairo, Egypt
Floor level	An intermediate floor
Room dimension & area	4m x 6m = 24 m^2
Orientation	South
WWR	90%
Occupancy Schedules	08:00 – 18:00
Office room usage pattern	
Occupant Load	**0.17** occupant/m2
Heating set point	**22°C**
Cooling set point	**26°C**
Infiltration rate	**0.5 ac/h**
Lighting Type & Load	(Recessed fluorescent luminaires) **11.74 W/m^2**
Equipment Load	**4.0 W/m^2**
Office room thermal properties	
External wall U-Value	**0.26 W/m^2K**
Internal wall /Ceiling / Floor	**Internal heat transfer was ignored (adiabtic)**
Office room optical properties and reflectance	
Walls Reflectance	**50%**
Ceiling Reflectance	**80%**
Floor Reflectance	**20%**
Screen Reflectance	Metal diffuse
Window optical and thermal properties	
Glazing type & Visual Transmittance (VT)	Double pane clear glass **80%**
Window U-Value	**2.61 W/m^2K**
Window Solar Heat Gain Coefficient (SHGC)	**0.60**

5.4. Screen design logic and parameters

The geometry and the shape of the proposed screen is not a focal point of this thesis, as the aim is to find a method for designing and evaluation non-conventional solar screens that could balance daylight and thermal performance with the maximum possible energy savings for office buildings. Rhinoceros and Grasshopper have been chosen as a software platform to generate a parametric diagrid-base screen model and serve as a form generation tool for better understanding of these screen configurations.

The main screen module was generated by a series of commands; rotate, scale, protrusion (extrude) and surfaces' filling where one module is drawn in each cell as following (Figure 5.4.);

1. Construct the base diagrid cells with 45° diagonal angle ……….**(a)**
2. Rotate a copy form each cell around its center by various rotation angles……………………………………………………………....**(b)**
3. Scale the rotated copy from its cell's center with various scale ratios...**(c)**
4. Protrude each point of the scaled copy's four corners perpendicularly on the main cell surface with different extrusion values for each point, forming a new diagrid-base polyline ….……………….………..…**(d)**
5. Finally, the 3D form of the proposed screen module created from the generated surfaces between the main cell (a), the extruded cell (d) and the scaled/rotated cell (c) respectively.

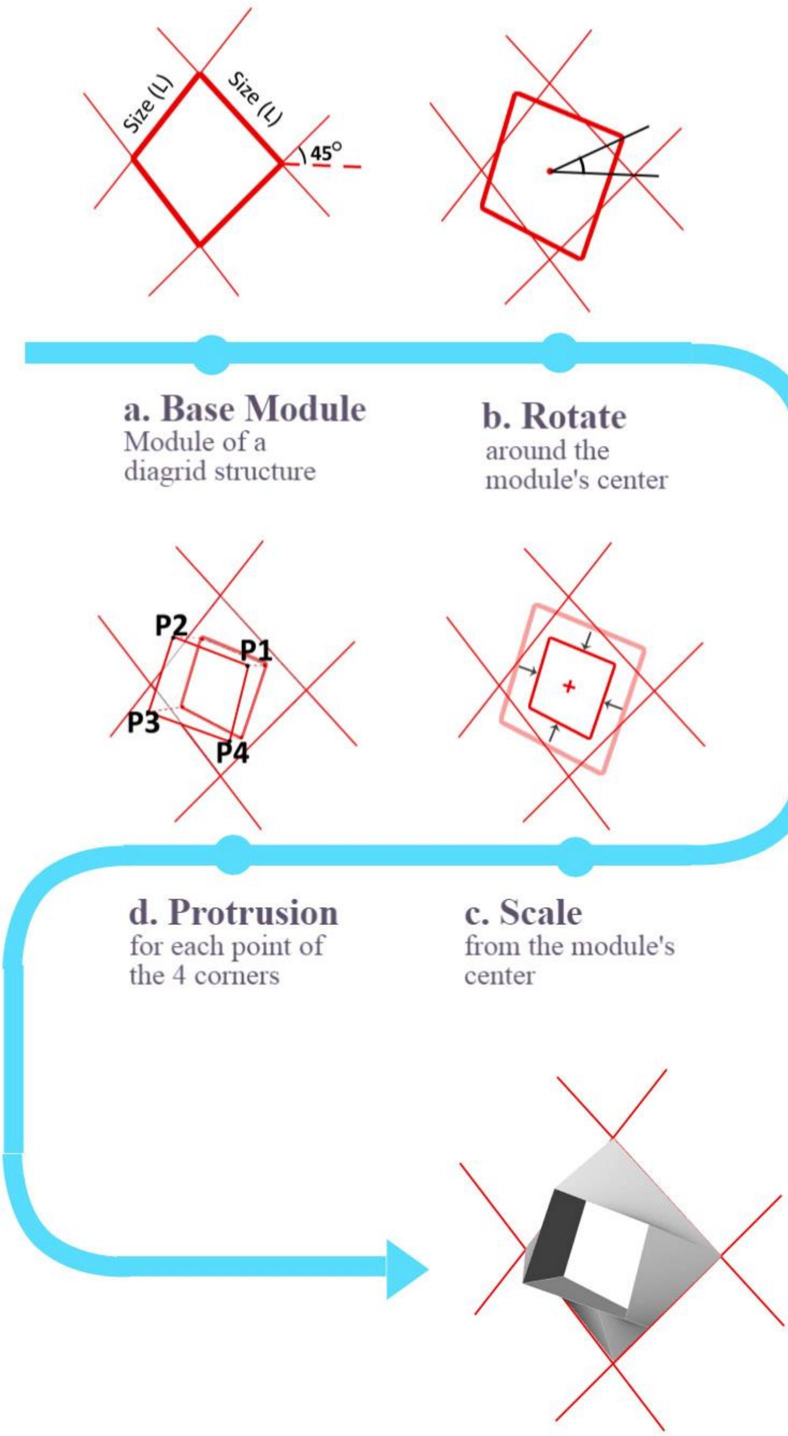


Figure 5.4 Main screen module form generation workflow

Four variables, unit size, angle of rotation, scale ratio and extrude values, were considered the main parameters of the proposed screen design which were controlled with numeric sliders and gene pool components within Grasshopper. These four variables were introduced to generate a wide range of configurations that would be generated and evaluated based on the dynamic 3D model developed in Grasshopper as shown in Appendix D.

Size variations: Three possible sizes of the screen module configurations were introduced starting from 120*120 cm of the main cell that could be divided into 4 cells each of 60*60cm which in turn could be divided into another 4 cells each of 30*30cm as shown in Table 5.2.

Rotation angles variation: Six different rotation angles starting from 0° to 75° with increment of 15° were used as shown in Table 5.2.

Scale variations: Various scale configurations ranging from 20% to 80% of the main cell area with increment of 15% were defined as illustrated in Table 5.2. However, it is important to notice that the scale range of each cell varies depending on its ration angle. As only screen module with 0° rotation angle has the possibility to be scaled from 20% to 80% of its main cell size while any other screen module with larger ration angles could only be scaled by 20% to 65% of its main cell size as shown in Figure 5. 5.

Protrusion values variation: protrusion values were ranging from 5, 15, 30, 45 and 60 cm for each point of the cell's four corners. Different combinations of extrusion values produce a non-conventional solar screen with a higher ability to adapt to the environmental performance as illustrated in Table 5.2.

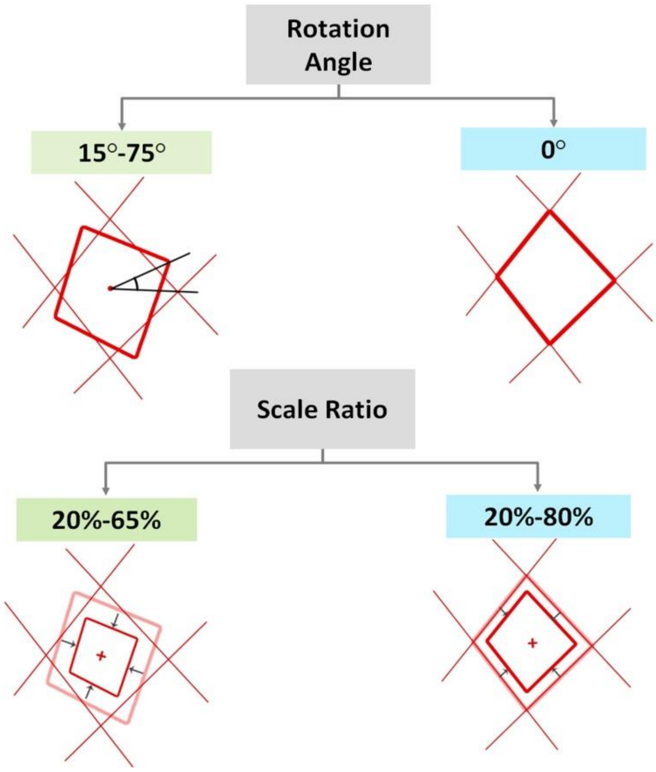
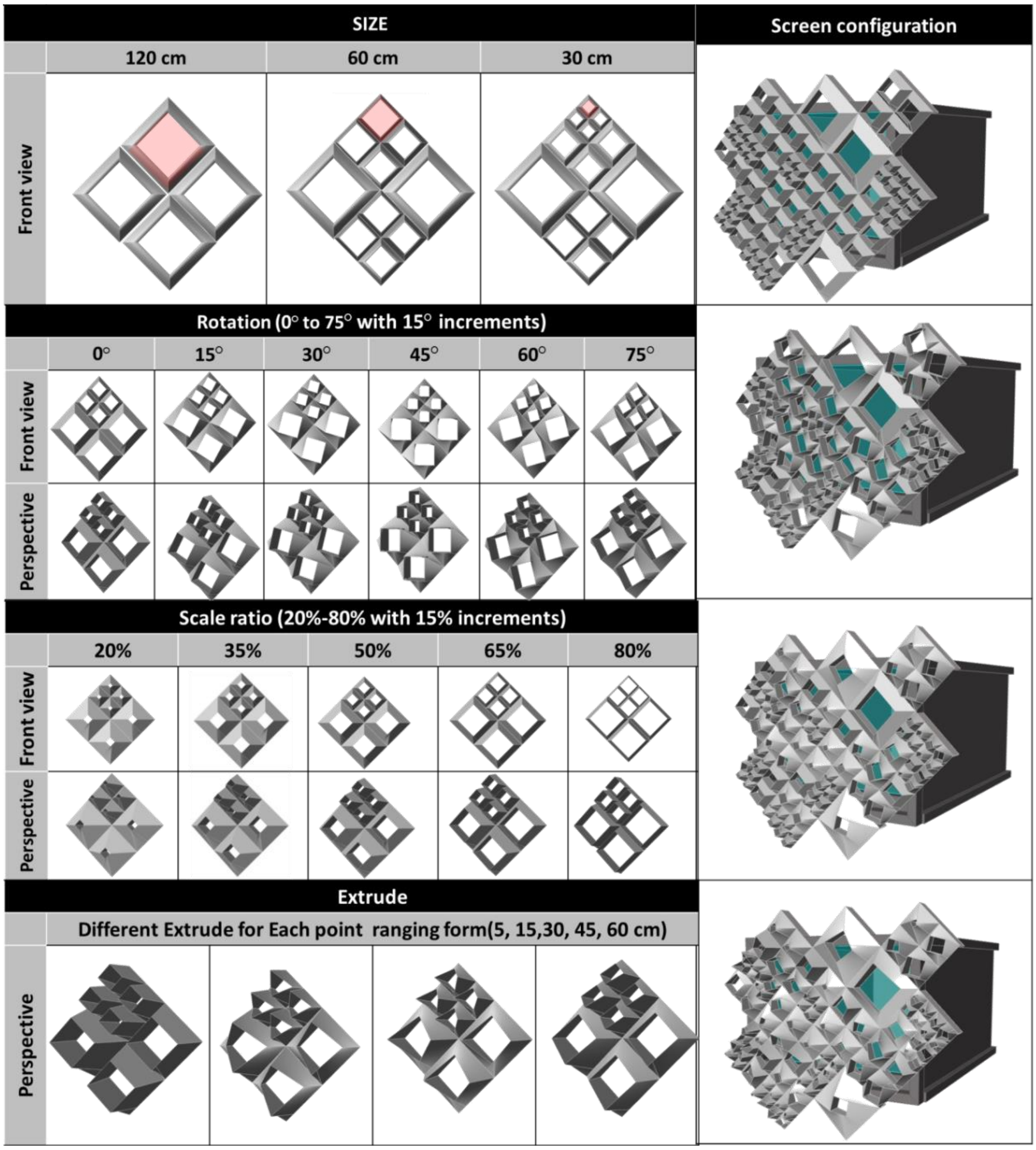


Figure 5. 5 The relation between rotation angles' ranges and scale ratios' ranges

For an accurate result the proposed screen was applied to the whole building. In order to focus on the screen effect on the selected base case, all the modules were fixed and have constant configurations of; 120 cm size, 0 rotation angle , 65% scale and 30 cm for both vertical and horizontal extrude points, except for the screen modules that affect the base case space as shown in Figure 5.6.

Table 5.2 Shows the screen parameters configuration (size, rotation, scale, protrusion)



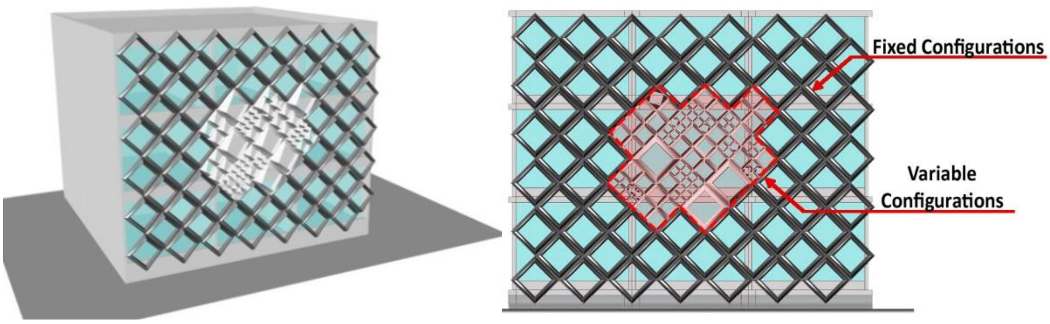


Figure 5.6 The screen modules applied to the whole building and have fixed configurations except for the ones that affect the base case

5.5. Performance Evaluation Criteria and Simulation procedure

In this section both the performance evaluation criteria and simulation procedure and setup process are presented and divided it two main parts. The first part showed the daylighting evaluation criteria in which the simulations will be based on as well as described the daylight simulation procedure. While the second part showed the criteria in which thermal performance analysis will rely on and the specific followed methodology to run a proper thermal simulations.

As previously mentioned, in the section 5.2, Diva-for-Grasshopper is used to interface DAYSIM / Radiance and EnergyPlus engines to measure daylight and thermal performance respectively. DIVA was chosen so that all modelling, daylight and thermal simulations could be carried out within the Rhino and Grasshopper environment without the need to export the model to various simulation tools.

5.5.1. Daylighting Evaluation Criteria

In this study, the daylight simulation results were analyzed based on the Daylight Dynamic Performance Metrics (DDPMs); Daylight availability, spatial daylight autonomy (sDA$_{300/50\%}$) and annual sun exposure (ASE$_{1000/250hr}$) where the last two comply with LEED V4 daylighting requirements and follow precisely the approved method by Illuminating Engineering Society (IES) described in report number LM-83-12. In LEED v4 and IES approved method; sDA$_{300/50\%}$ and ASE$_{1000/250hr}$ form together a clear picture of the daylight performance that can help architects to make good design decisions as discussed before in section 2 and Appendix A. For office spaces (sDA$_{300/50\%}$) must be achieved for at least 55% to achieve 2 LEED credits or 75% to achieve 3 LEED credits while (ASE$_{1000/250hr}$) must be less than 10% for both cases as shown in Table 5.3.

Daylight Availability (DA) was also evaluated as sDA combines both daylit and overlit area together. It has the same minimum threshold of the sDA, but it adds a maximum threshold that is ten times the minimum. DA divides the space into three zones: ‘daylit’, ‘partially daylit’ and ‘over lit’, as mentioned in details in chapter 2. Measuring ‘over lit’ area was critical in this study as it signifies the potential for solar heat gain and also might signify a potential for glare. Conclusion for lighting criteria used in evaluation of simulations results are shown in Table 5.3. For Daylight availability, sDA and ASE metrics Radiance parameters were set as shown in Table 5.4.

Table 5.3 Daylighting evaluation criteria used for simulation results

Lighting Criteria		
Target Illuminance		**300lux**
Spatial Daylight Autonomy (sDA)		**> 75%** – 3 credits on (LEED v4) & (IES) **> 55%** – 2 credits on (LEED v4)
Annual Sunlight Exposure (ASE)		•Must be: < 10 % (LEED v4) & (IES) •Preferred ratio: < 7 % –(IES) •The best case: < 3 % –(IES)
Daylight Availability (DA)	Partially lit	**< 50%** of hours less than 300 lux
	Day lit	**>= 50%** of hours between 300-3000
	Over lit	**< 5%** of hours exceed 3000 lux

Table 5.4 Radiance parameters for sDA, DA and ASE metrics.

Daylight evaluation metric	Ambient bounces	Ambient divisions	Direct threshold
sDA & DA	**6**	**1000**	**0**
ASE	**0**	**1000**	**0**

5.5.2. Daylight simulation procedure

One of the main aims of this study is to investigate the daylighting performance of the proposed screen various configurations. Thus, a full detailed 3D model for the office space and the proposed screen were modelled as shown in Figure 5.7 and have been assigned materials with specific reflectance as mentioned before in Table 5.1.

The reference plane, on which daylighting performance was simulated, located above finish floor at approximately 80 cm high, with 247 measuring points in a grid of 30x30 cm was selected in this study as shown in Figure 5.7. It represents an average of the different possible task heights in the assumed office space and complies with IES's standard that consider 60x60 cm grid as the maximum reference plane grid size.

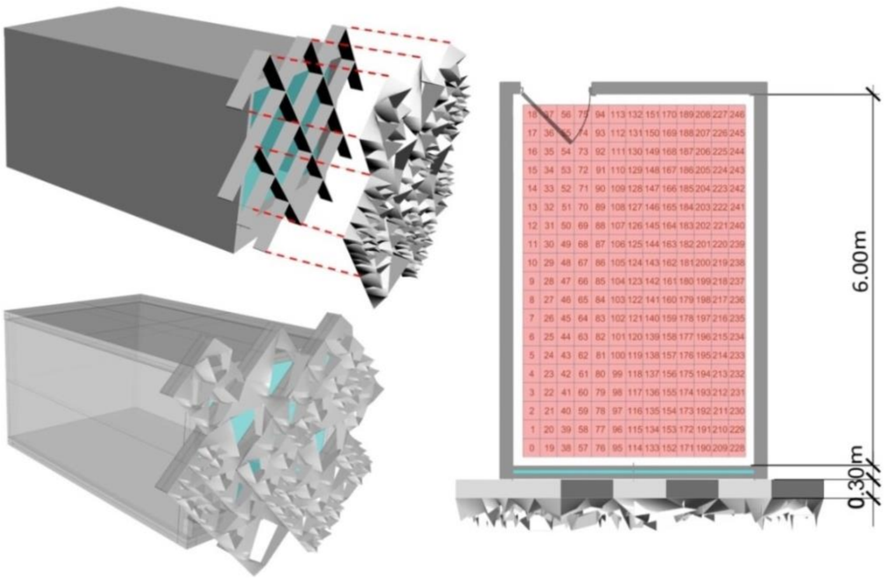


Figure 5.7 Detailed 3D office model for Daylight simulation aligned with the screen and analysis grid of 247 nodes at 80 cm height from floor level.

5.5.3. Thermal and energy evaluation criteria

As concluded form the literature review in chapter 3, there is no specific metric or threshold value to evaluate the thermal and energy performance. Consequently, the evaluation methodology followed in this study relied on a comparison approach between the annual thermal performance and energy consumption results of a specific base case and other tested instances. The thermal performance of each alternative was calculated including the cooling and heating loads as well as the annual energy consumption.

5.5.4. Thermal and Energy simulation procedure

The aim of these thermal simulations was to investigate the thermal performance and energy consumptions of the office space based on the various screen configurations in order to reach the minimum possible energy consumption. In this simulation, Viper-Diva Thermal Analysis for GH was used to conduct the thermal analysis of the Grasshopper model components using EnergyPlus. As thermal simulation tools including Energyplus deal with single surfaces only, a single surface 3D model for the office space and the proposed screen was modelled as shown in Figure 5.8 and connected to Viper to be simulated based on a TMY climate file, the occupancy type, and the thermal properties assigned to the construction elements of the model that have been shown in Table 5.1.

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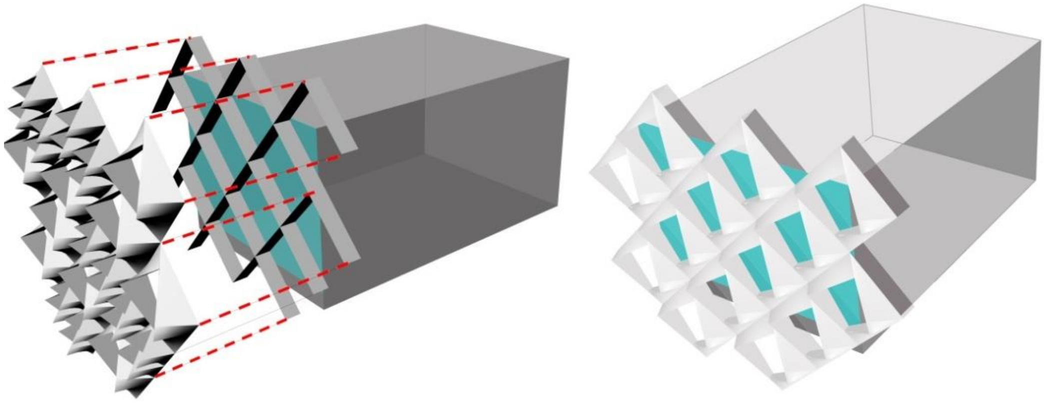


Figure 5.8 Single surface model for the office space for thermal simulation

However, current energy simulation software such as EnergyPlus posed a problem of having limitations in digitally modelling for any complex geometry such as the proposed screen in this study. This limit could be overcome using Grasshopper to model the screen geometry first then link it to Viper-Diva for GH component which interfaces with the EnergyPlus software for performing energy simulations. However, as mentioned before ,thermal simulations tools including EnergyPlus deal with single simple surfaces only for the analysis and can't sufficiently recognize the complex geometry of the proposed screen to study its behavior and effect on the thermal performance. Thus, directly linking the screen complex surface geometry is still infeasible using the current energy simulation tools.

