ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A RESEARCH ON THE EFFECTS OF THE COMPUTATIONAL DESIGN ON OPTIMIZATION OF THE LOUVER SYSTEMS OF OFFICE BUILDINGS

M.Sc. THESIS

Fatih GÜLPINAR

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

OFİS BİNALARINDAKİ PANJUR SİSTEMLERİNİN OPTİMİZASYONU SÜRECİNDE, BİLGİSAYAR DESTEKLİ TASARIMIN ETKİLERİ ÜZERİNE BİR ÇALIŞMA

YÜKSEK LİSANS TEZİ

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EKİM 2014

Fatih GÜLPINAR, a **M.Sc.** student of ITU **Institute of / Graduate School of Architecture** student ID 523101008 , successfully defended the **thesis/dissertation** entitled "**A RESEARCH ON THE EFFECTS OF THE COMPUTATIONAL DESIGN ON OPTIMIZATION OF THE LOUVER SYSTEMS OF OFFICE BUILDINGS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 24 October 2014
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To my Family,

FOREWORD

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December 2013

Fatih GÜLPINAR
(Architect)

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ABBREVIATIONS

BRE	**:** Building Research Establishment
CAD	**:** Computer Aided Drawing
CBR	**:** Case Based Reasoning
DF	**:** Daylight Factor
EA	**:** Evolutionary Algorithms
IES	**:** Illuminating Engineering Society
KBS	**:** Knowledge-Based Systems
NURBS	**:** Non-Uniform Rational Basis Spline
VB	**:** Visual Basic
VBA	**:** Visual Basic for Applications

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A RESEARCH ON THE EFFECTS OF THE COMPUTATIONAL DESIGN ON OPTIMIZATION OF THE LOUVER SYSTEMS OF OFFICE BUILDINGS

SUMMARY

Computational design is shown as a finished image for a design. Beside this computational design is a new way of understanding and a systematical thinking for architectural design. Its advantages for time efficiency and variability of the results without extra cost cannot be disregarded. This thesis proposes a computational design method to experience the advantages of new architectural computation design concept.

Environmental issues have always been one of the basic topics for architectural design. In order to have an efficient and environmentally satisfied building design, architects should have the knowledge of environmental issues in detail. Two of these issues become prominent in this research; daylight and the thermal environment. When all buildings were designed around a single, fixed light source – the sun – the difference between great architecture and mere building could be measured to a large degree by the skill with which that source was used. The shapes and sizes of rooms, as well as the materials and details in them, were determined largely by the appearance the room would take on when rendered by daylight. Moreover, daylight is an essential resource that is readily available – and unlikely to run out in forseeable future. Besides its energy saving characteristic, it also brings a visual comfort for the occupants of the building. On the other side, a building will be judged by the occupants according to its ability to satisfy the demand of thermal comfort. To provide all these comfort zones, shading devices are needed. Although shading of the whole building is beneficial, shading of the windows is crucial. The total solar load consists of three components: direct, diffuse and reflected radiation. To prevent passive solar heating, when it is not wanted, a window must always be shaded from the direct solar component and often also from the diffuse sky and reflected components. To cover these entire environmental problems a research has been done.

This thesis proposes an optimization model to solve the environmental problems in an optimum result. While doing this, it also examines the advantages of the computational design. The model consists of an office room located in a multistorey office building and louvers, as shading devices, designed connect to the windows type and size. The certain algorithms, which are created with the constraints and parameters obtained during the researches for environmental issues, are run during the process. Moreover, the results are evaluated to see the affects of the computational design and so over.

This thesis is comprised of two different parts. The first part, chapters 2 and 3, gives the reader brief technical knowledge about the computational design and the environmental issues. The second part of the thesis, chapters 4 and 5, explains the proposed model as an optimization model of a louver system for office buildings.