In order to overcome this limitation and study the effect of the screen on the thermal and energy performance of the space, specific performance criteria of the screen had to be measured based on the output of DAYSIM/ RADIANCE simulation results, which makes the energy calculation more accurate and sensitive for daylight results. These criteria include the screen's shading coefficient and an annual electric lighting schedule based on sDA & DA results. The data were then synchronized with a thermal analysis performance using Viper-Diva Thermal Analysis for GH. The Energy simulation definition in Grasshopper is shown in Figure 5.8.

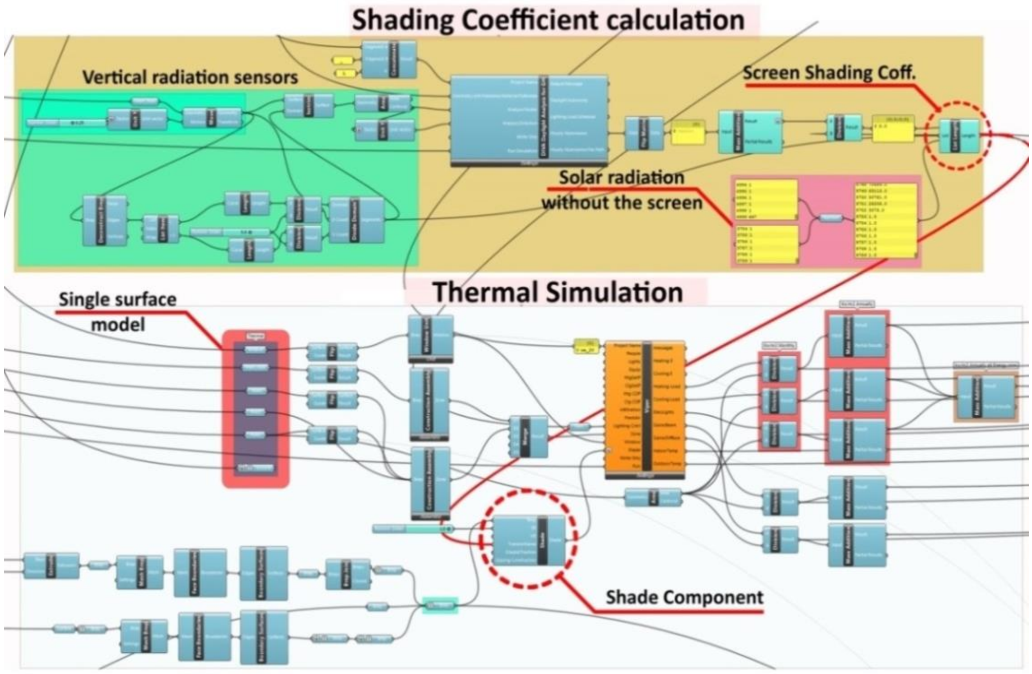


Figure 5.9 The Energy simulation definition in Grasshopper
Source: by the researcher

The calculation of the screen shading coefficient was based on the methodology presented in (David, Donn et al. 2011, Omidfar 2011, Omidfar, Torghabehi et al. 2014) as discussed in the literature review in chapter 3 and chapter 4. Thus, a grid of solar radiation sensors was placed vertically in the outside directly behind the screen so as to calculate the shading coefficient of each screen configuration to be connected to Viper for thermal analysis later, as shown in Figure 5.10. The shading coefficient was calculated through DIVA Daylight Analysis for GH by measuring the radiation penetration through the screen modules on the vertical test surface with and without the screen for every hour over the year (8760 hrs). The ratio of both values resulted in an hourly shading coefficient of the screen that was then connected to the transmittance schedule of the Shade component to be connected to Viper.

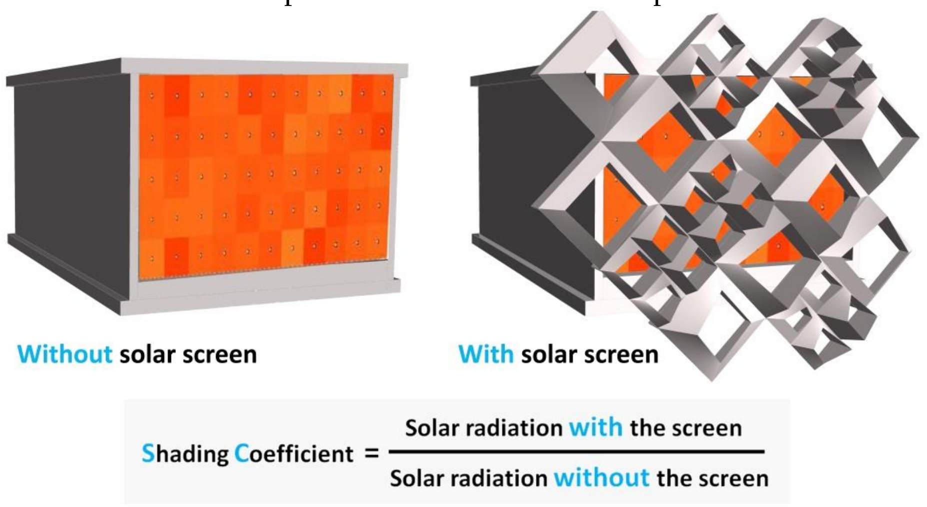


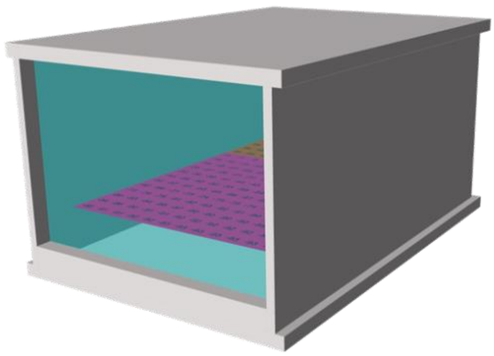
Figure 5.10 Sensor nodes on the exterior vertical surfaces to measure screen's shading coefficient.

5.6. Base case simulation results

A base case of the hypothetical office space with 90% WWR glazing area and without the screen was simulated for its daylight and thermal performance. The simulation results for daylight and thermal performance is shown in Figure 5.11. For daylighting performance, the base case showed 100% of sDA and 0% partially lit area, but the over-lit area reached 67% and ASE reached 40%, which exceeds the acceptable range in LEED and IES. For the thermal simulation, the extra amount of daylighting resulted in low electric lights loads by reaching 1.39 kWh/m^2 but on the other hand it allowed for extra amount of solar heat gains inside the space that raised the cooling loads to be 285.56 kWh/m^2 while the heating loads was only 9 kWh/m^2 due to the dominant heat arid weather of Cairo and thus raised the total energy consumption consequently to reach 295.95 kWh/m^2.

It is clearly obvious that a window without any improvements specially when accompanied by large WWRs can barely achieve an adequate amount of daylighting as it will achieve an extra amount of daylighting and thus extra solar heat gain and thermal loads.

Daylight Availability			sDA	ASE
PARTIALY DAYLIT	DAYLIT	OVERLIT		
0	33	67	100	40



Elect Kwh/m2	Cooling Kwh/m2	Heating Kwh/m2	Energy Kwh/m2
1.39	285.56	9	295.95

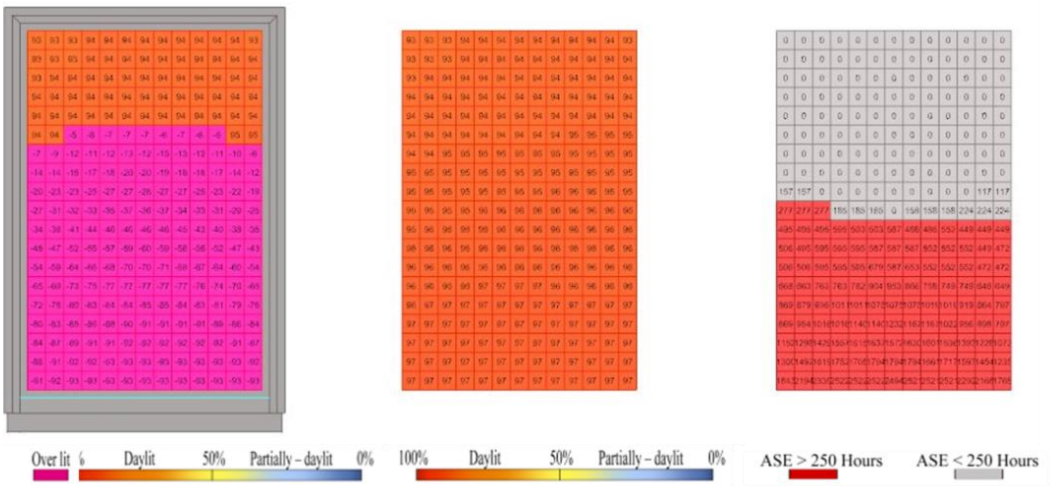


Figure 5.11 Base case simulation results

5.7. Genetic Algorithms optimization approach

This section focused on the use of evolutionary algorithm (EA) approach to determine the "near optimum" screen configurations that could achieve the balance between indoor daylight adequacy and thermal performance within the minimum possible energy performance.

As mentioned in the literature review in chapter 4, Genetic algorithms (GAs), the most popular type of EA were shown to be an effective optimization approach in exploring new solutions that matches desired performance goals. Thus in this section, Galapagos Evolutionary Solver, GAs component contained within Grasshopper (Rutten 2010)had been used to find the optimal solutions by optimizing multiple parameters of the proposed screen.

The process of the GAs optimization implemented here is shown in Figure 5.12. It is based on cyclic search techniques which start with changing the screen parameters to generate large sets of screen configurations (populations). Results will be evaluated based on their daylight and thermal performance using a specific fitness function. Then the basic genetic operators (re-combination, mutation and selection) were applied to that initial population, according to the fitness values of each solution. This process should then generate new screen configurations with higher average performance than the previous one. This process should stops when a satisfactory performance has been reached for the tested screen design.

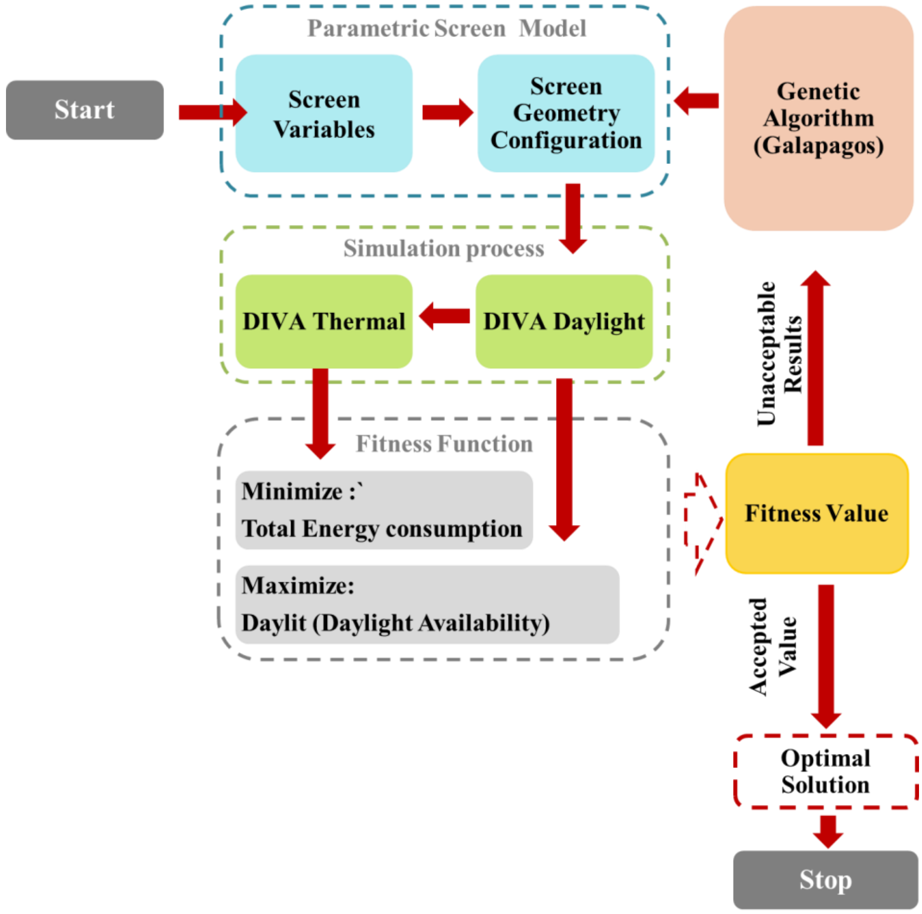


Figure 5.12 The implemented workflow for GAs optimization process

5.7.1. Fitness Function (FF)

In this study the main aim was to reach the balance between indoor daylight and thermal performance within minimum energy consumption. In order to attain this aim, the fitness function of the GAs process was to be set as following;

- **Maximize** Daylit value of the Daylight Availability (DA)
- **Minimize** the total Energy Consumption

However, Galapagos is considered as a Single-Objective Optimization tool that aims to find the "best" solution, which corresponds to the minimum or maximum value of a single objective function as shown before in *section 4.6.3.1*. Hence, the fitness function here has to combine the different two objectives into one maximize-targeted function. Moreover, to guide the genomes efficiently to the optimal results, the difference between the resulted fitness values need to be identified obviously. Thus, the main equation here was multiplied by 100 and then setting to the power 3 so as to enlarge the difference between the results. Consequently, the following equation (Eq. 5.1) was proposed by the researcher and embedded within the algorithm. The Galapagos component connected to the screen parameters (Genome) and the suggested fitness function are shown in Figure 5.12.

$$FF = \left[\left(\left(1 - \frac{\text{Energy consumption}}{\text{Base case Energy consumption}}\right) + \frac{\text{Daylit}}{100}\right) \times 100\right]^3$$

Eq. 5.1

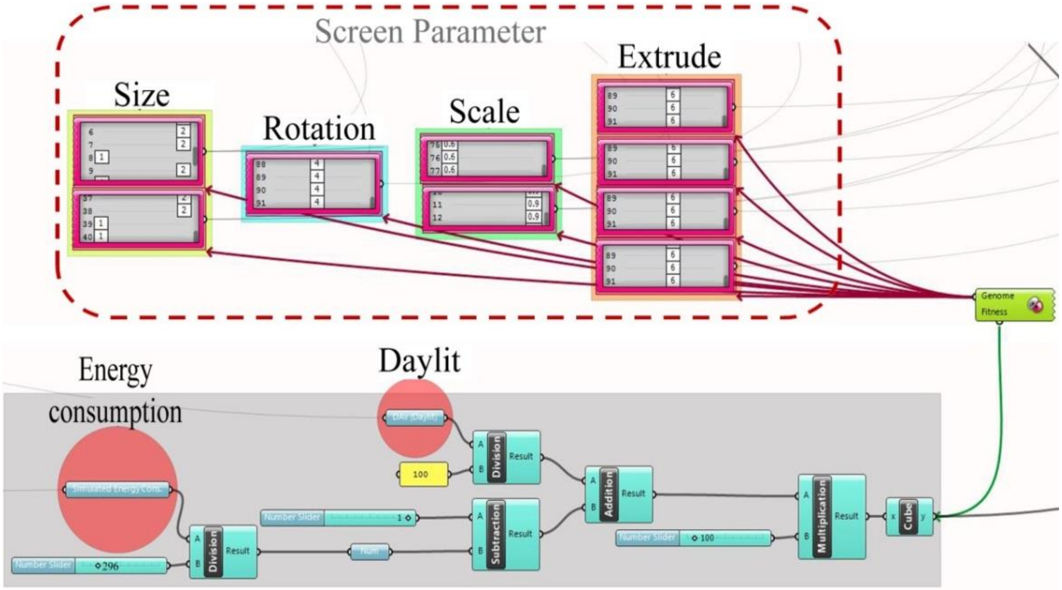


Figure 5.13 Galapagos component within Grasshopper connected to the screen parameters and the fitness function.
Source: by the researcher

5.7.2. Optimization Parameters

The main four screen parameters values that were used for this optimization process are shown in Table 5.5. Each screen's module could have different variables values than the others have resulting in enormous number of solutions, more than million solutions.

Table 5.5 The screen parameters and stepping values used for GAs optimization

Parameters		Values
Size (cm)		120, 60, 30
Rotation Angle (°)		0° to 75° with 15° increments
Scale ratio (%)	For 0°	20% to 80% with 15% increments
	For 15° to 75°	20% to 65% with 15% increments
Protrusion value (cm) (for each point)		5, 15, 30 , 45, 60

5.7.3. Results of GAs optimization

The optimization process was finished after 385 simulation iteration and 17 generations, by which the process took about 9 days to be completed on a desktop with core i7 processor. The graphs below (Figure 5.14) and (Figure 5.15) illustrate the daylighting and the thermal performance results for all the iteration of the GAs optimization process respectively. While samples of the optimum solutions are shown in Figure 5.16.

The daylighting performance was enhanced slightly by the GAs process till the 230 iteration as 11 accepted solutions were achieved that could hardly achieve 2 LEED credits with only one solution that achieved 3 LEED credits. However starting from the 231 iteration till the end of the optimization process, the daylight simulation results were getting worse as sDA and daylit areas decreased while partially daylit increased as shown in the graphs illustrated in Figure 5.14. This indicated to the popular problem of GAs optimization that had been discussed before in chapter 4, that the solution converged towards local optima and got stuck in it preventing any improvements and consequently being unable to find the real maximum.

On the other hand, thermal performance and energy loads were needed to be minimized to balance between daylighting performance and energy efficiency. The total annual energy consumption values for each solution were calculated and the values were expressed in kWh/m^2 for the cooling, heating and artificial lighting. The graph bellow shown in Figure 5.15 show that daylighting performance has a crucial effect on the total energy consumption as it proves that the total energy consumption decreases as it achieved better daylighting adequacy. Regarding heating loads, they were almost constant as they ranged from 8.78kWh/m^2 to 9 kWh/m^2 through the optimization process. In contrast, cooling loads were the most influential in such desert climate. It dropped from around 170 kWh/m^2 in the first generation to less than 140 kWh/m^2 for the optimal cases and to around 155 kWh/m^2 in the last generations.

Besides, the impact of electric loads specially the cases with high partially daylit were considerable as the lighting energy increased form around 6 kWh/m^2 in the optimal cases to more than 20 kWh/m^2 in the last generations. However, the lighting loads values were almost constant form the first simulation till the 160 simulation with very small spikes in between. Since the increase in lighting loads neutralized the decrease in the cooling loads, it caused an increase in total energy consumption.

In General, GAs optimization process didn't seem to be effective in this case; as it firstly took too much time to get an accepted solution that comply with the target performance. Secondly, only one solution achieved 3 LEED credits, sDA >75% & ASE< 10%, where all the other solutions could only obtain 2 LEED credits, sDA >55% & ASE < 10%. Thirdly, it was noticed that only the first four iterations had combinations of different unit sizes in their screen configuration, otherwise starting from the fifth iteration all the screen unit sizes had been fixed to the largest size of 120 cm as shown in Figure 5.16.

Moreover, the effect of the variations in screen parameters on daylighting and thermal performance couldn't be investigated as GAs optimization process doesn't provide an informative back-tracing exploration of design solutions so as to modify the process for better results.

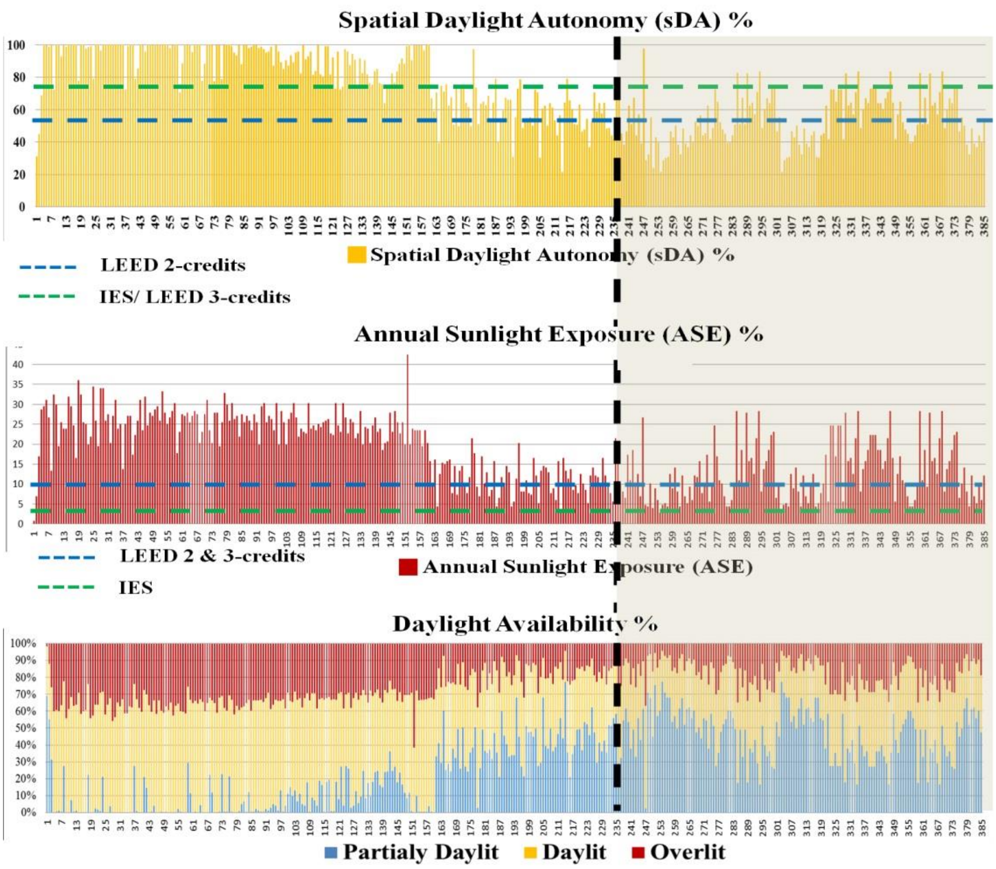


Figure 5.14 Daylight Availability, DA and ASE and performance through each Iteration of the GAs optimization process.

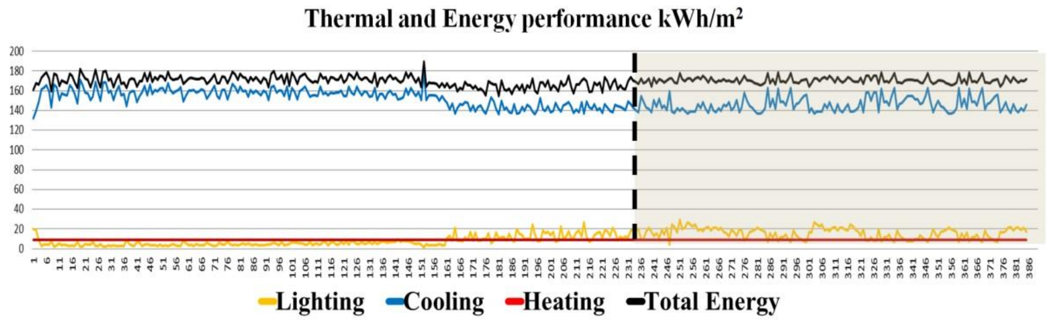


Figure 5.15 Annul energy consumption through each iteration of the GAs optimization process

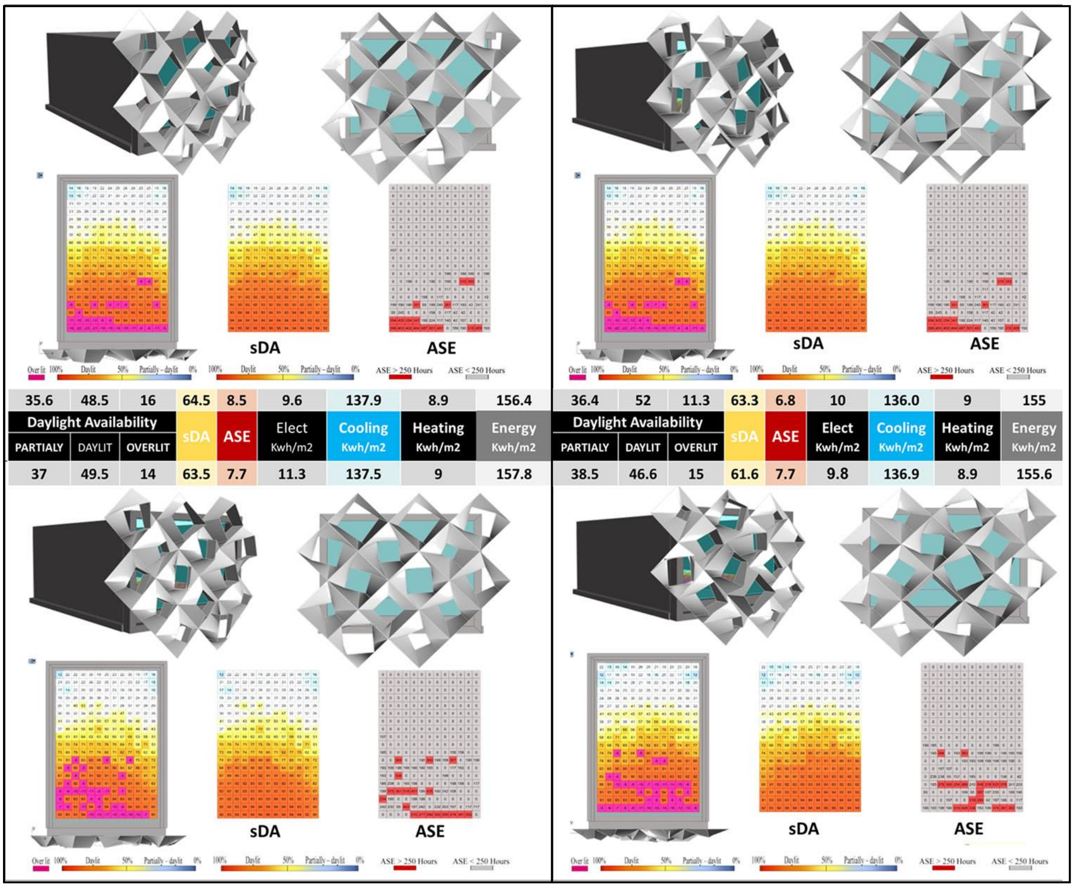


Figure 5.16 Daylight and thermal performance for the best four cases of GAs optimization process

5.8. Parametric simulation

In this section a parametric study was utilized to explicitly explore the influence trend of the interacting screen parameters on daylighting, thermal and energy performance and to recognize the potential of using parametric simulation for designing an ecological non-conventional screens.

5.8.1. Daylight algorithm for parallel simulations

The parametric algorithm was developed to follow specific procedures as shown in Figure 5.19. First, the screen parameters were set to have the same ranges and stepping values as the previous GAs process had shown earlier in Table 5.5. However, in order to reduce the number of the tested solutions to be applicable for the parametric analysis, all the screen modules were set to take the same values as shown in Figure 5.17. The other modification was that the protrusion points were simplified into two sets, horizontal two points and vertical two points, where each set would take the same extrude value as illustrated in Figure 5. 18. Then, all these ranges were converted into two lists that contain all states of each parameter. The first list contains 1500 alternatives with rotation angles ranging from (15° to 75°) and thus scale ratio ranging from (20% to 65%) as described above in section 5.4 and the second list with 375 alternatives of rotation angles 0° with scale ratio from (20% to 80%) resulting in 1875 different screen configurations as a total. After that, all possible combinations of the screen parameters were computed and sorted in groups based on a cross reference algorithm inside Grasshopper as shown in Figure 5.19.

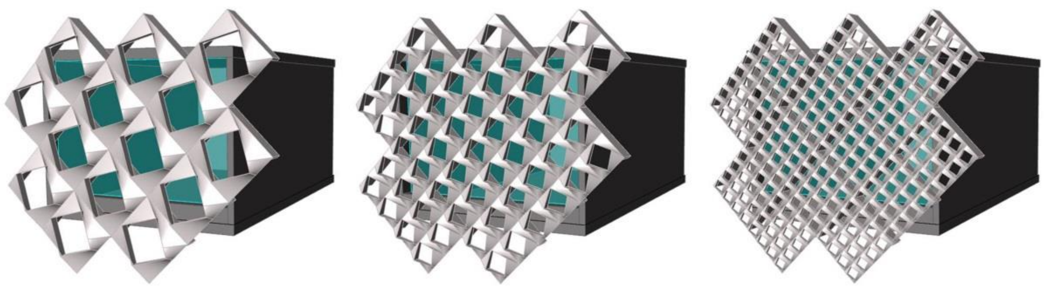


Figure 5.17 Examples of the alternatives used for the parametric simulations showing that for each solution, all screen modules had the same values

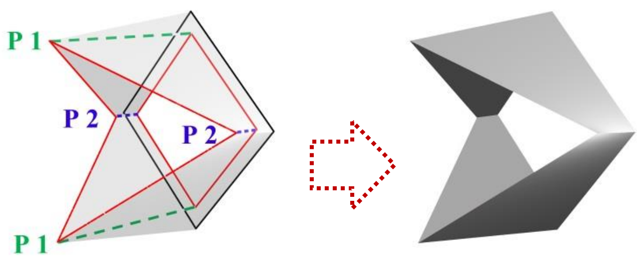


Figure 5. 18 Protrusion points grouped into 2 vertical points and 2 horizontal points each with the different value for the parametric simulations

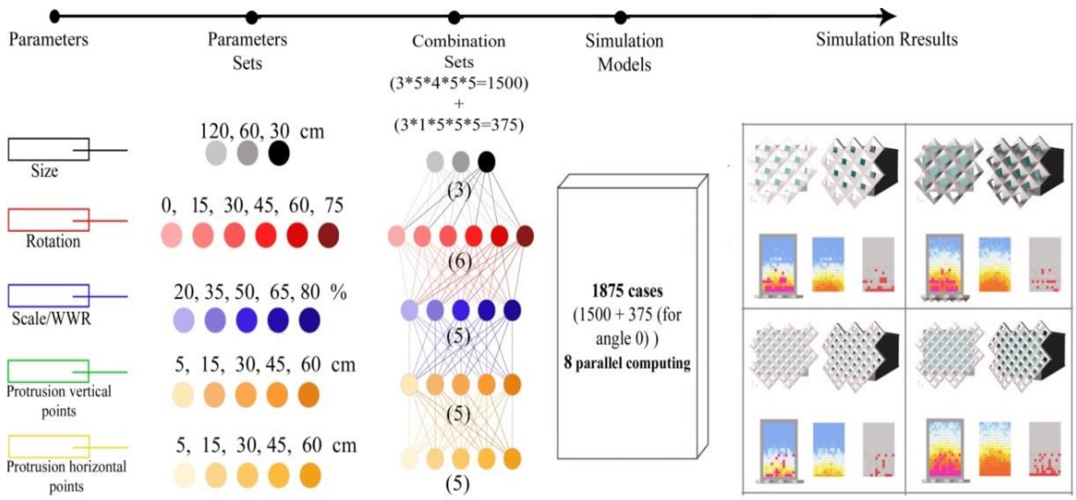


Figure 5.19 Parametric algorithms for computing all possible combinations

Source: by the researcher based on (Wagdy and Fathy 2015)

Although this method was usually avoided due to its running time, this problem was overcome by using parallel daylight simulations. The parallel algorithm was specifically designed for this type of research, where hundreds or thousands of simulation runs are needed to obtain precise evaluation of each parameter. Thus, the workflow is made to fully utilize the maximum count of available CPU cores. Based on that, the 1875 solutions were divided into 8 sub-lists each having about 235 solutions based on the available CPU cores of the used computer, which were 8 in this case. After that, parallel daylighting simulations using Diva Daylight Analysis for GH were automated to speed up the overall simulation by 8 times faster than the default runs resulting in a significant time savings by total duration of less than 5 days for all the 1875 cases instead of 40 days if using the default simulation runs. Finally, the simulation results were collected in MS Excel for analyzing and then were presented in different forms.

The only reaming problem was that this parallel simulation couldn't be applied for thermal simulations as EnergyPlus could only be runs for one case at a time unlike Radiance/DAYSIM for daylight simulations that has the ability to calculate the daylight performance for more than one cases at the same time. However, to overcome this limitation an original algorithm was specially developed for this study to achieve the maximum benefit of the parallel simulations potentials for both daylight and thermal parametric simulations. Following section will describe this algorithm in details.

5.8.2. Thermal and energy algorithm for parallel simulations

As previously mentioned, in *thermal simulation procedure section 5.5.4*, to ensure accurate thermal calculation and make it more sensitive for daylight results, specific performance criteria based on daylight simulations have to be measured firstly. These criteria include the screen's shading coefficient and annually electric lighting schedule.

Thus, the methodology implemented here developed a special algorithm inside Grasshopper that recall the annual electric lighting schedule file (***intgain.csv)** that had been generated and stored for each case during the parallel daylight simulations process to be connected to Viper component for thermal analysis. The Grasshopper definition of this algorithm can be divided into 4 main steps as following (Figure 5.20):

1. Connecting the slider of alternatives numbers from the parallel daylight simulation process to the algorithm.
2. Developing a series of commands that generate the text of the lighting control schedule **(***intgain.csv**)** file destination name using "Concatenate text" component.
3. Connecting the resulted file name to "File path" component.
4. Connecting the file path to the lighting control input of the Viper thermal component.

Then these 4 steps are automated within grasshopper to calculate all the 1875 cases thermal and energy results to be exported to MS Excel.

Thus, the methodology implemented here had the ability to automate thermal simulation runs for all the 1875 possible alternatives case-by-case after the completion of the parallel daylight simulation runs.

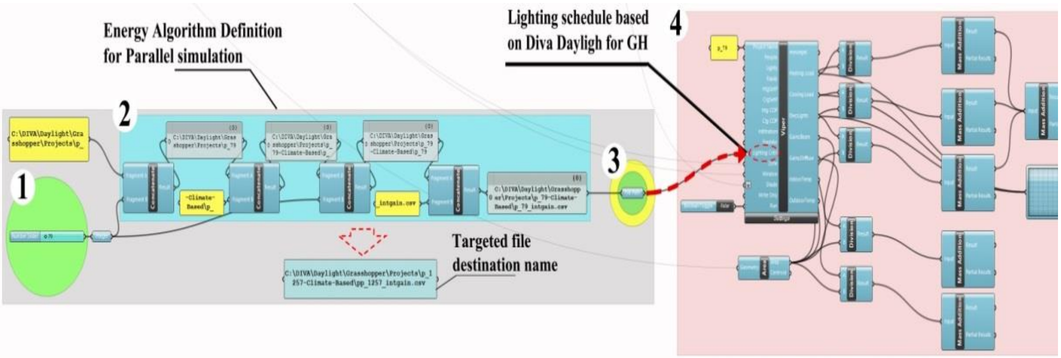


Figure 5.20 The Grasshopper definition of the thermal algorithm for parallel situations
Source: by the researcher

5.8.3. Results and discussion of parametric simulation runs

The simulation results were analyzed systematically in terms of four screen parameters; size, angles of rotation, scale or (WWR) and protrusion values, for both vertical and horizontal points. Basically, studying each parameter on its own, while fixing the others, doesn't give an accurate image about the overall performance. Apart from changing one variable at a time, the interactions of all screen variables were explored using an exhaustive search method. Thus, the general tendency of each parameter and the impact of the interaction between them on the overall daylighting, thermal and energy performance were explored giving more than one evaluation for each parameter effect.

First, the daylighting parallel parametric simulation results were analyzed in detail, showing the interaction of all parameters together. Second, the thermal and energy simulation results were analyzed showing the correlation between daylight and thermal loads especially the cooling ones. Consequently, the overall picture of the performance trend was represented in many forms. This information will help in understanding the general tendency of each of the screen configurations and the parameters' impact on the overall performance. In addition, it will help architects in improving the efficiency of the screens for similar case studies.

5.8.3.1. Results of Daylighting simulation analysis

Results of the sDA & ASE of the 1875 alternatives formed by all possible combinations of size, angles of rotation, scale or (WWR) and extrude (vertical and horizontal points) were analyzed.

Firstly, the effect of different angles of rotation on the screen performance was investigated by comparing the minimum (0°), (30°) and the maximum (75°) angles of rotation for each size separately. According to the line graphs for size (120 cm) illustrated in Table 5.6, almost no noticeable difference in sDA and ASE can be detected due to different angles of rotation as shown, for example, by comparing cell (d), cell (e) and cell (f) in Table 5.6. The same conclusion could be detected for the other two sizes, 60 cm and 30 cm, as shown in Table 5.7 and Table 5.8 respectively. However for both size 60 cm and 30 cm, 0° angle of rotation showed better performance for both sDA & ASE. These were especially the cases at 80% scale ratio aligned with 0° angle of rotation, as illustrated in cell (m) in Table 5.7 and Table 5.8 respectively.

Overall, angle of rotation did not have a relevant effect on the screen daylight performance. Thus, it can be argued that angle of rotation could have been fixed at any degree as it seemed to have no relevant effect when combined with other parameters. However, the use of 0° rotation angle is recommended, as it gave better performance for both sDA & ASE due to its ability to have larger scale ratios than other angles of rotation could have. In Table 5.6, Table 5.7 and Table 5.8 solutions that could obtain 2 credits in LEED V4 were denoted by solid circles while solutions that could obtain 3 credits in LEED V4 were denoted by solid squares where they can be found in: 1) Size 120 cm with 65% WWR. 2) Size 60 cm with 65% and 80% WWR. 3) Size 30 cm with 80% WWR.

Secondly, in order to analysis the other four parameters effect on the screen daylight performance, more illustrations had been described by the figures shown in **Table 5.**9 where 375 cases of the cases with 0° rotation angle were presented, differently emphasizing the interaction effect of the other four parameters.

The effect of screen module sizes was investigated by comparing the results of three proposed sizes; 120, 60, 30 cm. According to the line graphs, illustrated in **Table 5.**9, differences in sDA can be obviously detected starting from 50% to 80% scale ratios. For example, at 50% WWR with vertical and horizontal points have protrusion value of 15 cm sDA decreased from 57% to 40% then to 18% by decreasing the screen module size from 120 cm to 60 cm and then to 30 cm respectively as shown by comparing cell (j), cell (h) and cell (i) in **Table 5.**9. On the other hand, this effect was unnoticed at small scale ratios specifically with 20% and 35%, as a result of nominal sun penetration at small scale ratios. For the 20% scale ratio cases sDA showed a plateau of 0% for all screen sizes as shown in cell (a), cell (b) and cell (c) in **Table 5.**9. Similarly, was the case at 35% scale ratio with large extrusion values (starting from 45 cm) where the effect of the screen module sizes can barely be seen as shown by comparing cell (d), cell (e) and cell (f) in **Table 5.**9. The opposite case was noticed at large scale ratios, as sDA started to reach a plateau of 100% for all screen sizes. This was especially the case at 80% scale ratio with extrusion values from 5 cm to 30 cm, as a result of excessive sun penetration at small extrusion values as shown in cell (m), cell (n) and cell (o) in **Table 5.**9.

Moreover, a sloped fall in sDA was noticed as screen module sizes decreased, yet the effect became sharper with large extrusion values. For screen size 120 cm, no difference in sDA values were detected for the cases with vertical extrude of 45 cm as shown in cell (m) in **Table 5.**9. While screen with 60 cm and 30 cm sizes for the same cases of vertical extrude 45 cm, experienced a significant decrease in sDA by 20% and 55% respectively as illustrated in cell (n) and cell (o) in **Table 5.**9 respectively.

Similarly, the screen module sizes parameter had a major impact on the performance of Annual Sunlight Exposure (ASE) metric. According to the line graphs, illustrated in **Table 5.**9, differences in ASE can be detected obviously starting from 50% scale ratio. For example, at 65% scale ratio with 15 cm extrusion values for both horizontal and vertical points ASE decreased from 30% to 8% and then to 2% by decreasing the module sizes from 120 cm to 60cm and 30 cm respectively as shown by comparing cell (j), cell (k) and cell (l) in **Table 5.**9.

Adding the contribution of extrusion values, differences in ASE values are distinctly influenced by different extrusion values for each size separately. Starting by the 30 cm screen module size, shown in cell (i), cell (l) and cell (o) in **Table 5.**9, the lowest ASE values can be attained starting from 30 cm to 60 cm vertical extrusions, even with small horizontal extrusion values. However, the cases with lower vertical extrusions, 5cm and 15 cm, also attained lower ASE values but when combined with large horizontal extrusion values starting from 30 cm. Similar effect was noticed for 60 cm screen module sizes where the lowest ASE value can also be attained but in this case starting from 45 cm to 60 cm vertical extrusions with almost all horizontal extrusion values size as shown in cell (h), cell (k) and cell (n) in **Table 5.**9. On the other hand, the lowest ASE values could also be reached for smaller vertical extrusions but only when combined with larger horizontal extrusion value. For example, vertical protrusion values of 5cm, 15cm and 30cm reached the lowest ASE values when combined with 45cm, 30cm and 15 cm horizontal extrusion values respectively as illustrated in cell (k) in **Table 5.**9. Finally, the cases with 120 cm screen module size barely reached the lowest ASE .Those were specifically the cases with large extrusion values for both horizontal and vertical points combined with small scale ratios as shown in cell (g), cell (h) and cell (i) in **Table 5.**9.

In short, the integrated effect of screen module size and extrusion values had a remarkable outcome in converging solutions at large scale ratios (65% and 80%) where the accepted daylighting performance can be reached. In **Table 5.**9, accepted solutions with comply with LEED v4 2-credits criteria (55 % sDA and 10%ASE) were denoted by solid circles where they can be found in cases with 65% scale ratios as shown in cell (k) in **Table 5.**9. While optimum solutions that comply with LEED v4 3-credits criteria (75 % sDA and 10%ASE) were denoted by solid squares where they can be found in cases with 80% scale ratios for both 60cm and 30cm screen module size as illustrated in cell (n) and cell (o) in **Table 5.**9.