OFİS BİNALARINDAKİ PANJUR SİSTEMLERİNİN OPTİMİZASYONU SÜRECİNDE, BİLGİSAYAR DESTEKLİ TASARIMIN ETKİLERİ ÜZERİNE BİR ÇALIŞMA

ÖZET

Güneşin en büyük ısınma ve aydınlatma kaynağı olduğu ele alındığında, mimarlık ve güneş arasındaki ilişki de ortaya çıkmaktadır. Mekân bilincini insana aşılayan güneşin aydınlatıcı gücü, mimari elemanlar ve çevresel koşullarla da birleşerek insanın mimari ile kurduğu ilişkiyi belirler. Mevsimlerin sunduğu değişken değerlere göre insanların güneş ısısına ihtiyaç miktarları da farklılık göstermektedir. Özellikle yaz aylarında güneşin neden olduğu aşırı ısınmaya engel olunmalıdır. Bu işlevi yerine getirmesi açısından gölgelendirme sistemleri büyük önem taşımaktadır. Gölgelendirme sistemleri her zaman mimarlığın bir parçası olmuştur. Geleneksel mimariye bakıldığı zaman Yunan mimarlığından başlayıp Anadolu mimarisine ve modern mimarlığa ulaşan sistemler mevcuttur. Yunan mimarisinde büyük sütunlar üzerine yerleşen döşemeler bu işlevi görürken modern mimaride bunlar yerini çıkmalara daha sonra da özel tasarımlara bırakmıştır. Türk mimarisinde ise, ilk olarak yığma yapıların ortaya çıkardığı kalın duvarlar bu işlevi yerine getirirken, daha sonra bunları panjurlu pencereler takip etmiştir. Günümüzde ise çok farklı özel tasarımlarla uygulanmış gölgelendirme sistemleri mevcuttur. Bu tezde, gölgelendirme sistemlerinin optimizasyonu sürecinde hangi parametrelerin devreye girdiği ve bu parametrelerin hangi değerlendirme aşamalarından geçtiği incelenmektedir. Bu inceleme yapılırken, mimari bilişim sistemlerinin hangi biçimde ve ölçüde gölgelendirme sistemlerinin optimizasyonuna katkıda bulunduğu ve ne tür kolaylıklar sağladığı da ele alınmıştır.

Enerji ihtiyacının artması ve kaynaklarının azalması ele alındığında, gölgelendirme sistemlerinin ve doğal aydınlatmanın önemi daha da iyi anlaşılmaktadır. Özellikle ofis binaları ve ticari binalar için enerji sarfiyatının en aza indirilmesi büyük önem taşımaktadır. Bu iki program tipinden sadece ofis binalarının harcadığı enerji miktarı tüm binaların harcadığı enerjinin %40'ını oluşturmaktadır. Ofis binaları kendi içinde ise kullanılan enerjinin % 75'lik kısmını ısıtma, soğutma ve aydınlatmaya harcamaktadır. Çevresel faktörlerin doğru ve verimli kullanılması sonucu bu enerji harcamalarında önemli bir düşüş yaşanmaktadır. Bu sebeple, ofis binalarında sıcaklık ve aydınlık derecelerinin belli bir oranda olması gerekmektedir.

Ofis çalışanlarının verimliliğinin düşmemesi için iki adet konfor faktörüne ihtiyaç duyulmaktadır. Bunlardan birincisi, görsel konfor ve ikincisi ise ısısal konfordur. Görsel konfor çalışanların çalıştıkları süreç içerisinde herhangi bir görme zorluğu yaşamadan veya gözlerinde herhangi bir yorgunluk hissetmeden çalışabilecekleri bir ortam yaratılması olarak tanımlanabilir. Görsel konforu sağlamak ve enerji harcamalarını kısıtlamak için gün ışığının doğru kullanılması gerekmektedir. Mekânlardaki gün ışığı kalitesini ve oranını ölçmek için kullanılan en yaygın yöntem günışığı faktörünün hesaplanmasıdır. Günışığı faktörü hesaplanırken birçok parametre kullanılmaktadır. Bunlardan bazıları pencere açıklık ölçüleri, mekân