Table 5.6 Comparing rotation angles, scale ratios and protrusion values (vertical & horizontal) for units size = 120cm

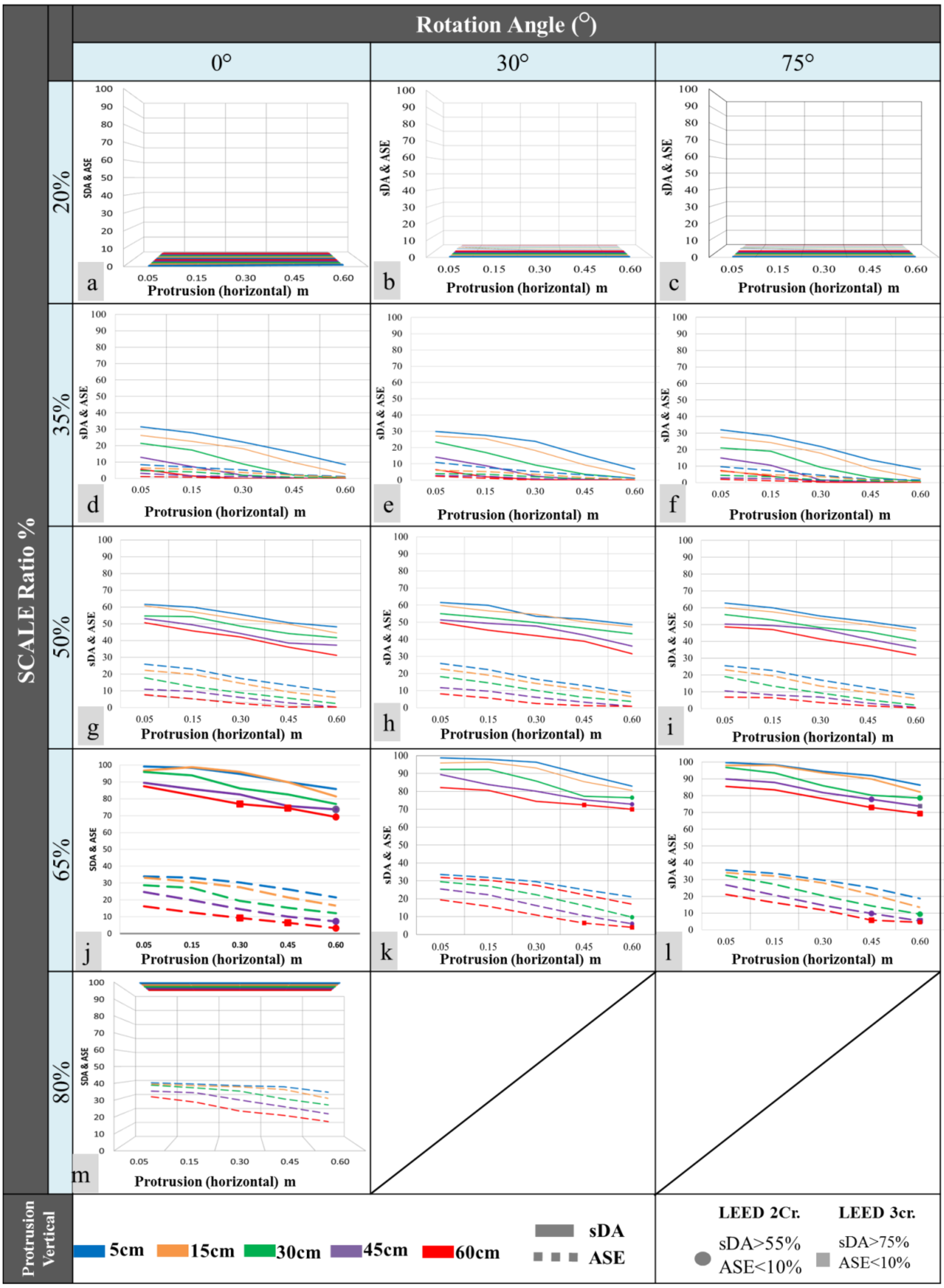


Table 5.7 Comparing rotation angles, scale ratios and protrusion values (vertical & horizontal) for units size = 60cm

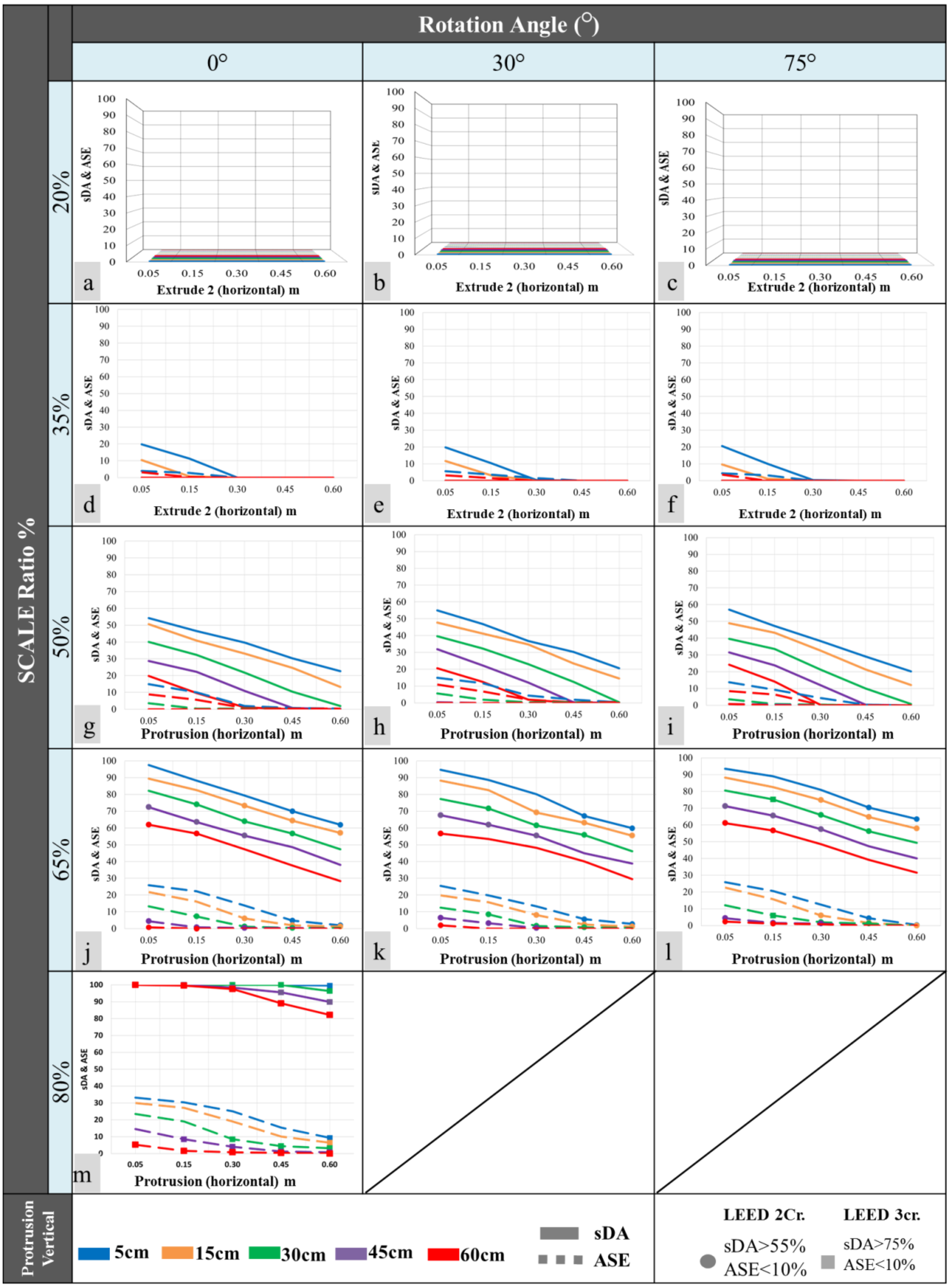


Table 5.8 Comparing rotation angles, scale ratios and protrusion values (vertical & horizontal) for units size = 30cm

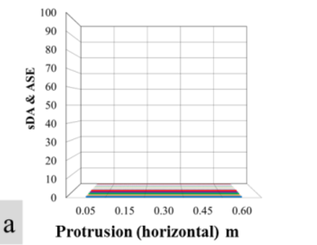
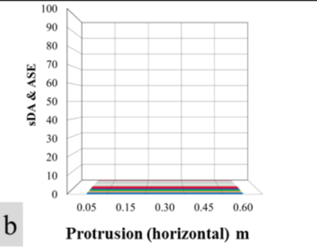
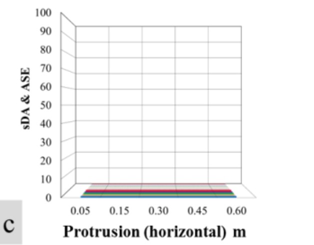
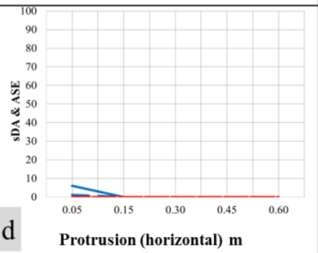
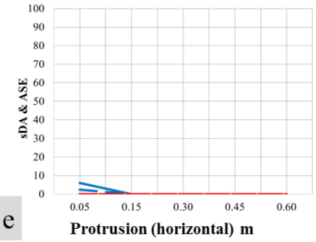
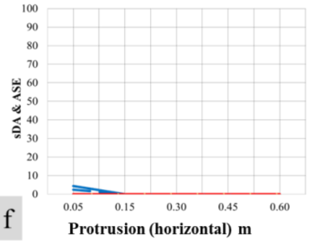
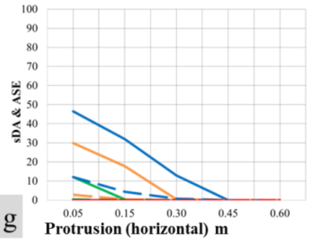
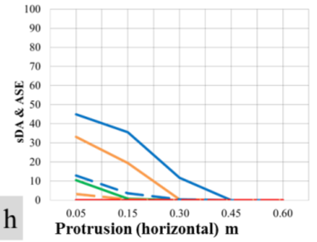
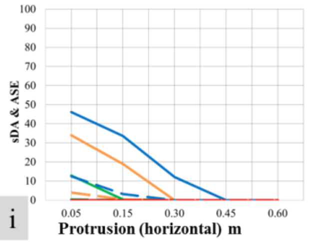
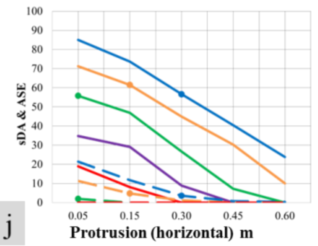
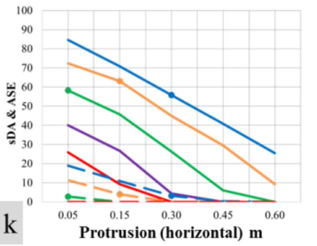
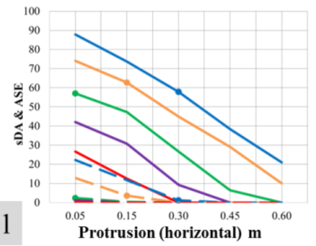
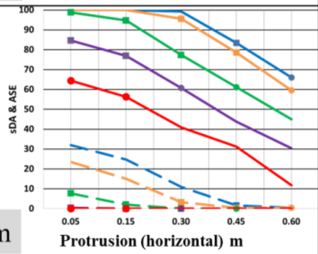
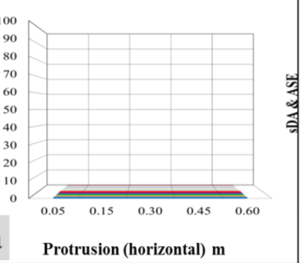
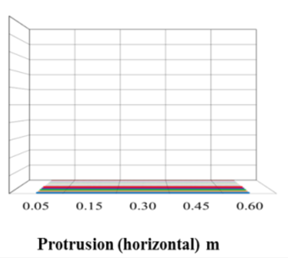
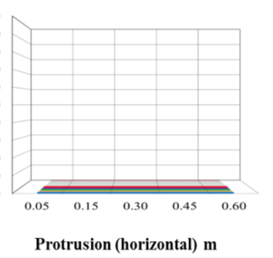
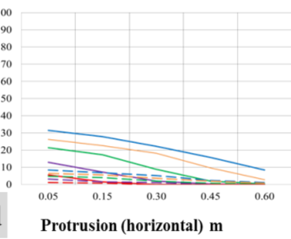
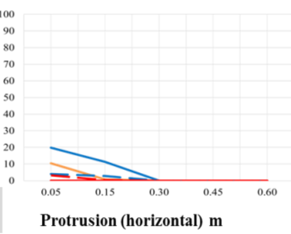
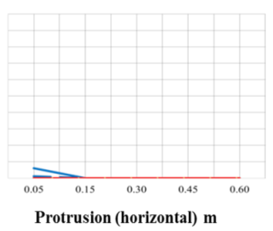
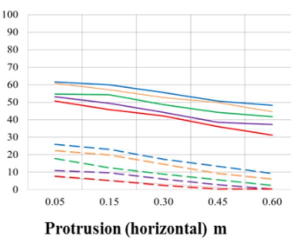
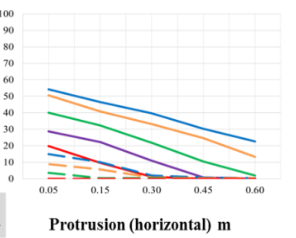
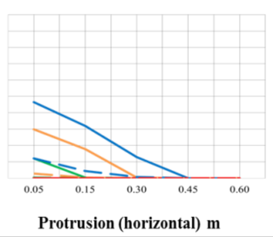
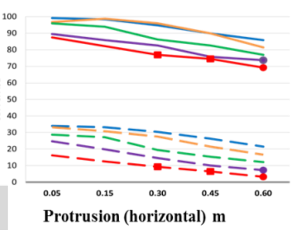
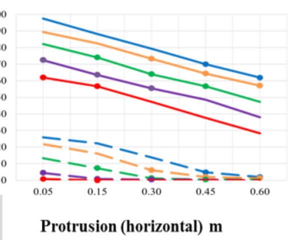
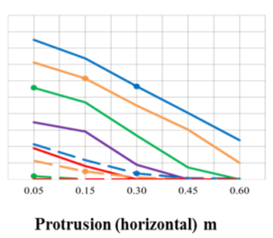
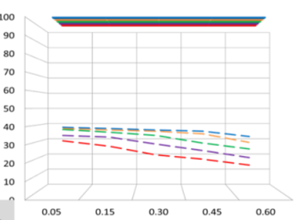
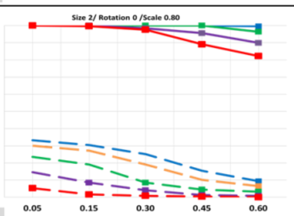
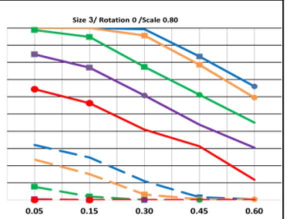
SCALE Ratio %	Rotation Angle (°)		
	0°	30°	75°
20%	a 	b 	c 
35%	d 	e 	f 
50%	g 	h 	i 
65%	j 	k 	l 
80%	m 		
Protrusion Vertical	5cm 15cm 30cm 45cm 60cm	sDA ASE	LEED 2Cr.: sDA>55% ASE<10% LEED 3cr.: sDA>75% ASE<10%

Table 5.9 Comparing units' sizes, scale ratios and protrusion values (vertical & horizontal) for rotation angle = 0

SCALE Ratio %		Units' Size cm		
		120 cm	60 cm	30 cm
	20%	a 	b 	c 
	35%	d 	e 	f 
	50%	g 	h 	i 
	65%	j 	k 	l 
	80%	m 	n 	o 
Protrusion Vertical		5cm 15cm 30cm 45cm 60cm	sDA / ASE	LEED 2Cr. sDA>55% ASE<10% — LEED 3cr. sDA>75% ASE<10%

5.8.3.2. Results of thermal simulation analysis

This section aims to analysis the thermal results of the parametric simulation and their correlations according to the daylight performance so as to find the optimal alternative for each screen size that could balance daylight and thermal performance with the maximum possible energy savings. Thus, the best optimum alternatives for each size from the previous daylighting analysis and their corresponding thermal loads will be explored as shown in Table 5.10, Table 5.11 and Table 5.12 below. Energy savings percentages were calculated compared to the bases case energy load, 295.95kWh/m^2, showed in *section 5.6*.

Regarding heating loads, they were almost constant at a certain level for each size. They ranged from 8.94 kWh/m^2 to 10.82 kWh/m^2 for cases with 30 cm units' sizes, from 9.31 kWh/m^2 to 11.17 kWh/m^2 for cases with 60 cm units' sizes and from 11.39 to 11.49 kWh/m^2 for cases with 120 kWh/m^2 cm units' sizes. In contrast, cooling loads were the most influential in such hot arid climate. Thus, the optimum alternatives for each size were ordered ascending according to their cooling loads.

Table 5.10 120 cm screen units' size optimum alternatives from the perspective of daylighting and their corresponding thermal and energy performance

No.	Screen Parameters					Daylight Performance					Energy consumption				Daylight Evaluation criteria		
						Daylight Availability						Thermal Performance					
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Partially	Daylit	Overlit	sDA	ASE	Lighting Load (kWh/m2)	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Energy saving %	IES	LEED v4 3 credits	LEED v4 2 credits
1	120	0	65	60	60	30.8	59.5	9.7	69.2	3.2	8.02	115.61	11.49	54.4			●
2	120	0	65	60	45	25.5	58.3	16.2	75.0	6.5	6.49	117.21	11.48	54.4		●	
3	120	0	65	45	60	26.3	55.9	17.8	73.7	7.3	8.03	118.89	11.39	53.3			●

Table 5.11 60 cm screen units' size optimum alternatives from the perspective of daylighting and their corresponding thermal and energy performance

No.	Screen Parameters					Daylight Performance					Energy consumption				Daylight Evaluation criteria		
						Daylight Availability %						Thermal Performance					
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Partially	Daylit	Overlit	sDA %	ASE %	Lighting Load (kWh/m2)	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Energy saving %	IES	LEED v4 3 credits	LEED v4 2 credits
1	60	0	80	60	45	10.9	83.0	6.1	89.1	0.4	4.78	134.73	11.17	49.1	●	●	
2	60	0	80	45	60	10.1	80.2	9.7	89.9	0.8	5.00	134.85	11.07	49.0	●	●	
3	60	0	80	60	30	2.4	84.2	13.4	97.6	0.8	4.86	135.18	11.09	48.9	●	●	
4	60	0	80	45	45	4.5	79.4	16.2	95.5	1.2	4.09	135.27	11.16	49.1	●	●	
5	60	0	80	60	15	0.4	80.2	19.4	99.6	1.6	3.41	135.81	11.00	49.2	●	●	
6	60	0	80	60	5	0.0	73.3	26.7	100.0	5.3	3.54	136.90	10.95	48.9		●	
7	60	0	80	45	30	1.6	73.3	25.1	98.4	4.0	4.07	137.39	10.99	48.5		●	
8	60	0	80	30	60	3.6	76.5	19.8	96.4	3.2	4.19	137.57	11.13	48.3		●	
9	60	0	80	30	45	0.0	75.3	24.7	100.0	4.5	3.02	138.41	11.07	48.5		●	
10	60	0	80	15	60	3.2	68.4	28.3	96.8	6.5	4.26	139.07	11.03	47.9		●	
11	60	0	80	45	15	0.0	68.8	31.2	100.0	8.5	3.30	139.10	10.87	48.2		●	
12	60	0	80	5	60	0.4	68.4	31.2	99.6	9.3	3.30	140.50	11.07	47.7		●	
13	60	0	80	30	30	0.0	66.8	33.2	100.0	8.5	3.20	141.69	10.95	47.4		●	

Table 5.12 30 cm screen units' size optimum alternatives from the perspective of daylighting and their corresponding thermal and energy performance

No.	Screen Parameters					Daylight Performance					Energy consumption				Daylight Evaluation criteria		
						Daylight Availability						Thermal Performance					
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Partially	Daylit	Overlit	sDA	ASE	Lighting Load (kWh/m2)	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Energy saving %	IES	LEED v4 3 credits	LEED v4 2 credits
1	30	0	80	45	15	23.1	76.9	0.0	76.9	0.0	4.96	156.09	10.82	41.93	●	●	
2	30	0	80	30	30	22.7	74.1	3.2	77.3	0.0	5.49	156.58	10.83	41.59	●	●	
3	30	0	80	30	15	5.3	80.6	14.2	94.7	2.0	4.04	156.76	10.81	42.02	●	●	
4	30	0	80	45	5	15.4	82.2	2.4	84.6	0.4	5.43	157.03	10.79	41.47	●	●	
5	30	0	80	30	45	38.9	60.3	0.8	61.1	0.0	7.18	157.77	8.97	41.24			●
6	30	0	80	60	5	35.6	64.4	0.0	64.4	0.0	7.39	158.00	10.73	40.50			●
7	30	0	80	60	15	43.7	56.3	0.0	56.3	0.0	7.45	158.03	8.94	41.07			●
8	30	0	80	15	45	21.5	74.1	4.5	78.5	0.4	6.69	158.66	10.78	40.50	●	●	
9	30	0	80	45	30	39.3	60.7	0.0	60.7	0.0	8.14	158.69	8.96	40.61			●
10	30	0	80	15	60	40.5	58.3	1.2	59.5	0.4	8.16	159.21	10.76	39.82			●
11	30	0	80	5	45	16.6	69.6	13.8	83.4	1.6	5.24	159.74	10.73	40.64	●	●	
12	30	0	80	5	60	34.0	62.8	3.2	66.0	0.4	7.38	159.76	10.68	39.93			●
13	30	0	80	30	5	1.2	71.3	27.5	98.8	7.7	4.28	160.43	10.69	40.74		●	
14	30	0	80	15	30	4.5	72.5	23.1	95.5	3.2	4.70	161.59	10.79	40.17		●	

A correlation between ASE, overlit area and increasing cooling loads was deduced. And it was also shown that for the alternatives that had the same ASE value with convergent sDA values, higher overlit area indicated increasing in cooling loads. For example, by comparing cases no. 2 and no.3 with 60 cm units' sizes (shown in in Table 5.11), both of them had 0.8 ASE value while the first one had 9.7% overlit area and the second one had 13.4% overlit area indicating 134.85 kWh/m^2 and 135.18 kWh/m^2 respectively. The same results could be conducted by analyzing cases no.4 and no.8 with 30 cm units' size as shown in Table 5.12.

Another correlation between partially daylit area increasing lighting loads was deduced. As shown in the above tables, the highest partially daylit areas indicated the highest lighting loads for each size as shown for case no.1 for 120cm units' sizes, case no.6 for 60cm units' sizes and case no.10 for 30cm screen units' sizes as shown in Table 5.10, Table 5.11 and Table 5.12, respectively.

It was also shown that alternatives that comply with IES criteria mostly indicated better cooling loads than others. Therefore, calculating Daylight Availability, sDA and ASE could give an indication about cooling loads. Hence daylighting optimum cases can be sorted regarding thermal and energy performance without even being calculated.

From the above correlations, it could be proposed that the optimal cases that could balance daylight and thermal performance with maximum possible energy savings could be indicated based on daylight simulation results only by selecting the case that comply with the following workflow, descending in its impact, shown in Figure 5.21.

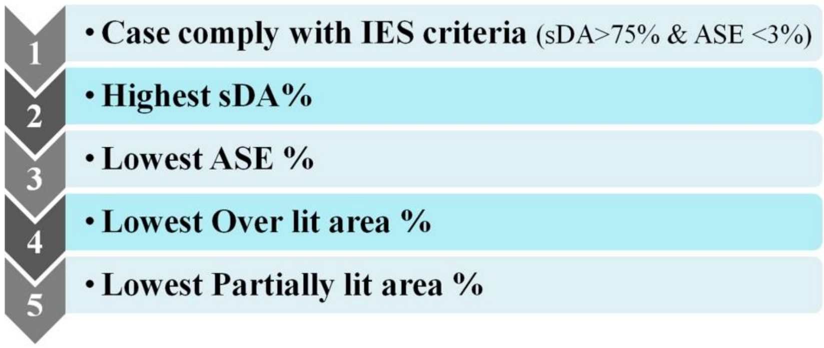


Figure 5.21 Workflow of the proposed selection criteria that indicate the optimal balance between daylight, thermal and energy saving based on daylight simulation only

In another words, the optimal cases that could balance daylight and thermal performance with highest possible energy savings could be mostly achieved by the following selection criteria; firstly define the alternatives that comply with IES and optimal requirements (sDA> 75% & ASE <3%). Then select the case with the highest sDA value among them. If there are similar cases, choose the case with lowest ASE value. In case of similar ASE values, select the case with the lowest overlit area. Finally, if there are similar cases, indicate the case with the lowest partially lit area as the optimal case.

5.8.4. Parametric simulation Optimal cases

The optimal cases for each screen units' size, 120cm, 60cm and 30cm, that could balance daylight and thermal performance with maximum possible energy savings according to the previous selection criteria was highlighted with the red dashed boundaries shown in Table 5.10, Table 5.11 and Table 5.12 respectively.

For the screens with 120 cm units' size, the configuration of 0° rotation angle, 65% scale ratio, 60cm vertical points' protrusion value and 45cm horizontal points' protrusion values was the optimal case for this size that balance daylighting and thermal performance. It achieved 75% sDA with 6.5% ASE that couldn't comply with IES but comply with LEED v4 3-credits criteria, as well as achieving 22.5%, 58.3%, and 16.2% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 117.21kWh/m^2, 11.48kWh/m^2, and 6.49 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 42% energy savings compared to the base case as illustrated in Figure 5.22.

While **for screens with 60 cm units’** size, the configuration of 0° rotation angle, 80% scale ratio, 60cm vertical points’ protrusion value and 15cm horizontal points’ protrusion values had proven its superiority in balancing daylighting and thermal performance. It achieved 99.6% sDA with 1.6% ASE that comply with both IES and LEED v4 3-credits criteria, as well as achieving 0.4%, 80.2%, and 19.4% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 135.81 kWh/m^2, 11 kWh/m^2, 3.41 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 49% energy savings compared to the base case as illustrated in Figure 5.23.

Finally, for screens with 30 cm units’ size, the configuration of 0° rotation angle, 80% scale ratio, 30cm vertical points’ protrusion value and 15cm horizontal points’ protrusion values was the optimal case for this size for balancing daylighting and thermal performance. It achieved 95% sDA with 2% ASE that comply with both IES and LEED v4 3-credits criteria, as well as achieving 5.3%, 80.6%, and 14.2% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 156.76 kWh/m^2, 10.81 kWh/m^2, and 4.0481 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 42% energy savings compared to the base case as illustrated in Figure 5.24.

Case No.	Size	Rotation	Scale	Vertical pr.	Horizontal pr.
2	120*120cm	0°	65%	60 cm	45 cm

Daylight Availability			sDA	ASE	Elect	Cooling	Heating	Energy
Partially	DAYLIT	OVERLIT			Kwh/m2	Kwh/m2	Kwh/m2	Saving %
25.51	58.30	16.2	75	6.5	6.49	117.21	11.48	54.4

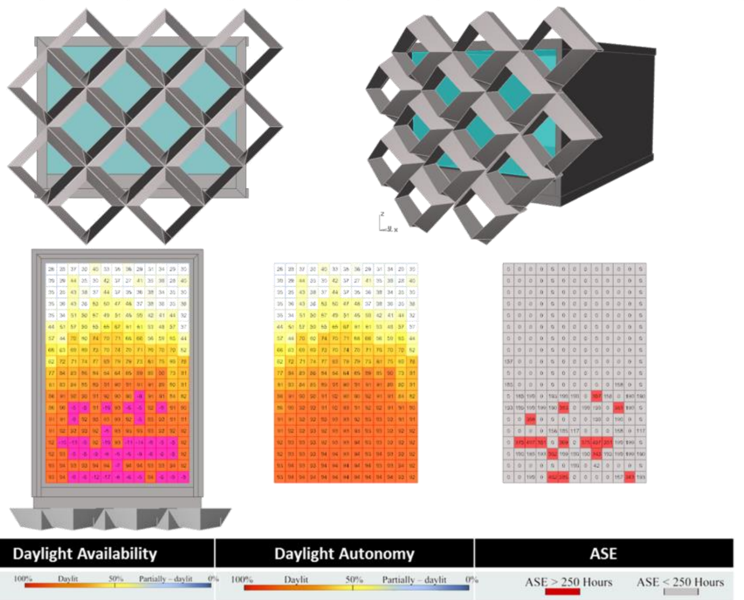


Figure 5.22 The optimum configuration for the 120 cm size screen and its daylight and thermal performance

Case No.	Size	Rotation	Scale	Vertical pr.	Horizontal pr.
5	60*60 cm	0°	80%	60 cm	15 cm

Daylight Availability			sDA	ASE	Elect	Cooling	Heating	Energy
Partially	DAYLIT	OVERLIT			Kwh/m2	Kwh/m2	Kwh/m2	Saving %
0.4	80.2	19.4	99.6	1.6	3.41	135.81	11.00	49.2

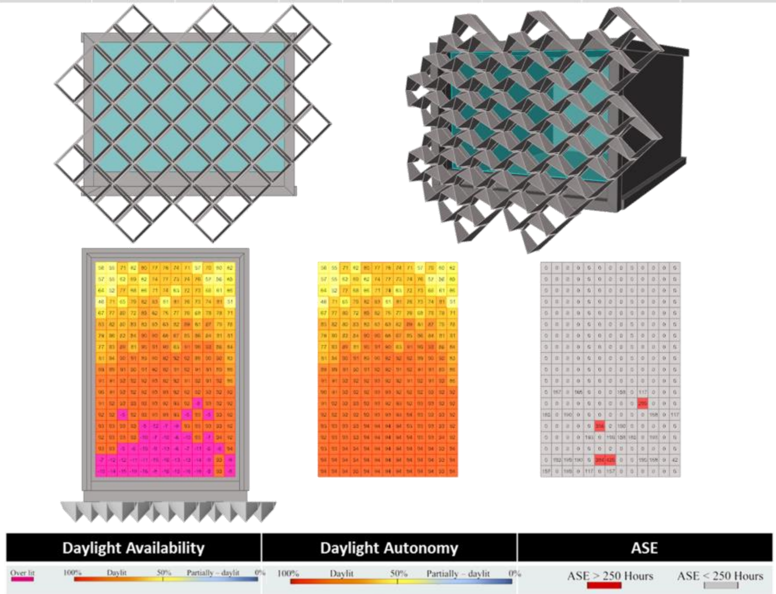


Figure 5.23 The optimum configuration for the 60 cm size screen and its daylight and thermal performance

Case No.	Size	Rotation	Scale	Vertical pr.	Horizontal pr.
3	30x30 cm	0°	80%	30 cm	15 cm

Daylight Availability			sDA	ASE	Elect	Cooling	Heating	Energy
Partially	DAYLIT	OVERLIT			Kwh/m2	Kwh/m2	Kwh/m2	Saving %
5.3	80.6	14.2	94.7	2	4.04	156.76	10.81	42

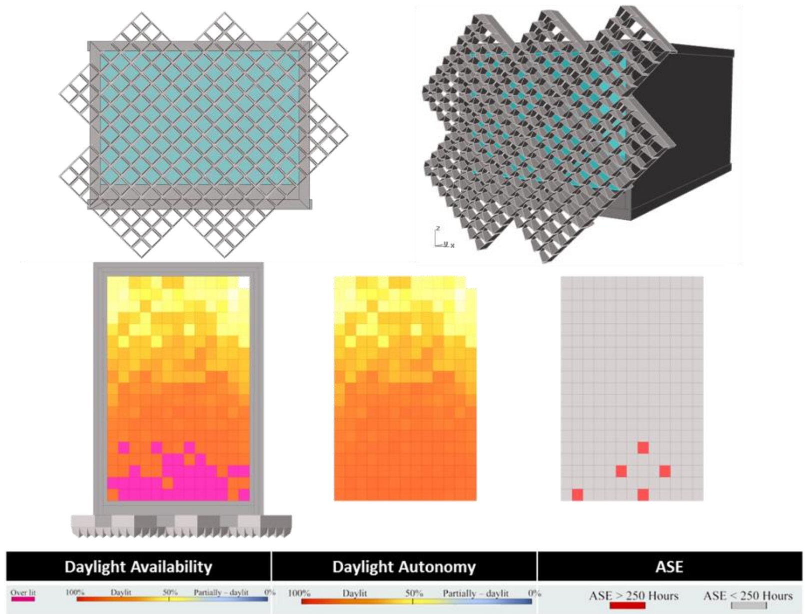


Figure 5.24 The optimum configuration for the 30 cm size screen and its daylight and thermal performance

5.9. Comparison between Genetic Algorithm optimization and parametric simulations

A comparison had been conducted between the GAs optimization approach and the parallel parametric simulation approach exploring each approach's effectiveness in balancing daylight and thermal performance through the proposed screen design. The results showed that the use of GAs optimization with Galapagos allowed wide variety of screen configurations to be explored and accepted cases were found (11 case).But generally, GAs optimization process didn't seem to be effective in this research; as it took too much time to get an accepted solution (9 days) that comply with the target performance and it failed to reach accepted solutions with different sizes combinations of the screen configurations as all the screen unit sizes had been fixed to the largest size,120 cm. Moreover, the effect of the variations in screen parameters on daylighting and thermal performance couldn't be investigated as GAs optimization process doesn't provide an informative back-tracing exploration of design solutions.

From the parametric results analysis, the initial GAs optimization fitness landscape could be recognized more distinctly. And it became evident now that the optimization fitness landscape has too many peaks with accepted solution and with wide range in results causing many local optima peaks where the genome got stuck in one of them on the previous GAs process as shown in Figure 5.25. Every point on the surface represents a unique screen configuration. However, it's not quite as simple as the figure but it wasn't easy to model the actual fitness landscape and this could generalize the fitness landscape for explorations. It is important to note that the actual fitness landscape is not quite as simple as the image shown in Figure 5.25. As the actual fitness landscape for this process would be more organic and un-box-like which isn't easy to be illustrated.

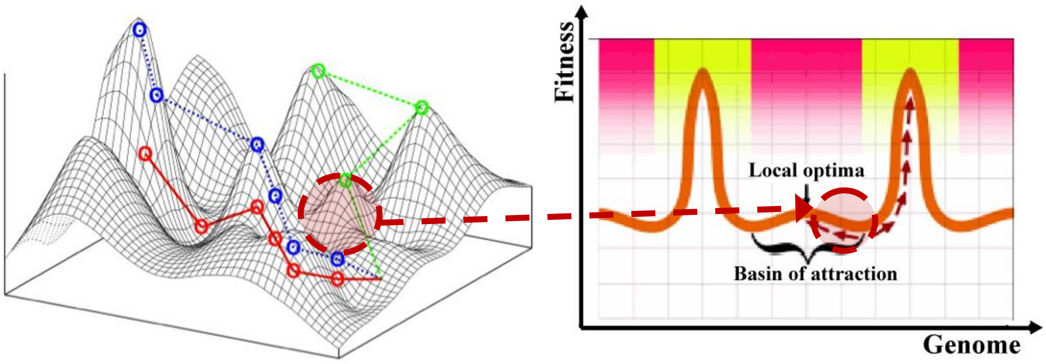


Figure 5.25 On the left: the GAs conceptual fitness landscape. On the right: 2D graph to generalize this landscape

Source: http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles

On the other hand, the previously addressed limitations of parametric simulations were avoided by using parallel parametric algorithms for the simulation runs and an exhaustive search method for analyzing the results. Results showed great potentials of the parallel parametric simulation approach in exploring the effect of each screen parameter as well as the effect of their interactions together on daylight and thermal performance as well as energy savings by testing large number of tested solutions, 1875 solutions, in a reasonable time (5 days). However without this large number of tested solutions such exploration couldn't be achieved. This approach also achieved accepted and near optimal solutions that comply with the target performance criteria but they failed to address various combination of screen different parameters as the generated alternatives were based on fixed variables for all modules of the same screen.

In order to and make a worthwhile investment from those explorations by trying to get solutions that combine both parametric and optimization potentials with the minimum possible limitations; two parametric-based optimization methods were suggested as shown in Figure 5.26. The first methodology was based on modifying the genetic algorithms parameters and procedure due to the parametric results exploration of the current fitness space. The second methodology relied on a special algorithm developed in Grasshopper by the author based on the parametric optimal results that would apply the main GAs optimization potential of exploring wide screen variations but in this case by directing simulation process that offer the optimal time consuming. Next sections will present those two approaches in details.

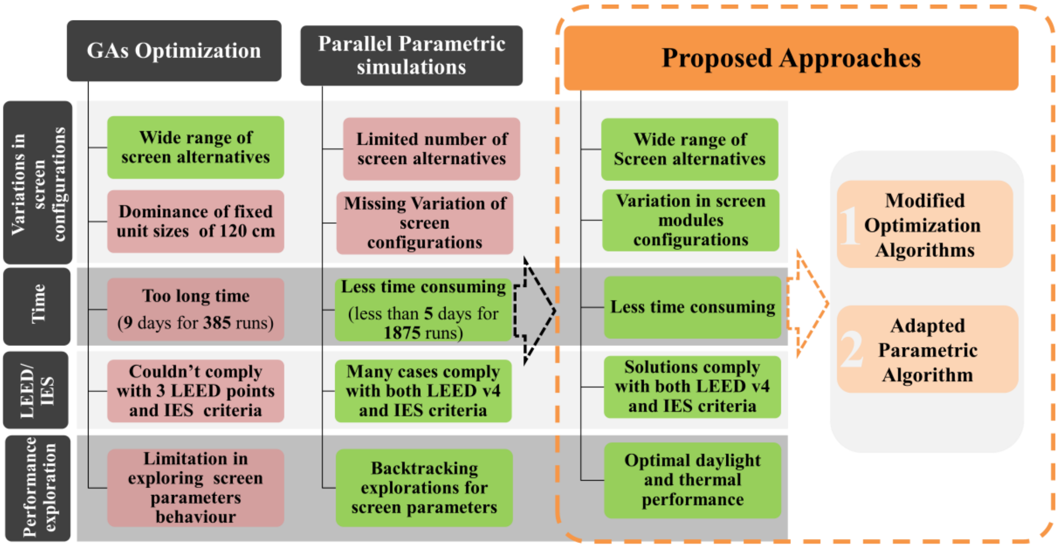


Figure 5.26 The potentials and limitations of GAs optimization & parametric simulations and the targeted potentials of the new approaches

5.10. Modified Genetic Algorithms

Based on the analysis of the parametric simulations results and the screen parameters exploration of their effect on daylight and thermal performance, well-informed modifications could be applied to the GAs process so as to improve its results. These included modifications in the screen parameters and values as well as the fitness landscape.

5.10.1. Modified Genetic Algorithms procedure

Firstly, a parametric simulation runs are needed so as to analysis the fitness landscape of the initial optimization. Secondly, based on the results of these analyses, the GAs optimization's definition, parameters and algorithms could be modified to efficiently guide the genomes to the optimal solutions.

Based on that, the ranges of the screen parameters of the initial GAs process were modified this optimization process as shown in Table 5.13, noticing that the modified parameters are highlighted in red. The unit's sizes hadn't been changed while the rotation angles had been fixed at 0° as it showed the best performance in the previous parametric simulation analysis. On the other hand the scale ratios were modified by excluding the ratios from 20% to 65% and focusing instead on larger ratios starting from 70% to 90% with 5% stepping value and finally the extrude values were improved by adding values from 75 cm to 120c m with 15 cm increments so as to comply with the 120 cm size units.

Table 5.13 The modified screen parameters and stepping values for the Modified GAs optimization

Parameters	Values
Size (cm)	**120, 60, 30**
Rotation Angle (○)	**0**
Scale %	**70, 75, 80, 85, 90**
Extrude (cm) (for each point)	**5, 15, 30 , 45, 60, 75, 90,1.05, 120**

Another essential modification was to fix the screen base modules configurations to any desirable configurations including any combination of different units' sizes before starting the optimization process. In another word, this modification aims to determine an exact peak from the fitness landscape, shown in Figure 5.25, for the genome to be pulled uphill, without the risk of getting stuck in other local optima peaks. Thus, a new more directed and efficient fitness landscape could be achieved. A conceptual fitness landscape for the Modified GAs is illustrated in Figure 5.27.

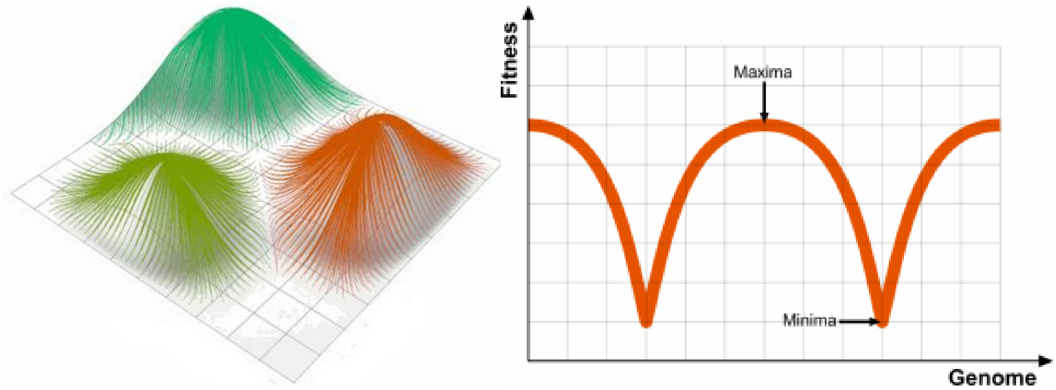


Figure 5.27 The conceptual fitness landscape of the modified GAs optimization without local optima peaks

Source: http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles

5.10.2. Results of the modified GAs optimization

5.10.2.1. Results of case A

The optimization process was finished after 220 simulation iteration and 8 generations, by which the process took about four continues days to be completed on a desktop with core i7 processor. The graphs below, shown in Figure 5.28 and Figure 5.29, illustrate the daylighting performance results and thermal and energy performance results respectively. The daylighting performance was enhanced gradually by the genetic algorithm throughout 9 Generations, by which the objective was set to maximize daylit area percentage and to minimize the total energy consumption. In the last generation, by the end of the optimization process, 24 optimum solutions were defined that met the targeted criteria. However, the last 47 individual solutions alone can achieve 3 credits in LEED v4, except 2 solutions that achieve 2 LEED credits only. One of the optimal cases that comply with both IES and LEED v4 3-credits criteria is shown in Figure 5.30 showing its daylight, thermal and energy performance.

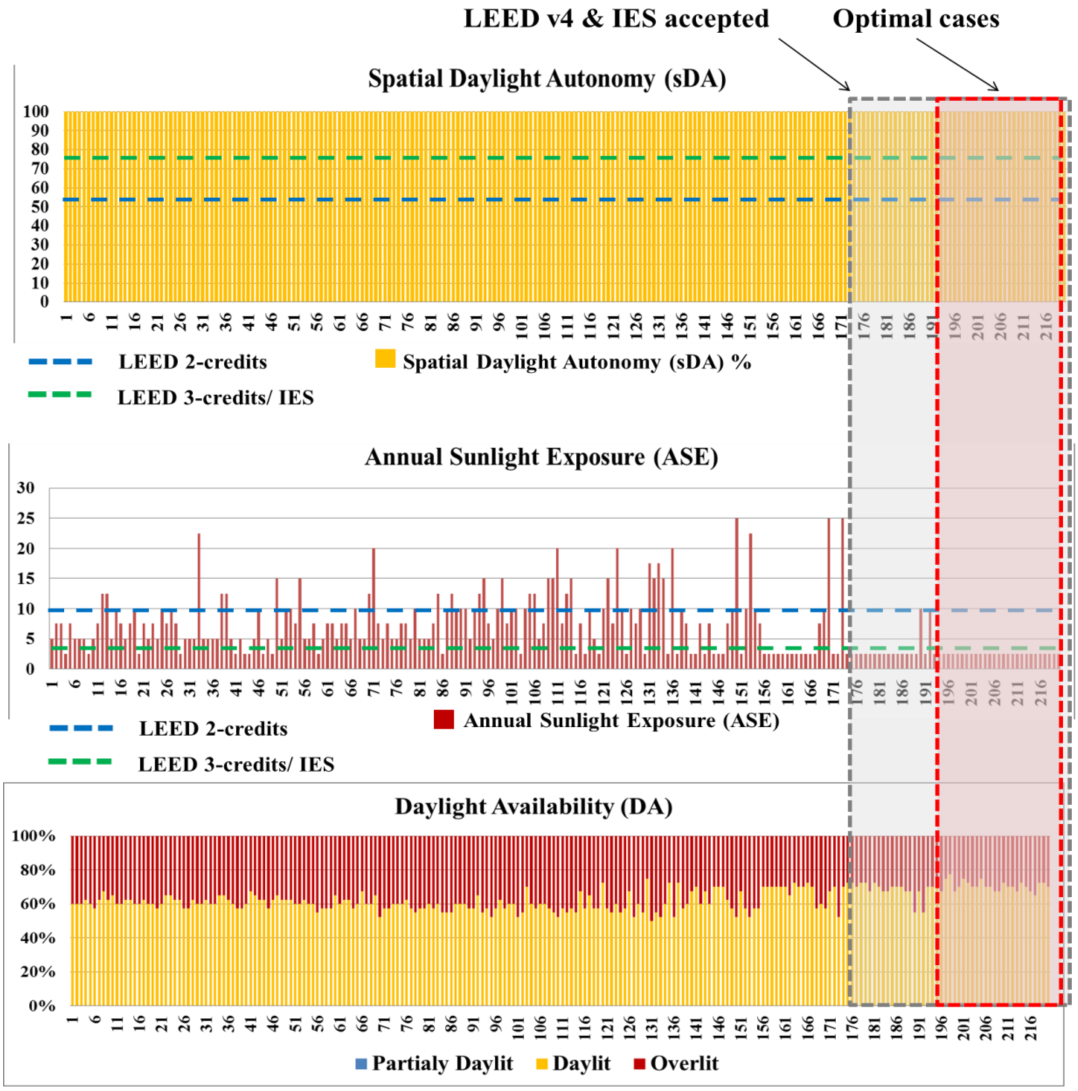


Figure 5.28 Daylight Availability, sDA and ASE performance for each iteration of case A of the Modified GAs optimization process.

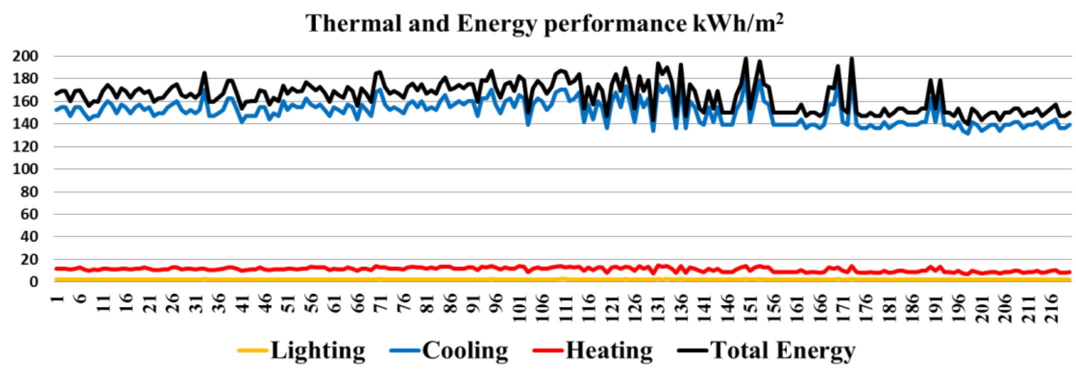
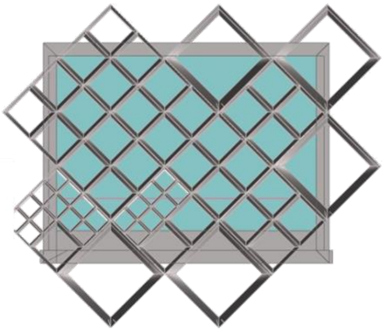
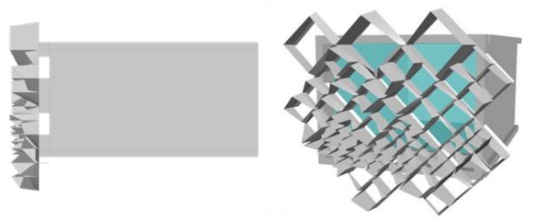


Figure 5.29 Annual thermal loads and total energy consumption for each iteration of case A of the Modified GAs optimization process.