ölçüleri, iç mekânın malzemeleri, yansıtma katsayıları ve hava şartlarıdır. Gün ışığı ele alınırken iki farklı hava şartı göz önünde bulundurulur. Bunlar; standart kapalı gökyüzü ve açık gökyüzüdür. Isısal konfor şartları ise genelde mevsimsel dönemlere ve mekânı kullan kişi sayısına göre farklılık göstermektedir. Optimum sıcaklık derecesinin oluşturulması genel olarak ısısal konfor için yeterlidir. Bunu doğal yollardan sağlamak için ise sıcaklığın fazla olduğu zaman periyodunda, güneş ışınlarının içeriye girmesini önlemek ve tersi durumlarda ise güneş ışınlarının içeriye girmesine izin vermek gerekmektedir. Güneş ışınlarını engelleme aşamasında gölgelendirme sistemlerinin kullanılması büyük kolaylıklar sağlamaktadır.

Tez iki parçadan oluşur. Tezin ilk kısmı, okuyucuya bilgisayar destekli tasarım, çevresel kontrol sistemleri ve gölgelendirme sistemleri hakkında teknik bilgiler ve kısa bir tarihçe sunar ve 2, 3 ve 4 numaralı bölümleri kapsar. Tezin ikinci kısmı ise, mevcut proje örneklerini değerlendirerek, bu problemlere çözüm oluşturabilecek bir modelin nasıl geliştirilebileceğini anlatır ve 5 numaralı bölümü içerir. Tezin 1 ve 6 numaraları bölümleri ise projenin amaç, yöntem ve sonuç kısımlarını içerir.

Birinci bölüm; tezin yazılma amacı ve yazılması sürecinde hangi metotların kullanıldığına dair kısa bir bilgilendirme sunmaktadır.

İkinci bölüm; üç alt başlıktan oluşmaktadır. Bunlar algoritmalar, kod yazılımı ve optimizasyon şeklinde sıralanmıştır. Bu üç başlık, proje kısmının teknik altyapısını oluşturmaktadır. Proje, panjur sistemlerinin optimizasyonu üzerine odaklanmıştır. Bu bölümde de optimizasyon türleri ve çözüm yöntemleri irdelenmiştir Buna ek olarak optimizasyon aşamasında kullanılacak kod yazılımı ve yazılımdaki kısıt ve parametrelerin oluşturacağı algoritmalar hakkında kısa bir bilgi verilmiştir. Algoritmalar bir işin hangi adımlar izlenerek yapılması gerektiğini ve hangi kısıtlara bağlı kalınmasının gerekli olduğunu belirten reçeteler olarak tanımlanabilir. Optimizasyon ise farklı parametreler kullanılarak ortaya çıkan sonuçlardan en uygun olanın seçme şeklinde tanımlanabilir.

Üçüncü bölüm; ofis kullanıcı konforu için gerekli çevresel kontrol sistemlerini tanıtıp, bu sistemler hakkında teknik bilgiler içermektedir. Görsel ve ısısal konforun ofis çalışanlarının verimliliği açısından önemi tartışılmaktadır. Bu tartışma ışığında, kullanıcı konforlarının sağlanması sürecinde ortaya çıkan problemler hakkında kısaca bilgi verilip, olası çözüm yöntemleri geliştirilmiş; görsel konforun oluşturulmasında rol oynayan kıstasları tanımlamak için gerekli olan günışığı faktörü hakkında detaylı bir çalışma yapılmıştır. Bunlara ek olarak, ofis binalarındaki enerji harcamaları hakkında kısa bir bilgi verildikten sonra enerji tasarrufu ne tür önlemler altında gerçekleştirilebilir, bu konular hakkında tartışılmaktadır.