Modified GAs (Case A)

Daylight Availability			sDA	ASE	Elect kWh/m2	Cooling kWh/m2	Heating kWh/m2	Energy Savings %
PARTIALY DAYLIT	DAYLIT	OVERLIT						
0	73	26	100	2.5	2.0	136.5	8.2	50.5%





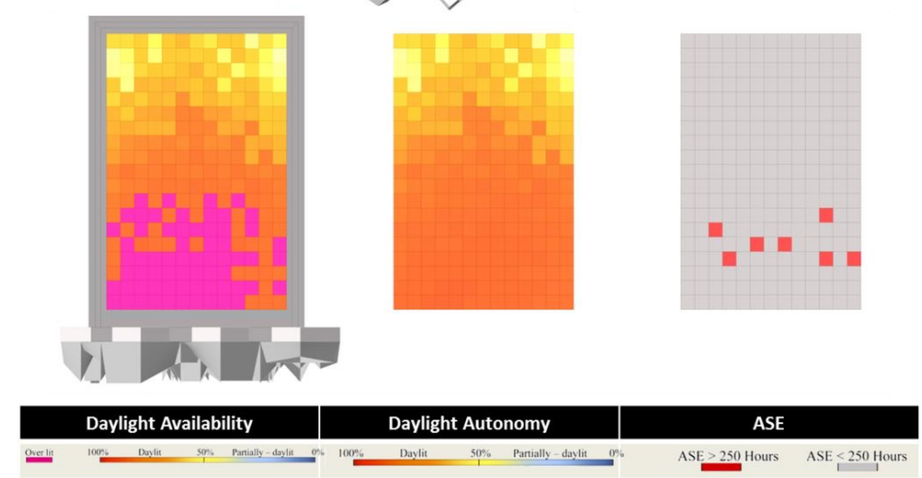


Figure 5.30 The optimal solution of case A of the Modified GAs optimization process

5.10.2.2. Results of Case B

The optimization process was finished after 320 simulation iteration and 13 generations, by which the process took about six continues days to be completed on a desktop with core i7 processor. The graphs below shown in Figure 5.31 and Figure 5.32 illustrate the daylighting performance results and energy performance results respectively. The daylighting performance was enhanced gradually by the genetic algorithm throughout 13 generations, by which the objective was set to maximize daylit area percentage and to minimize the total energy consumption. In the last generation, by the end of the optimization process, three optimum solutions were defined that met the targeted criteria. However, the last 33 individual solutions alone can achieve 3 credits in LEED v4. One of these optimal solutions is illustrated in Figure 5.33 showing its daylight, thermal and energy performance.

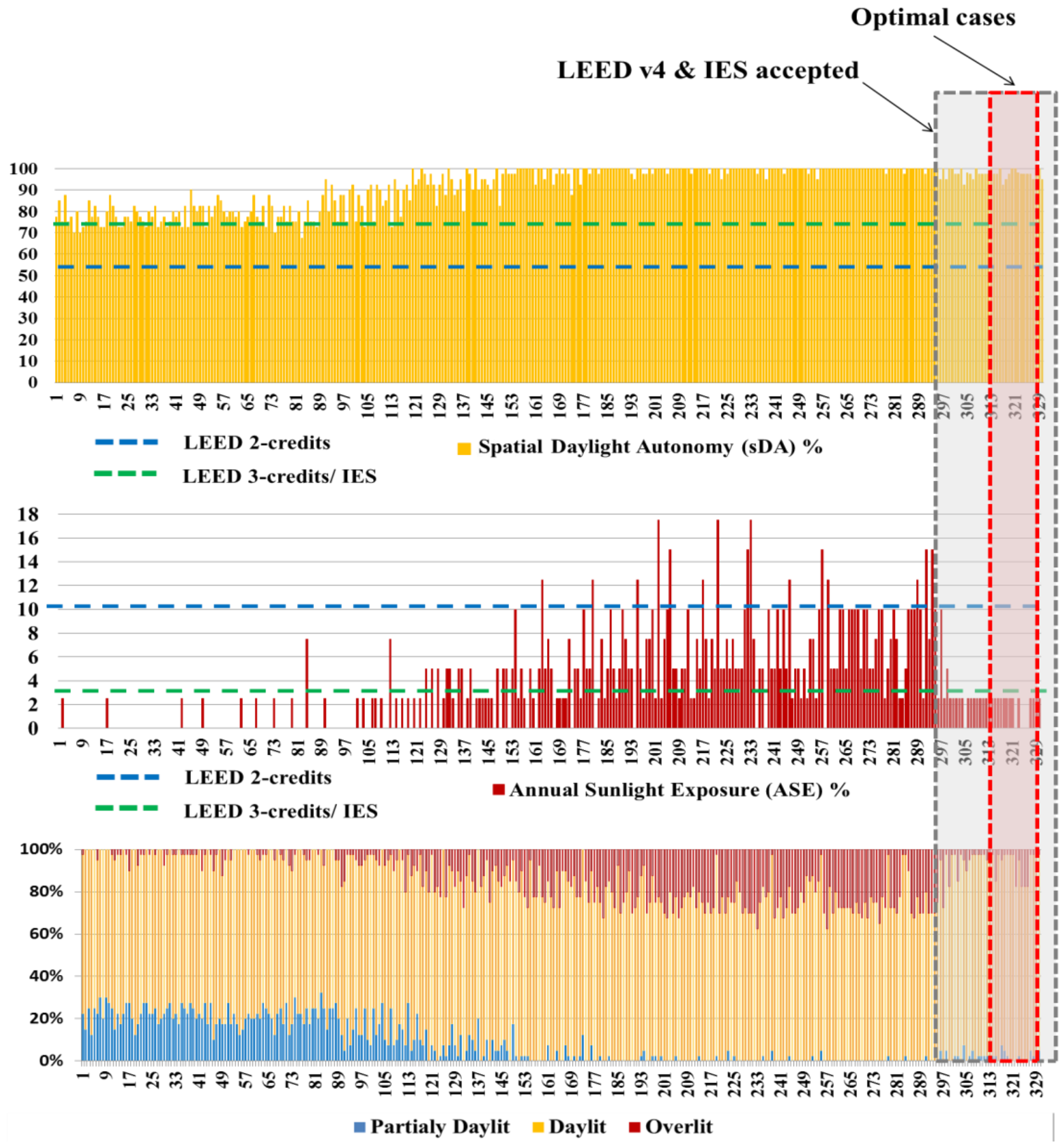


Figure 5.31 Daylight Availability, sDA and ASE performance for each Iteration of the Modified GAs optimization process case B

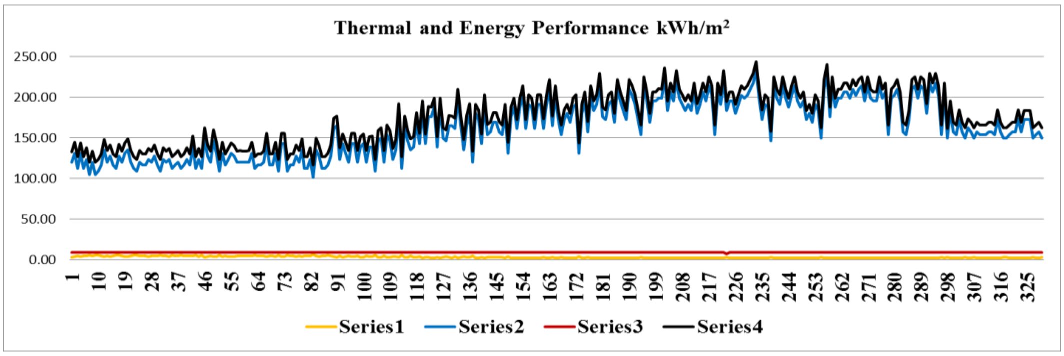
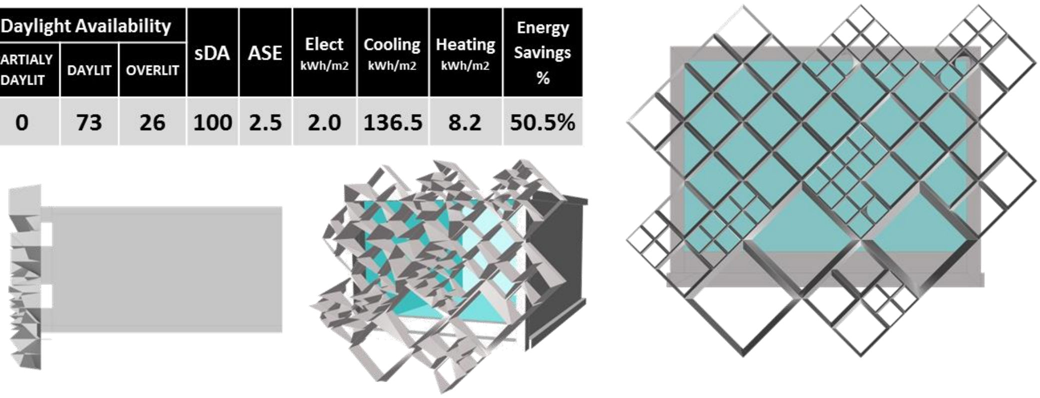


Figure 5.32 Annual thermal loads and total energy consumption for each iteration of case B of the Modified GAs optimization process

Modified GAs (Case B)

Daylight Availability			sDA	ASE	Elect kWh/m2	Cooling kWh/m2	Heating kWh/m2	Energy Savings %
PARTIALY DAYLIT	DAYLIT	OVERLIT						
0	73	26	100	2.5	2.0	136.5	8.2	50.5%



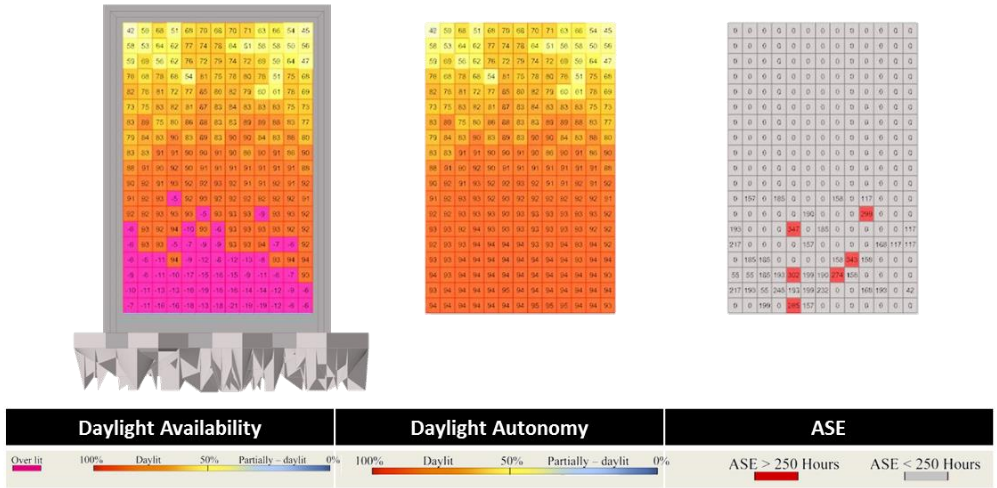


Figure 5.33 The optimal solution of case B of the Modified GAs optimization process

5.11. Adapted Parametric Algorithm approach

In this adapted algorithm approach, previous optimal parametric simulations results were used for mapping the solution space to ensure achieving the optimal balance between daylight and thermal performance while reducing the total energy consumption.

The methodology implemented through this approach aims to expand the benefits of the previous parametric simulations and make a worthwhile investment of the screen parameters exploration to generate various combinations that all could satisfy daylight and thermal performance as well as the designer's intents. Thus, by this methodology a wide range of well performing solutions can be generated that all comply with both LEED V4 and IES requirements while ensuring the optimal thermal performance with efficient energy consumption.

5.11.1. Adapted Parametric Algorithm procedure

In this solution a new parametric algorithm was developed based on the optimal solutions of the previous parametric simulations. Firstly, any combinations of three units' sizes, 120, 60 or 30 cm, generated the base module by changing size parameters in grasshopper using Gene pool component. Secondly, each unit size was classified through its area to be divided into three groups representing the three unit sizes. Thirdly, each group of the same units sizes were applied its optimal parameters according to the parametric simulations results shown before in *section 5.8.4*. After that, the final screen configuration is connected to DIVA Daylight Analysis for GH for daylight simulation and then to Viper for thermal simulation. Finally the results are visualized in Rhinoceros and exported to Excel sheet using TT Tool box for GH. The adapted algorithm workflow is illustrated in Figure 5.34.

Thus, for each screen unit's size best configurations that attained the optimal required performance were chosen to be applied in this new group-based parametric algorithm as shown in Table 5.14. Note that for screen units with 120 cm size the extrude value of the vertical points were redefined to be 120 cm. One of the main potential of the results of this approach is that the units standardizing into 3 main configurations could facilitate the final fabrication process by providing the exact dimensions of the selected case.

Table 5.14 Optimal configurations for each unit size to be assigned for the Adapted Parametric Algorithm approach

Unit's Size	120x120 cm	60x60 cm	30x30 cm
			
Rotation Angle	0°	0°	0°
Scale Ratio	80%	80%	80%
Vertical Protrusion	120 cm	60 cm	30 cm
Horizontal Protrusion	15 cm	15 cm	15 cm

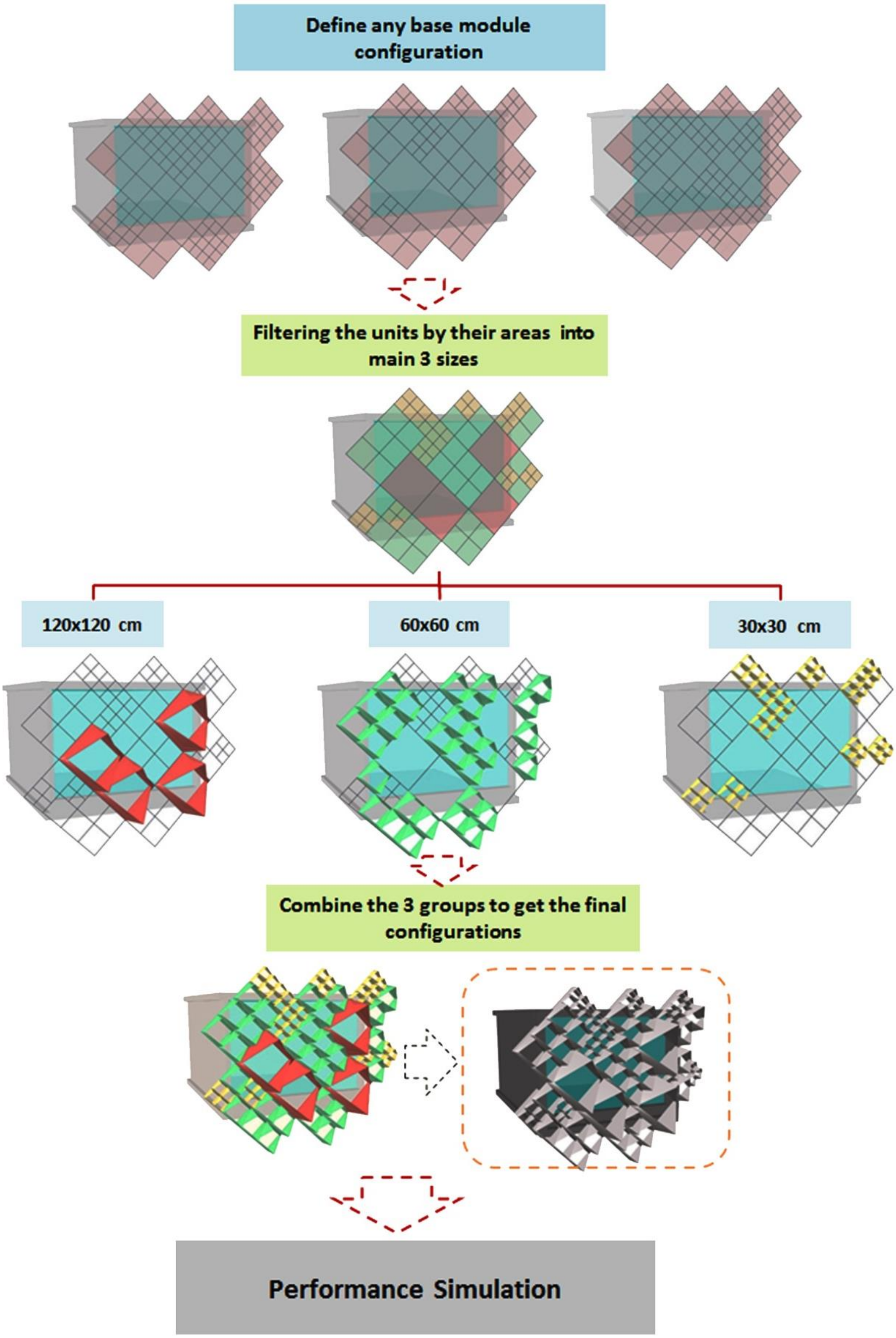


Figure 5.34 Adapted Parametric Algorithm workflow

5.11.2. Results of the simulation runs

Non limits number of solutions could be achieved now using this Adapted Algorithm Methodology by a direct parametric simulation. All solutions were able to obtain 3 credits in LEED v4 while comply with IES approved method's requirements with an acceptable daylight availability ranges that could ensure the required thermal balance as well as achieving sufficient energy savings. Next, two alternatives using this method are presented in the next sections..

5.11.2.1. Adapted Parametric Algorithm (Case A)

In this case, the main diagrid module was generated randomly using the Gene Pool components within Grasshopper as shown in Figure 5.35, the Adapted Algorithm Methodology was applied then to the resulted base grid so as to analysis their modules' areas and assigned the appropriate configurations for each modules' size. Result showed that 100% sDA with 1.5% ASE was achieved that complies with both LEED v4 3 credits and IES criteria, it was also formulated by 78% daylit area, 22% over lit area and 0% partially daylit area over the Daylight Availability metric. The result also proved that the total energy consumption decreased by applying this methods and configurations, as the cooling energy loads dropped from around 296 kWh/m^2 in the base case to less than 139 kWh/m^2 in this case, while the lighting loads was increased slightly to be 3.5 kWh/m^2 instead of 1.39 kWh/m^2 in the base case due to less excessive daylight penetrations into the space and finally the heating energy loads was decreased from 9 kWh/m^2 to achieve 7.7 kWh/m^2. The total energy consumption was dropped obviously to reach 137.9 kWh/m^2 from 296 kWh/m^2 in the base case resulting in about 53% energy savings as shown in Figure 5.35.

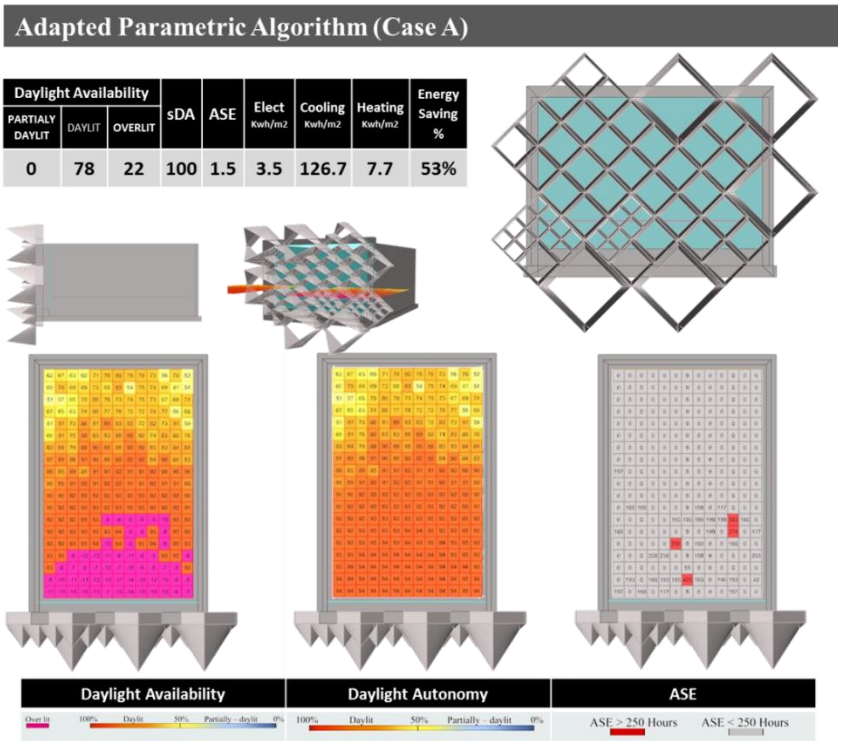


Figure 5.35 Case A simulation results using the Adapted Algorithm Methodology

5.11.2.2. Adated Parametric Algorithm (Case B)

In this case, case B, another diagrid based cells was generated randomly using the Gene Pool components within Grasshopper as shown in Figure 5.36 to ensure the validity and efficiency of the proposed Adapted Algorithm Methodology. The result approved with the previous case A as, 100% sDA with 2% ASE was achieved that complies with both LEED v4 3 credits and IES criteria, 77% daylit area, 23% over lit area and 0% partially daylit area over the Daylight Availability metric. The result also proved that the total energy consumption was decreased and showed results similar to the previous case ones, as the cooling energy loads dropped from around 285.56 kWh/m^2 in the base case to reach less than 127 kWh/m^2 in this case, while the lighting loads was increased slightly to be 3.8 kWh/m^2 instead of 1.39 kWh/m^2 in the base case due to less excessive daylight penetrations into the space and finally the heating energy loads was decreased from 9 kWh/m^2 to achieve 7.7 kWh/m^2. The total energy consumption was dropped obviously to reach 138.3 kWh/m^2 instead of 296 kWh/m^2 in the base case resulting in about 53% energy savings as shown in Figure 5.36.

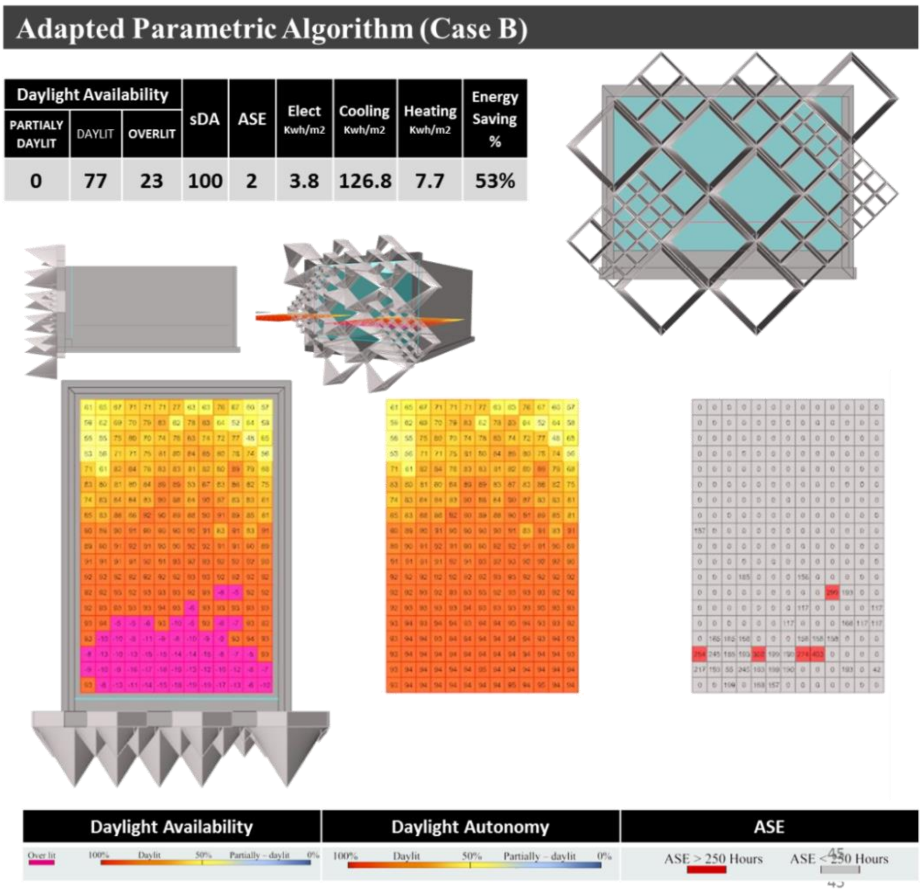


Figure 5.36 Case B simulation results using the Adapted Algorithm Methodology

5.12. Conclusion

This chapter presented a simulation-based study for a non-conventional solar screen design driven by daylight and thermal performance. It was based on the integration of performance simulation tool with parametric design approach and Genetic Algorithms method using DIVA, Grasshopper and Galapagos respectively.

The simulations were conducted for a south-oriented office space's façade in Cairo, Egypt. The solar screen various parameters; size, rotation angle, scale ratio, and protrusion value, with their predefined ranges and configurations were modelled parametrically using Grasshopper and aligned to this façade. Daylight analysis was conducted using the Daylight Dynamic Performance Metrics (DDPMs) specifically; Daylight Availability, Spatial Daylight Autonomy (sDA300/50%) and Annual Sunlight Exposure (ASE1000/250hr), the last two were complied with both LEED v4 and the new IES approved method criteria. While thermal analysis was based a comparison approach of the thermal performance and energy consumption results to a specific base case. The methodology implemented in this chapter was divided into **three consecutive stages;**

The first stage was conducted using Genetic Algorithms (GAs) optimization for a wide range of screen parameters. The optimization process was finished after 385 simulation iteration and 17 generations. Results showed that 11 accepted solutions were achieved; only one solution achieved 3 LEED credits where all the other solutions could only obtain 2 LEED credits and none of them achieved IES requirements.

The second stage was done using a parallel computing algorithm that automate parametric simulation runs for specific screen parameters' ranges resulting in 1875 alternatives. Parallel Radiance simulation runs saved time by 8 times more than the default parametric runs, by making the maximum benefits of the available CPU cores of the used computer, which were 8 in this case. In addition, an algorithm inside Grasshopper was developed specially for this study, to overcome current EnergyPlus limitation of running parallel thermal simulation. Thus, all the 1875 alternatives thermal simulation runs were automated after the completion of the parallel daylight simulation runs. The parametric simulations results were analyzed systematically using an exhaustive search method through two phases; first dealt with daylight simulation analysis while the other concerned with the thermal and energy analysis.

For daylight analysis; screen's rotation angles didn't have a relevant effect on the screen performance however, the 0° rotation angle was recommended. Screen's scale ratio combined with protrusion values impacted the daylight performance of each unit's size strongly, as sDA and ASE decreased obviously with small scale ratios and large protrusion values. Meanwhile, screen's protrusion values and units' size had the most remarkable effect on the screen's daylight performance. Generally, for each screen size, vertical and horizontal point's protrusion values were inversely related to achieve accepted results. As the higher the vertical points, the lower the horizontal points with specific proportions related to the size value of each unit. This explains the lack of the ability of the large units' size of 120 cm to reach acceptable results due to the protrusion value limitations form 5cm to 60cm.

For thermal analysis; the best optimum alternatives for each size from the previous daylighting analysis and their corresponding thermal loads were explored. Regarding heating loads, they were almost constant at a certain level for each size. In contrast, cooling loads were the most influential in such hot arid climate.

A correlation between ASE, overlit area and increasing cooling loads was deduced. And it was also shown that for the alternatives that had the same ASE values with convergent sDA values, higher overlit area indicated increasing in cooling loads. Another correlation between partially daylit area increasing lighting loads was deduced. It was also shown that alternatives that comply with IES criteria mostly indicated better cooling loads than others. Therefore, calculating Daylight Availability, sDA and ASE could give an indication about cooling loads. Hence daylighting optimum cases can be sorted regarding thermal and energy performance without even being calculated.

Finally, it was concluded that the optimal cases that could balance daylight and thermal performance with highest possible energy savings could be mostly achieved by a specific suggested selection criteria. From the previous analysis and based on this selection criteria, the optimal screen configurations for each size were defined. For screens with 30 cm units' size, the optima configuration had 0° rotation angle, 80% scale ratio, 30 cm vertical points' protrusion value and 15cm horizontal points' protrusion values. While for screens with 60 cm units' size, the optimal configuration had 0° rotation angle, 80% scale ratio, 60cm vertical points' protrusion value and 15cm horizontal points' protrusion values. Finally for the screens with 120 cm units' size, the optimal configuration had 0° rotation angle, 65% scale ratio, 60 cm vertical points' protrusion value and 45cm horizontal points' protrusion values.

After that, the third stage was based on a comprehensive comparison between the two previous approaches, GAs optimization and parallel parametric simulation, addressing the potentials and limitations of each of them. The comparison showed that; GAs optimization didn't seem to be effective; as it took too much time to get an accepted solution. Moreover, the effect of the variations in screen parameters on daylighting and thermal performance couldn't be investigated. On the other hand, parallel parametric simulation approach showed great potential in exploring the effect of each screen parameter as well as the interactions of them together on the whole performance within a reasonable simulation running time. This approach also allowed identifying optimal solutions but they were all with fixed variables for all screen modules

Finally, two parametric-based optimization methods were proposed, modified GAs optimization method and Adapted Algorithms method. The results proved their ability to optimize solar screens efficiently for specific target performance.

Chapter 6 Conclusion and Recommendations

6.1. General conclusion

Growing interest in digital design tools and generative systems in the architectural discourse, especially parametric systems and optimization algorithms, has the potential to be of greater value if capable of expanding their scope from form generation tools to a more ecological-conscious approach by coupling them with performance simulation tools within a comprehensive collaborative methodology. Adopting this methodology in the current architectural practice can contribute in solving the energy problem in Egypt.

Commercial office buildings in Egypt consumed 8.2% of primary energy and about 18% of the nation's electricity in 2011. Air conditioning and lighting were found to be accounted for over two thirds of electricity consumption in commercial buildings sector in Egypt. Attributing to this rising energy demand is the office building facades. In hot arid climates like Egypt, the facade's configuration is responsible for up to 45% of the cooling loads. Consequently, the urgent need for balancing thermal and daylight performance in office buildings in order to reduce the total energy consumption while enhance occupant comfort in an environmentally sustainable manner, has become a vital issue. Thus, this thesis showed the potentials of ecological façade, and specially the ecological solar screens in enhancing office buildings daylight, thermal and energy performance through investigating comprehensive analysis for recent academic studies. Consequently, thermal and daylight performance integration methodologies were defined addressing their linking parameter, tools and process.

Simulation tools had proven to be powerful tools for studying the environmental performance of the building with the ability to engage daylight with thermal analysis through the design process. However, current simulations are based on the scenario-by-scenario approach where limited alternatives are modeled and evaluated to make design decisions. This is mainly due to effort and time consuming limitations of modeling large number of alternatives. Thus, parametric generative systems with their potentials to linking parametric modeling tools with performance simulation tools were introduced as a generative-explorative design method that could overcome the traditional simulation methods' limitations. But, with the wide span of the search space and the numbers of resulting solutions, it becomes almost impossible for the architects to evaluate each solution systematically based on the targeted performance due to time consuming and other limitations. Therefore, design exploration methodologies that integrated parametric design tools with computational search methods could help architects to achieve the optimal solutions that respond to the desired performance values and overcome the previous limitations. In this context, Genetic optimization algorithms were addressed as a supportive methodology that aim to guide the parametric generation to the optimal or near optimal solutions without the need to explore all of the alternatives.

6.1.1. Integrated methodology tools

- **Parametric modelling tool:**

Grasshopper parametric modelling plugin for Rhinoceros 3D modeling software, was chosen as it is graphical-base tool which doesn't require scripting knowledge to use it and thus, it is the most preferable parametric tools for architects. Grasshopper was also chosen due to its ability to include many other plugins, such as environmental simulations plugins, to expand the parametric model ability to include performance aspects.

- **Performance simulation tool:**

DIVA-for-Rhino is used to interface DAYSIM / Radiance and EnergyPlus engines to measure daylight and thermal performance respectively. DIVA was chosen so that all modelling, daylight and thermal simulations could be carried out within the Rhino and Grasshopper environment without the need to export the model to various simulation tools. These were conducted mainly using DIVA Daylight Analysis component and Viper: DIVA Thermal Analysis components plugins for Grasshopper.

- **Genetic Optimization tool:**

Galapagos is used as a Genetic Algorithms global single-objective optimization tool. It is generic component of Grasshopper that has the ability to control the input parameters using numeric sliders (single genes) and gene pool components (a collection of genes) which were required for this study.

6.1.2. Integrated daylight and thermal parametric simulation methodology

Firstly two 3D models for the office space were modelled within Grasshopper, one with full details and real thicknesses to be used for the DIVA daylight simulations and another simplifying one to be connected to Viper thermal analysis as thermal simulations tools could only deal with single surfaces models. Secondly the proposed screen was parametrically modelled and applied to this south façade. A wide range of screen configurations could be processed by changing parameters in Grasshopper. After that each screen alternative was linked to DIVA Daylight Analysis component within Grasshopper to firstly, measure the daylight performance inside the office space, secondly, to generate the electric lighting schedule and to calculate the screen shading coefficient to be linked to the thermal simulation later. Then the thermal simulation was conducted using Viper component within Grasshopper. Finally the simulation results aligned with their specific configurations are collected and exported to a Microsoft Excel sheet using TT tool box plugin for Grasshopper that contains a fast Excel Writer which can transform results' numbers into excel to be analyzed and evaluated.

The calculation of the screen shading coefficient was conducted to overcome EnergyPlus current limitation as default runs can't sufficiently recognize complex geometries such as the solar screen of this research.

6.1.3. Solar screen analysis and explorations

This research presented a simulation-based study for evaluating the effect of a non-conventional ecological solar screen's parameters on indoor daylight adequacy and thermal performance within the maximum possible energy savings.

Parallel parametric simulations results were analyzed systematically using an exhaustive search method to explore the general tendency of each parameter and the impact of their interactions. The simulation was conducted for a south-oriented facade of an office space in Cairo, Egypt to evaluate different solar screen parameters; size, rotation angle, scale ratio and vertical and horizontal point's protrusion values, with specific ranges resulting in 1875 alternatives.

Radiance simulation engine has the ability to conduct parallel simulations according to the available CPU cores of the used computer, which were 8 in this case. Thus, the simulation runs showed their potential to run about 235 simulations parallel and save total running time by 8 times more than the default parametric runs. However, EnergyPlus could not run parallel thermal simulation thus, a special algorithm definition was developed within Grasshopper that could automatically recall the needed data generated during the parallel daylight simulations process to be connected to Viper for the thermal analysis. Thus, all the 1875 alternatives' thermal simulation runs were automated after the completion of the parallel daylight simulation runs. Results were analyzed through three phases; daylight analysis, thermal analysis and integrating both of them to reach the optimal results.

For daylight analysis; screen's rotation angles didn't have a relevant effect on the screen performance however, the 0° rotation angle was recommended as it gave better daylight performance due to its ability to have larger scale ratios then other angles. Screen's scale ratio combined with protrusion values impacted the daylight performance of each unit's size strongly, as sDA and ASE decreased obviously with small scale ratios and large protrusion values. However, accepted results that comply with targeted performance couldn't be achieved until large scale ratios were used, 65% and 80%. Meanwhile, screen's protrusion values and units' size had the most remarkable effect on the screen's daylight performance. Generally, for each screen size, vertical and horizontal point's protrusion values were inversely related to achieve accepted results. As the higher the vertical points, the lower the horizontal points with specific proportions related to the size value of each unit. This explains the lack of the ability of the large units' size of 120 cm to reach acceptable results due to the protrusion value limitations form 5cm to 60cm.

For thermal analysis; the best optimum alternatives for each size from the previous daylighting analysis and their corresponding thermal loads were explored while energy savings percentages were calculated compared to the bases case energy load. Regarding heating loads, they were almost constant at a certain level for each size. In contrast, cooling loads were the most influential in such hot arid climate.

A correlation between ASE, overlit area and increasing cooling loads was deduced. And it was also shown that for the alternatives that had the same ASE value with convergent sDA values, higher overlit area indicated increasing in cooling loads. Another correlation between partially daylit area increasing lighting loads was deduced. It was also shown that alternatives that comply with IES criteria mostly indicated better cooling loads than others. Therefore, calculating Daylight Availability, sDA and ASE could give an indication about cooling loads. Hence daylighting optimum cases can be sorted regarding thermal and energy performance without even being calculated.

It was concluded that the optimal cases that could balance daylight and thermal performance with highest possible energy savings could be mostly achieved by the following selection criteria; firstly define the alternatives that comply with IES and optimal requirements (sDA> 75% & ASE <3%). Then select the case with the highest sDA value among them. If there are similar cases, choose the case with lowest ASE value. In case of similar ASE values, select the case with the lowest overlit area. Finally, if there are similar cases, indicate the case with the lowest partially lit area as the optimal case. This selection criteria also approved with the results found in (Wagdy and Fathy 2016).

From the previous analysis, the optimal screen configurations for each size were defined;

- **For screens with 30 cm units' size**, the configuration of 0° rotation angle, 80% scale ratio, 30cm vertical points' protrusion value and 15cm horizontal points' protrusion values was the optimal case for this size for balancing daylighting and thermal performance. It achieved 95% sDA with 2% ASE that comply with both IES and LEED v4 3-credits criteria, as well as achieving 5.3%, 80.6%, and 14.2% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 156.76 kWh/m^2, 10.81 kWh/m^{2,} and 4.0481 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 42% energy savings compared to the base case.
- **For screens with 60 cm units' size**, the configuration of 0° rotation angle, 80% scale ratio, 60cm vertical points' protrusion value and 15cm horizontal points' protrusion values had proven its superiority in balancing daylighting and thermal performance. It achieved 99.6% sDA with 1.6% ASE that comply with both IES and LEED v4 3-credits criteria, as well as achieving 0.4%, 80.2%, and 19.4% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 135.81 kWh/m^{2,} 11 kWh/m^2, 3.41 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 49% energy savings compared to the base case.
- For **the screens with 120 cm units' size**, the configuration of 0° rotation angle, 65% scale ratio, 60cm vertical points' protrusion value and 45cm horizontal points' protrusion values was the optimal case for this size. It achieved 75% sDA with 6.5% ASE that couldn't comply with IES but comply with LEED v4 3-credits criteria, as well as achieving 22.5%, 58.3%, and 16.2% for partially daylit area, daylit area, and overlit area respectively. These were accompanied with 117.21 kWh/m^2, 11.48 kWh/m^2, and 6.49 kWh/m^2 cooling, heating and electric lighting loads respectively. Resulting in 54% energy savings compared to the base case.

6.1.4. Parametric design and Genetic Algorisms effectiveness for ecological designs

Both parametric design and optimization algorithms approaches showed their effectiveness in balancing daylight and thermal performance of office buildings through exploring the proposed solar screen designs.

Generally, parametric design systems allow the modelling of unlimited set of design variations depending on the parametric definition which in turn opens a wide range of possibilities to explore, evaluate and even regenerate the design model to comply with targeted aim. However, these potentials become more effective when integrated with simulation tools to address performative aspects in a comprehensive cycle between form generation and performance evaluation to find the optimal ecological designs.

Consequently, parametric design aspects and modeling tools can assist designers to overcome the current limitations of traditional simulation tools that are based on scenario-by-scenario where limited alternatives are modeled and evaluated to make design decisions due to remodeling effort time consuming.

However, in spite of these potentials, the wide span of the search space and generated solutions could make it impossible for the designers to evaluate each solution systematically based on the targeted performance due to time consuming and other limitations.

Thus, Genetic Algorisms showed great potentials in guiding the parametric generations to the optimal or near optimal solutions without the need to explore all of the alternatives. Optimization algorithms, in contrast with the parametric systems, can facilitate the search of a far greater range of solutions that are very important through the design process exploration. However, GAs doesn't guarantee optimal solutions; it could stuck at local optimal solution instead. Thus, the process could tend to run on indefinitely, never reaching the optimal solutions if the problem hasn't been well-defined earlier. This includes a pre well-defined fitness equation accompanied with appropriate parameters and search space, which isn't always an easy task especially at early design phases.

Based on the practical analysis of the case studies;

A comprehensive comparison between the two previous approaches, GAs optimization and parallel parametric simulation were conducted. The comparison showed that; GAs optimization initial process didn't seem to be effective; as it took too much time to get an accepted solution that complies with the target performance. The main reason of this drawback was that; the optimization fitness landscape had too many peaks with accepted solution and with wide range in results causing many local optima peaks where the process got stuck in one of them. Moreover, the effect of the variations in screen parameters on daylighting and thermal performance couldn't be investigated as GAs optimization process doesn't provide an informative back-tracing exploration of design solutions so as to modify the process for better results.

On the other hand, the previously addressed limitations of parametric simulations were avoided by using parallel parametric algorithms for the simulation runs and an exhaustive search method for analyzing the results. Results showed great potential in exploring the effect of each screen parameter as well as the interactions of them together on the whole performance within a reasonable simulation running time. However, this approach failed to address various combination screen parameters as the alternative were based on fixing the parameter for all modules of each same screen.

6.1.5. Suggested parametric-based optimization methods

In order to make a worthwhile investment from the above explorations and help architects to efficiently optimize any solar screens for specific target performance, two parametric-based optimization methods were suggested by the end of this thesis. They aim to combine both parametric and optimization potentials with the minimum possible limitations into more efficient solutions. The first method, Modified GAs, was based on modifying the genetic algorithms parameters by considering the parametric results exploration to overcome the limitations of the previous fitness space. While the second method, Adapted Parametric Algorithms, relied on a special algorithm developed in Grasshopper by the researcher that aim to generate almost unlimited number of well-performed screen configurations that relied on the optimal cases of the parametric simulation results. Through this method, the optimal solution of the previous parametric simulations will map the solution space to ensure achieving the optimal balance between daylight and thermal performance while reducing the total energy consumption. Thus, the main GAs optimization's advantage of exploring wide screen variations will be achieved but in this case immediately through a parametric simulation process that offers the optimal time consuming. By this adapted method, almost unlimited number of alternatives that all could balance daylight and thermal performance will be achieved within minimum possible time.

6.2. Research Recommendations

6.2.1. Recommendations for those interested in the domain of academic architectural studies:

- As a result of today's new digital design methodologies; an extended academic course for undergraduate students is recommended to integrate parametric system and optimization algorithms through the design exploration process form early design phases.
- Using parallel parametric simulation for integration both daylight and thermal analyzing based on the methodology and developed parametric algorithm presented in this reach to fully explore shading devices within a reasonable time.
- Applying the proposed parametric-based methods to effectively achieve optimal design configurations for various ecological façade components within a specific target performance
- Using shading coefficient calculation for addressing thermal simulation for complex solar screen and shading systems to overcome EnergyPlus default analysis limitation of a complex geometries.

6.2.2. Recommendations for general architectural and construction community:

- Integrating digital fabrication methodologies and integrate them with parametric optimization algorithms and performance simulation tools within a continual design-feedback loop process to get executable novel forms that respond to specific target performance.
- Combining parametric design modeling with Genetic optimization to generate non-conventional, geometric-based and any novel ecological solar screens.

6.2.3. Recommendations for those working in the field of sustainability and energy conservation:

- Depending on Dynamic Daylight Performance Metrics when conducting daylight analysis ensures accurate results that varies according to different location, orientations and time.
- Using the proposed selection criteria to indicate the optimal or near optimal solutions that could balance daylight and thermal performance within the maximum possible energy saving based on daylight simulations only.

6.3. Future Work

The research can be extended in several ways such as;

- Implementing the methodology of this research for open plan office workstations to optimize their environmental needs.
- Implementing the methodology of this research for different climatic zones and different orientations, east and west facades, addressing the difference in solar screens configurations for each case.
- Exploring the effect of solar screens on natural ventilation and structural aspects can be studied for office spaces.
- Exploring the effect of different materials of the solar screens on daylight, thermal and energy performance.
- Investigating various novel screen patterns and configurations following the methodology of this research.
- Investigating the use of dynamic and kinetic systems for more adaptive solar screens and comparing the feasibility of dynamic systems and fixed systems may give a better guide for designing even more performativity facades.
- Integrating life cycle cost study for the solar screen within the same methodology of this research.
- Integrating digital fabrication techniques within the methodology of this research.
- Conducting practical experimentation on physical models to validate the parametric optimization results due to various performance aspects.