Dördüncü bölümde; gölgelendirme sistemlerinin kısa bir tarihçesi sunulmaktadır. Tarihçenin arkasından ise gölgelendirme sistemleri çeşitleri, tasarım kıstasları ve teknik konular hakkında bilgiler verilmektedir. Bu bölüm, projede kullanılmış olan panjur sisteminin seçilmesi konusunda alınan kararlara teknik arka plan oluşturmaktadır. Ayrıca hangi dönemlerde gölgeye ihtiyaç duyulduğu, hangi dönemlerde ise ısınma amaçlı güneş ışığına ihtiyaç duyulduğu grafiksel ve anlatımlı olarak sunulmaktadır.

Beşinci bölümde ise; geliştirilen model detaylı bir şekilde anlatılmaktadır. Model oluşturulmadan önce literatürde bulunan diğer proje örnekleri incelenip hangi konularda eksik kaldıkları tespit edilmiştir. Ardından projenin parametreleri, kısıtları ve kullanılacak olan metot ayrıntılı bir şekilde anlatılmıştır. Projede kullanılan algoritmalar ve bu algoritmalar öncülüğünde yazılmış olan kod hakkında detaylı bilgi verilmiştir. Proje modeli için hazırlanan kod, dijital ortamda daha önceden belirlenen durumlar eşliğinde çalıştırılmıştır. Beş farklı durum analizi sonucu çıkan sonuçlar hakkında detaylı bir çalışma yapılmıştır.

Son bölümde ise; tasarlanan modelin hangi yönlerden eksik kaldığı ve ileriye dönük çalışma potansiyeli üzerinde durulmuştur. Belirlenen hedeflere ne ölçüde ulaşıldığı belirlenmiştir. Önerinin geliştirilmesi için öneriler ortaya konmuştur ve yapılan çalışmanın önemine değinilerek tez tamamlanmıştır.

1. INTRODUCTION

1.1 Purpose of Thesis

From the beginning of architecture, environment is one of the most important topics of designing spaces. The need of shelter came into existence because of the environment, people had to have a place to protect themselves from sun, snow, wind etc.

With developing architectural design shelters became living spaces and need of light became a major problem. To solve this problem architects start putting windows on the facades. Due to the lack of different structural materials this windows used to be too small. The new technologies gave architects an opportunity to have bigger openings. With the new technologies and aesthetical concerns architects started to have windows which cover all the façade. That brings the sun shading systems because of overheating and daylighting in the buildings. As people need sunlight during the day, they would be bothered with the extra. Therefore, it should be on the optimum quantity. It is much more important for the office buildings. Employees have their all day at a table in the office so they should have their comfort zone. This comfort zone consists of visual comfort and thermal comfort. Moreover, these comfort issues mostly solved with the shading design technologies.

In this thesis, optimizing the daylight and solar heating in an office room is aimed. Nevertheless, with the computational technologies, software allows the designer to have simulation and optimize the design. So in the thesis while optimizing the environmental control systems, effects of the new tools of computational design are experienced. A computational model supporting the theory is proposed and its implementation discussed briefly.

1.2 Scope of Thesis

Environmental design and computational design are the two different areas of the architecture. On the other hand, they become together some parts of the design phase. Such as, the methods of the computation can be used to solve environmental control issues. With computational methods, it is much easier and faster to solve problems rather than the traditional ones. During the thesis concepts of both computational design and environmental control systems is researched and discussed. While doing that, the focus of the building is the facades. The concepts, which are much more related to facades, environmental design systems are considered. In addition, new links between computational design tools, energy analysis tools and optimization algorithms give an opportunity to customize the design or it components to prevent the anticipated energy use. To achieve variability with efficient time and cost control, scripting is chosen as computational design tool. Then other studies in the literature, dealing with the shading devices and daylighting optimization, are discussed briefly. After these researches and discussions, most proper methods are integrated to have a project about a room of an office building. Parameters for the project and constraint will be detailed to focus on the results, which are taken with the optimization algorithm.