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Appendix A: Dynamic Daylight Metrics

The main advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together. Dynamic daylight performance metrics are based on time series of illumination within a building, usually extend over the whole year, and are based on external, annual solar radiation data for the building site. Some of these metrics are;

1) Daylight Autonomy (DA)

Daylight autonomy uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone. The definition of daylight autonomy as "the percentage of the year when a minimum illuminance threshold is met by daylight alone" goes at least as far back as 1989 when it was mentioned in a Swiss norm Association Suisse des Electriciens, (1989). After that it disappeared until the new millennium when (Reinhart and Walkenhorst 2001) proposed this metric to replace daylight factor (DF) because DF had many limitations as mentioned before. The daylight autonomy at a point in a building was defined later with some modifications as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone.

In contrast to daylight factor, daylight autonomy considers all sky conditions throughout the year. Daylight Autonomy can work very efficiently to detect low day lit spaces, but there are two main limitations to this metric. First, Daylight Autonomy fails to give significance to those daylight illuminances that are below the threshold but which are nevertheless valued by occupants and may also have the potential to displace all or part of the electric lighting loads. Second, the absence of having any upper limit to report the daylight illuminances that exceeded the threshold at any particular area, which can inform about glare and thermal discomfort.

2) Continuous Daylight Autonomy (DAcon)

Continuous Daylight Autonomy (DAcon) recently proposed by Rogers (2005) as another set of dynamic metrics. Continuous Daylight Autonomy use the same technique of Daylight Autonomy but this metric gives partial credit to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 500 lx are required and 400 lx are provided by daylight at a given time step, a partial credit of 400 lx/500 lx = 0.8 is given for that time step. The result is that instead of a hard threshold the transition between compliance and noncompliance becomes softened Rogers (2005).

Essentially, the metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial. However, lack of upper threshold criteria in Continuous Daylight Autonomy is the main limitation where there is no indication for occurrence of direct sunlight or other potentially glary conditions.

3) Maximum Daylight Autonomy (DAmax)

To overcome (DAcon) limitation, a second quantity, maximum Daylight Autonomy (DAmax), is reported together with DAcon to indicate the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present. Assuming that the threshold of potentially glary conditions depends on the space type, DAmax was defined to be a sliding level equal to ten times the design illuminance of a space. For example, if a computer lab requires design illuminance of 150 lux, DAmax will correspond to 1500 lux. This upper threshold criterion is essentially a measure of the occurrence of direct sunlight or other potentially glary conditions and can give an indication of how often and where large illuminance contrasts appear in a space.

4) Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA), a measure of daylight illuminance sufficiency for a given area. It is defined as the percentage of an analysis area that meets a minimum daylight illuminance level for a specified percentage of the occupied hours per year For example, ($sDA_{300,50\%}$) metric describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. In 2012 (IES) (IES 2012) recommended using the annual occupied hours as from 8am to 6pm local clock time (10 hours per day).

While alternative thresholds and analysis periods may be appropriately used for more detailed performance analysis of an individual daylit space, these standard analysis thresholds – of 300 lux and 50% temporal threshold over a 10 hour day—are recommended for specification and reporting so that comparisons can also be made to a consistent performance standard.

5) Useful Daylight Illuminances (UDI)

Useful Daylight Illuminances (UDI) was proposed by (Nabil and Mardaljevic 2005). UDI addresses some of the issues related to DF and DA. It is a dynamic daylight performance metric based also on work plane Illuminances.

As its name suggests, it aims to determine when daylight levels are 'useful' for the occupant, that is; neither too dark (<100 lx) nor too bright (>2000 lx). Based on the upper and lower thresholds of 2000 lx and 100 lx, UDI results in three metrics, that is, the percentages of the occupied times of the year when;

- UDI is achieved (100–2000 lx)
- Fall short of the UDI range (less than 100 lx)
- Exceed UDI range (greater than 2000 lx)

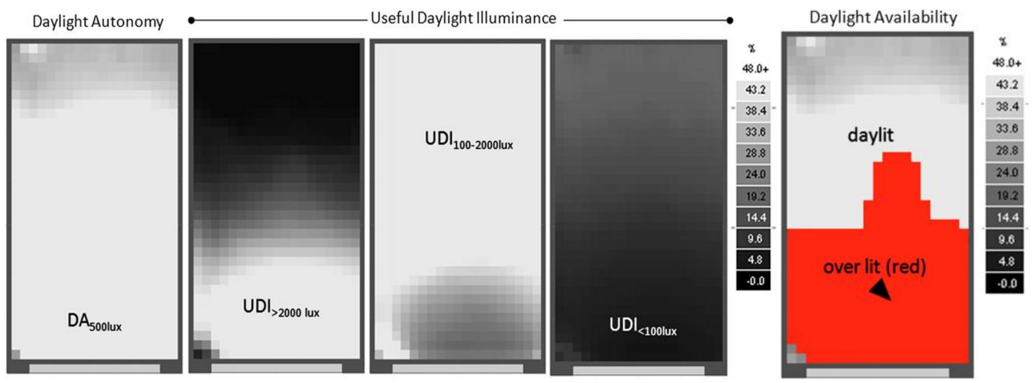
The metric proposes that if the daylight illuminance is too small (<100 lx), it may not contribute in any useful manner to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too great (>2000 lx), it may generate visual or thermal discomfort, or both. This last condition is meant to detect the likely appearance of glare. (Li and Wong 2007) considered 1000 lux as the upper illuminance level. From his standpoint, 2000 lux still considered accepted value for human eye but this value would lead for more heat gain, which is not acceptable for subtropical or hot arid climate.

6) Daylight Availability

Daylight availability is a new metric that is meant to integrate DA and UDI information into a single figure. Daylight Availability proposes three evaluation levels to use;

- The "daylit" areas are those that received sufficient daylight at least half of the year-round occupied time.
- The "partially daylit" areas are those that did not receive sufficient daylight through the year-round occupied time.
- The "over lit" areas are those areas that received an oversupply of daylight, where 10 times the target illuminance was reached for at least 5% of the year-round occupied time.

The 5% criterion was selected as an analogue method to thermal assessments according to British Standard BS EN 15251[3]. The standard defines threshold levels for several thermal comfort categories which may be exceeded 3-5% percent of the occupied times of the year (Reinhart and Wienold 2011).



Figue A. 1 Plan view of the Daylight Autonomy and Useful Daylight Illuminance distributions in the sidelit office from

Source: (Reinhart and Wienold 2011).

7) Annual Sunlight Exposure (ASE)

Annual Sunlight Exposure (ASE) is a metric that describes the potential for visual discomfort in interior work environments, particularly the presence of direct sunlight. It is defined as the percent of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year. According to the Approved Method IES, described in Illuminating Engineering Society report number LM-83-12, the recommended settings for ASE analysis determines the percentage of the analysis points that exceeds a specified illuminance level, 1000 lux, for at least 250 hours per year of the occupied hours ($ASE_{1000,250h}$), without any contribution from the sky (IES 2012).

Appendix B: Daylight and thermal performance of Ecological facades Literature review

No.	Refrence	Design approach			Building function	case study		Parameters Studied							Performance Considerations					Location		Tools			Performance metric
										Shading Technique															
		Scenario-by-Scenario	Parametric	Optimization		Real	Hypothetical	Windows design/ Ratio (WWR)	Glazing	Shading devices	Perforated Screen	Non-conventional screens	Material	Orientation	Energy Consumption	Visual comfort (Glare)	Thermal Performance	Daylight	Others	Case study (City)	Orientation	Parametric modeling	Optimization algorithm (evolutionary optimization)	Simulation analysis	
1	(A. Wagdy et al. 2015)			●	Office space		●					●			●		●	●		Aswan,Egypt	South	Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE)
2	(Arafa, 2012)	●	●	●	Residential		●				●				●					Kharga Oasis, Egypt	All facades		GenOp	EnergyPlus	———
3	(Ayman Wagdy & Fathy, 2015)		●		classroom		●	●		●			●			●		●		Cairo, Egypt			_____	Diva for Rhino	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability Annual Daylight Glare Probability (DGP)
4	(Ayman Wagdy & Fathy, 2016)		●		Class room		●			●					●			●		Cairo, Egypt	South	Grasshopper		DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability
5	(Chalabee, 2013)			●	office buildings		●	●							●		●	●		Somerville, Boston, United stated	West	Grasshopper	Galapagos	DIVA	———
6	(Elghazi, Wagdy, Mohamed, & Hassan, 2014)	●		●	living room		●					●						●		Cairo, Egypt	South	Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability LEED v4
7	(Emami, Khodadadi, & von Buelow, 2014)		●	●	Office space		●					●						●	Structural performance	Phoenix, AZ,USA	South	Grasshopper	ParaGen	Diva-for-Rhino ANSYS (structural sim.)	Daylight Autonomy Daylight factor (DF) %
8	(Hegazy and Wagdy 2016)			●	office space	●		●				●						●		Cairo, Egypt	South	Rhinoceros / Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability
9	(Naboni et al. 2013)	●	●	●	Student work/study place	●	●			●			●	●	●		●			Copenhagen,Denmark		jEplus	jEplus+EA	Openstudio	———
10	(Naboni, Zhang, Maccarini, Hirsch, & Lezzi, 2013)		●		office space		●		●	●			●	●	●		●			Copenhagen,Denmark	All facades	jEplus,	_____	Openstudio	Danish standard BR10
11	(Omidfar, 2011)		●		open-plan office space		●					●			●			●	View	Boston MA	South	Grasshopper		DIVA Design Builder	Daylight Autonomy (DA) Shading coefficient
12	(Omidfar, 2015)				Office space		●					●						●	tructuralس performance	New York City, USA	South East West	Grasshopper	ParaGen	DIVA STAAD.Pro (structural)	Daylight autonomy (DA) Radiation (RAD) Bi-Directional Transmission Method
13	(Omidfar, Torghabehi et al. 2014)			●	Office space	●						●						●	tructuralس performance	New York City, USA	South East West	Grasshopper	ParaGen	DIVA STAAD.Pro (structural)	Daylight Autonomy (DA) Radiation (RAD)
14	(Portugal & Guedes, 2012)			●	Residential		●	●									●			Somerville, MA,USA		Grasshopper	Galapagos	Diva-for-Rhino SpeedSim-for-DIVA	Daylight Autonomy (DA)
15	(Sherif, Sabry, Wagdy, Mashaly, & Arafa, 2016)		●		hospital patient room		●			●								●	View	Cairo,Egypt	South	Grasshoper		Diva-for-Rhino SpeedSim-for-DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) External View Factor (EVF)
16	(Torres & Sakamoto, 2007)			●				●		●			●		●			●		Tokyo, Japan.			Script within Radiance	Radiance	Glare index (DGP)
17	(Turrin, von Buelow, & Stouffs, 2011)			●			●					●					●	●	structural performance			Generative Components	ParaGen	Ecotect STAAD.Pro	———

Appendix c: Parametric design and Optimization algorithms Literature review

No.	Refrence	Design approach			Building function	case study		Parameters Studied								Performance Considerations					Location		Tools			Performance metric
										Shading Technique																
		Scenario-by-Scenario	Parametric	Optimization		Real	Hypothetical	Windows design/ Ratio (WWR)	Glazing	Shading devices	Perforated Screen	Non-conventional screens (Geometrical	Moveable / Kinetic Skin	Material	Orientation	Energy Consumption	Visual comfort /Glare	Thermal Performance	Daylight	Others	Case study (City)	Orientation	Parametric modeling	Optimization algorithm (evolutionary optimization)	Simulation analysis	
1	(A. Wagdy et al. 2015)			●	Office space		●					●				●		●	●		Aswan,Egypt	South	Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE)
2	(Arafa, 2012)	●	●	●	Residential		●				●					●					Kharga Oasis, Egypt			GenOp	EnergyPlus	————
3	(Ayman Wagdy & Fathy, 2015)		●		classroom		●	●		●				●			●		●		Cairo, Egypt		Rhinoceros and Grasshopper	———	Diva for Rhino	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability Annual Daylight Glare Probability (DGP)
4	(Ayman Wagdy & Fathy, 2016)		●		Class room		●			●						●			●		Cairo, Egypt	South	Grasshopper		DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability
5	(Chalabee, 2013)			●	office buildings		●	●								●		●	●		Somerville, Boston, United stated	West	Grasshopper	Galapagos	DIVA	————
6	(Elghazi, Wagdy, Mohamed, & Hassan, 2014)	●		●	living room		●					●							●		Cairo, Egypt	South	Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability LEED v4
7	(Emami, Khodadadi, & von Buelow, 2014)		●	●	Office space		●					●							●	Structural performance	Phoenix, AZ,USA	South	Grasshopper	ParaGen	Diva-for-Rhino ANSYS (structural sim.)	Daylight Autonomy Daylight factor (DF) %
8	(Hegazy and Wagdy 2016)			●	office space	●		●				●							●		Cairo, Egypt	South	Rhinoceros / Grasshopper	Galapagos	DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) Daylight Availability
9	(Naboni et al. 2013)	●	●	●	Student work/study place	●	●			●				●	●	●		●			Copenhagen,Denmark		jEplus	jEplus+EA	Openstudio	———
10	(Naboni, Zhang, Maccarini, Hirsch, & Lezzi, 2013)		●		office space		●		●	●				●	●	●		●			Copenhagen,Denmark	All facades	jEplus,	———	Openstudio	Danish standard BR10
11	(Omidfar, 2011)		●		open-plan office space		●					●				●			●	View	Boston MA	South	Grasshopper		DIVA Design Builder	Daylight Autonomy (DA) Shading coefficient
12	(Omidfar, 2015)				Office space		●					●							●	tructural performance	New York City, USA	South East West	Grasshopper	ParaGen	DIVA STAAD.Pro (structural)	Daylight autonomy (DA) Radiation (RAD) Bi-Directional Transmission Method
13	(Omidfar, Torghabehi et al. 2014)			●	Office space	●						●							●	tructural performance	New York City, USA	South East West	Grasshopper	ParaGen	DIVA STAAD.Pro (structural)	Daylight Autonomy (DA) Radiation (RAD)
14	(Portugal & Guedes, 2012)			●	Residential		●	●										●			Somerville, MA,USA		Grasshopper	Galapagos	Diva-for-Rhino SpeedSim-for-DIVA	Daylight Autonomy (DA)
15	(Sherif, Sabry, Wagdy, Mashaly, & Arafa, 2016)		●		hospital patient room		●			●									●	View	Cairo,Egypt	South	Grasshoper		Diva-for-Rhino SpeedSim-for-DIVA	Spatial Daylight Autonomy (sDA) Annual Sunlight Exposure (ASE) External View Factor (EVF)
16	(Torres & Sakamoto, 2007)			●				●		●				●		●			●		Tokyo, Japan.			Script within Radiance	Radiance	Glare index (DGP)
17	(Turrin, von Buelow, & Stouffs, 2011)			●			●					●						●	●	structural performance			Generative Components	ParaGen	Ecotect STAAD.Pro	———

الملخص

يعتبر المهندس المعماري المتحكم الرئيسى في عملية التصميم بأكملها بدءا من مراحل التصميم الأولى حتى نهاية المنتج المعماري . ولكنه بمرور الوقت و مع استخدام آليات البناء ذات الإنتاج الضخم مما أدى الى انفصال المهندسين المعماريين عن العديد من الجوانب الرئيسية لإنتاج المباني. و لكن بظهور التكنولوجيات الجديدة التى تتضمن أنظمة التصميم و التصنيع الرقمية، أمكن تضييق الفجوة بين التصميم المعماري و جوانبه الهندسية و الانشائية و دمجها في عملية تكاملية، عاد للمعماري دوره الرئيسى مرة أخرى.

يتناول البحث مجالات وطرق إستخدام التصميم البارمتري (Parametric design) ومجالات التحسين الأمثل التطوري (Evolutionary optimization) ، التى حولت العملية التصميمة من تصميم "المجسم" الى تصميم "المنطق" ، مع إعتبار منهج التحسين الأمثل التصميم البارمتري كأداة استكشافية لخلق تصميمات حديثة.

تلعب الواجهة دورا هاما في مجال العمارة، فهى تعتبر الحد الفاصل بين الفراغات الداخلية والبيئة الخارجية. ومن ذلك نتبين أن الاعتماد المتزايد داخل المباني الادارية على أنظمة الإضاءة الاصطناعية و تكييف الهواء يشير إلى فشل واجهة المبنى فى أداء وظيفتها، رغم ما أثبتته واجهات المبانى إمكاناتها لتعزيز الأداء البيئي و توفير الراحة والتحكم البيئي .
لذلك فان الهدف من البحث هو إظهار وتوضيح اهمية التصميم البارمتري
(Parametric design) ومجالات التحسين الأمثل الوراثية (Genetic optimization) وطرق ادماجهم مع أدوات محاكاة الاداء البيئي لتصميم ستائر الحماية الشمسية للواجات
(Solar screens) لضمان توفير افضل توازن ممكن بين الاضاءة الطبيعية والاداء الحراري داخل للفراغات الادارية ذات الواجهات الجنوبية بالقاهرة, مصر وبما يضمن اقل استهلاك ممكن للطاقة.

الملخص

و تنقسم الدراسة فى هذا البحث الى جزئين كما يلي:

- **أولا، الدراسة النظرية** ، يستعرض البحث أسس الاضاءة الطبيعية و الأداء الحراري للمباني الادارية و التي تؤثر على استهلاك الطاقة. وكذلك عرض مقاييس الأداء البيئى ، نظم التصنيف و أدوات المحاكاة لتأسيس المعرفة الأساسية لهذه الدراسة. ويختتم هذا الجزء بعرض منهجية متكاملة تجمع بين الاضاءة الطبيعية و الأداء الحراري للمباني الادارية . كما تتطرق الدراسة الى التعرف على منهجيات وأساليب التصميم الرقمى التحليلي لتحسين الأداء البيئى لتصميمات المباني.

- **ثانيا الدراسة التطبيقية التجريبية** ، على أساس المحاكاة الحاسوبية باستخدام مزيج من المنهجيات السابقة . حيث تم اختبار الاضاءة الطبيعية و الأداء الحراري باستخدام DIVA ، Grasshopper و Galapagos على التوالي حيث كان يستخدم لتقييم و تحسين شاشة شمسية غير تقليدية ، لتحقيق التوازن بين الاضاءة الطبيعية و الأداء الحراري مع تقليل استهلاك الطاقة. وقد أجريت هذة التجارب على واجهة جنوبية لفراغ اداري في القاهرة ، مصر.

وهكذا ، قدمت الدراسة أطروحة تحليل شامل لتأثير العوامل المختلفة لتصميم ستائر الحماية الشمسية للواجهات على كل من الاضاءة الطبيعية و الأداء الحراري للمباني الادارية، وتناولت معايير التقييم التي أعطت مؤشرا عن استهلاك الطاقة . كما أجرى هذا البحث مقارنة تحليلية بين التحسين الأمثل التطوري و نهج المحاكاة البارمتري مع اختبار فعالية كل نهج في تحقيق التوازن بين الاضاءة الطبيعية و الأداء الحراري للواجهة المقترحة. كذلك تم عرض مبادئ توجيهية تساعد المهندسين المعماريين فى تصميم واجهات شمسية غير التقليدية ذات كفاءة بيئية، وينتهي البحث بعرض لأهم النتائج والتوصيات.

الكلمات الدالة:

التصميم البارامتري، الخوارزميات الجينية ، ستائر الحماية الشمسية ، الأضاءة الطبيعية– الاداء الحراري، المباني الأدارية.

مهندس: أسماء جمال عبدالفتاح السيد حسن

تاريخ الميلاد: 1989\11\20

الجنسية: مصري

تاريخ التسجيل: 2011/10/2

تاريخ المنح: / / 2016

القسم: الهندسة المعمارية

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أ.د. أحمد رضا عابدين (المشرف الرئيسي)

عنوان الرسالة:

نحو التصميم البارامتري الأمثل لستائر الحماية الشمسية للواجهات

مدخل لتحقيق التوازن بين الأداء الحراري والإضاءة الطبيعية للمباني الإدارية في مصر

الكلمات الدالة:

التصميم البارامتري، الخوارزميات الجينية ، ستائر الحماية الشمسية ، الأضاءة الطبيعية–الاداء الحراري، المباني الأدارية.

ملخص الرسالة:

يقوم البحث بتقديم أطروحة تحليل شامل لتأثير العوامل المختلفة لتصميم ستائر الحماية الشمسية للواجهات على كل من الاضاءة الطبيعية و الأداء الحراري للمباني الادارية، وتناولت معايير التقييم التي أعطت مؤشرا عن استهلاك الطاقة . كما أجرى هذا البحث مقارنة تحليلية بين التحسين الأمثل التطوري و نهج المحاكاة البارمتري مع اختبار فعالية كل نهج في تحقيق التوازن بين الاضاءة الطبيعية و الأداء الحراري للواجهة المقترحة. كذلك تم عرض مبادئ توجيهية تساعد المهندسين المعماريين فى تصميم واجهات شمسية غير التقليدية ذات كفاءة بيئية، وينتهي البحث بعرض لأهم النتائج والتوصيات.

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مدخل لتحقيق التوازن بين الأداء الحراري والإضاءة الطبيعية للمباني الإدارية في مصر

اعداد
أسماء جمال عبد الفتاح السيد حسن

رسالة مقدمة إلى كلية الهندسة – جامعة القاهرة
كجزء من متطلبات الحصول على درجة ماجستير العلوم
في
الهندسة المعمارية

يعتمد من لجنة الممتحنين:

الاستاذ الدكتور: أحمد رضا عابدين — المشرف الرئيسي

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الاستاذ الدكتور: عباس محمد الزعفراني — الممتحن الخارجي
عميد كلية التخطيط الإقليمي و العمراني بجامعة القاهرة

كليـة الهندسـة- جامعـة القاهـرة
الجيـزة- جمهوريـة مصـر العربيـة
2016

نحو التصميم البارامتري الأمثل لستائر الحماية الشمسية للواجهات
مدخل لتحقيق التوازن بين الأداء الحراري والأضاءة الطبيعية للمباني الأدراية في مصر

اعداد
أسماء جمال عبد الفتاح السيد حسن

رسالة مقدمة إلى كلية الهندسة – جامعة القاهرة
كجزء من متطلبات الحصول على درجة ماجستير العلوم
في
الهندسة المعمارية

تحت اشراف

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الجيـزة - جمهوريـة مصـر العربيــة

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مدخل لتحقيق التوازن بين الأداء الحراري والإضاءة الطبيعية للمباني
الإدارية في مصر

اعداد

أسماء جمال عبد الفتاح السيد حسن

رسالة مقدمة إلى كلية الهندسة - جامعة القاهرة
كجزء من متطلبات الحصول على درجة ماجستير العلوم
في
الهندسة المعمارية

كليـة الهندسـة - جامعـة القاهـرة
الجيـزة - جمهوريـة مصـر العربيـة

2016