1.3 Method of Thesis

This thesis proposes a optimization model that aims to give the designer an insight about the shading design performance of an office room. Such a methodology can be considered useful for architectural projects located in countries with climate that exhibits high temperature. For preparations of system bases, with the purposes of the study, a detailed research has been done about methods of the computational design, which are algorithms, scripting and optimization, and concepts of environmental control systems, which are daylighting, thermal environment and energy saving strategies. These researches have been taken as a basis for the theoretical background of "Effects of the computational design on optimization of the louver systems of office buildings".

As a result of researches done during the thesis, parametric design has been chosen as a method to optimize sun-shading systems. Firstly, parameters and constraints are decided to create the algorithms. In addition, an office room is chosen for the base of the model and parameters are specified and explained for the model. Secondly with these algorithms a script was written in Monkey © which is a plug-in for Rhinoceros NURBS ©. Thirdly five different cases are specified and four specific result taken for each case to examine the impacts of the case parameters. Finally, all these results are evaluated as inputs for the optimization. Best results have been chosen for the design.

2. COMPUTATIONAL OPTIMIZATION METHODS IN FAÇADE DESIGN

"The recent hard work with computational Technologies in architecture seems to have a hypnotizing effect that, there emerge a need to set back and question what is going on. The works of computational design are mostly presented by the images of very high graphic quality that, fascination with that impressive visual bombardment, captivates our faculties of architectural evaluation most of the times. We find ourselves charmed by the elegant images; and the very sterile world exhibited thereby" (Çinici, 2009).

Computational design is a new way of understanding and a systematical thinking for architectural design. Figure 2.1 shows a product of computational design that seems like shiny design with curvatures but on the background, it has all the calculations and relationships. In computational design, parameters do not control the geometry directly. Rather, they control the operations of a procedure that generates a geometry. Once formulated, such a computational approach can be applied repeatedly. That is why in this chapter to get into the computational optimization; its methods will be discussed in detail.

In 2.1, a short brief will be given about algorithms, and its pros cons will be discussed. Two types of the algorithms will be reviewed. Later, its main components, which are constraints and parameters, and their relations, will be explained. After in 2.2 scripting, and its basics & logic will be determined. In 2.3 a detailed explanation about the optimization will be given. Moreover, a discussion will be done about the optimization algorithms and solution methods.

Figure 2.1 : Aqua tower façade design.

2.1 Algorithms

Terzidis (2006) mentions that; for architects, algorithmic design enables the role of the designer to shift from “architecture programming” to “programming architecture.” Then he describes an algorithm as a process of addressing a problem in a finite number of steps using logical if-then-else operations. Moreover, he makes this addition to his description; an algorithm is not only a computer implementation, a series of lines of code in a program, or a language, it is also a theoretical construct with deep philosophical, social, design, and artistic repercussions.

In plenty of resources, an algorithm described as a recipe. For instance to boil an egg you should have a pot, water and an egg. Then first, you should stir water into the pot then put the pot on fire then release the egg into the water. Wait until the water is boiled then count for 15 min. Therefore, that is a recipe but also it is a basic algorithm. Sometimes solution to a basic problem can be described as an algorithm (Figure2.2).

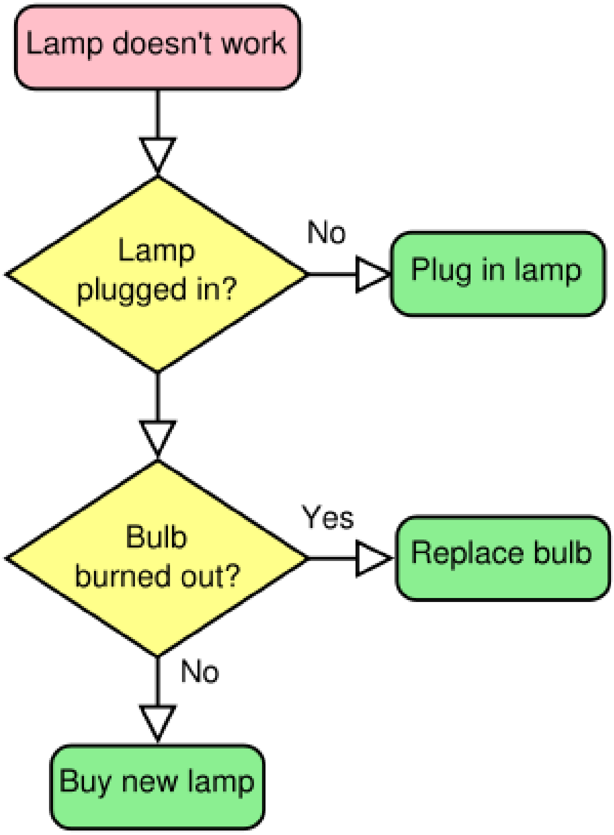

Figure 2.2 : An algorithm for broken lamps.

Algorithms can be listed in two main parts as following, Traditional algorithms and Evolutionary algorithms.

2.1.1 Traditional algorithms

Xu (2009) has described traditional algorithms in design as following:

- Processes of creating the entities are translated into language (VBA, VB, and C++). Computer will generate forms according to the scripts instead of 'mouse clicks'.
- The computer follows 'a finite sequence of instructions an explicit, procedure for solving a problem'. It could not change or choose the solutions or results by itself.

In addition to his description, it can be summarized as instead of doing design steps manually, all these steps are given into a program via algorithm and it is done step by step. It related to the complexity of the constraints which is included in to the design algorithm. To not to skip any important step or rules, it is much easier to do it via traditional algorithms based design.

2.1.2 Evolutionary algorithms

'An evolutionary algorithm (EA) is a subset of evolutionary computation, a generic population-based metaheuristic optimization algorithm' (Xu, 2009). The term of evolution used in EA is a biological evolution such as mutation, recombination etc. So while running an EA, the identities of the inputs are also changing. They turn into new spieces, which are evolved from the input parameters. Eiben et al. (1999) explains the process of EA as the following; When defining an evolutionary algorithm one needs to choose its components, such as variation operators (mutation and recombination) that suit the representation, selection mechanisms for selecting parents and survivors, and an initial population. Each of these components may have parameters, for instance: the probability of mutation, the tournament size of selection, or the population size. The values of these parameters greatly determine whether the algorithm will find a near-optimum solution and whether it will find such a solution efficiently.

2.1.3 Constraints

In algorithmic design, constraints can be commented as drawing borders for the design route. Gross (1985) explains constraints as following; Constraints are the rules, requirements, relations, conventions, and principles that define the context of designing. There are many constraints on a design and they come from different sources. Constraints are imposed by nature, culture, convention, and the marketplace. Some are imposed externally, while others are imposed by the designer. Some are site-specific, others not. Some are the result of higher-level design decisions; some are universal, a part of every design.Moreover, Monedero (2009) mentions that a constraint is a relation that limits the behavior of an entity or a group of entities. This limitation is mostly to have a standing project instead of having nonsense details. Because it has to be mentioned as a basic, slabs should intersect with the walls. Therefore, in that sense there must be always constraints to have a proper design. On the other hand, designer should be careful about the amount of it otherwise, designer could have an over constrained or an under constraint model. In addition, when the topic came to think about in what sense constrained should be perceived. As observed by Monedero (2009), Constraints can also be of two different types that sometimes are referred to as geometric constraints and physical or engineering constraints. Parallelism, perpendicularity, tangency, dimensionality are geometric constraints. Nevertheless, a model can also be based on Formula like areasforcerpressure. Constraints can also be specified as conditional relations such as If *D*1+ *D*2>*D*3 then *D*1s10 cm else *D*1s20 cm. A major difference between systems is the way in which the constraints are input and controlled.

2.1.4 Parameters

Parameters can be described as inputs for the parametric design. There are three different types of inputs, which are geometric inputs, numeric inputs and Booleans. Geometric inputs could be lines, polylines, splines or points. Numbers could be real numbers, integers, rational numbers etc. In addition, Booleans have two options either true or false. Therefore, with that much amount of inputs the output varies. Moreover, with parameters it is possible to try different choices and have various design outputs. That means without changing all design from beginning, designer have the ability to design an optimized product. The relation between constraints and parameters can be seen below in figure 2.3.

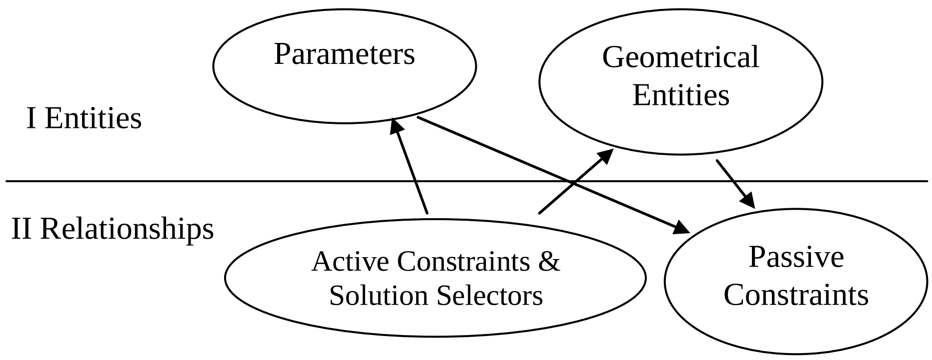

Figure 2.3 : Constraints and parameters relationship chart.

2.2 Scripting

'You write a few lines of code and suddenly life is better for a hundred million people.' (Charles Simonyi, inventor of Microsoft Word)

'When God calculates and exercises his thought, the world is created.' (Leibniz, 1677)

Today, when architects calculate and exercise their thoughts, everything turns into algorithms! Computation, the writing and rewriting of code through simple rules (see figure2.4), plays an ever-increasing role in architecture (Rocker, 2006). Moreover, Learning programming means learning computation, which is one view of design, and thus can have its place in an architectural design curriculum. Learning programming also leads designers to think about the algorithms for the design phase and it is ended with specifying constraints and parameters for the design. Rocker (2006) also mentions that most architects now use computers and interactive software programs as exploratory tools. All their work is informed by, and thus dependent on the software they are using, which inscribes its logic, perhaps even unnoticed, onto their everyday routines. Such users of software packages have little or no knowledge of the algorithms powering the programs they employ. Most of the interactivity is reduced to a manipulation of displayed forms on the screen, neglecting the underlying mathematical calculations behind them. All of this – even though implemented on computers – has little to do with the logics of computation. On the other hand, many designers are now aware of the potential of scripting, but it is still seen as a difficult arena to enter. However, today, programming in architecture has become a much more open process with the online libraries and shared codes.

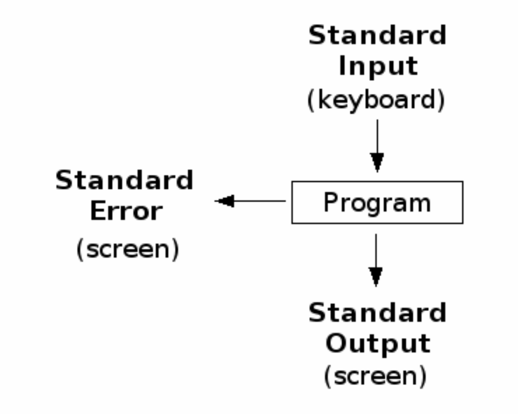

Figure 2.4 : Scripting basics diagram

2.3 Optimization

"The word optimization can be explained as the task of obtaining the best configuration for a system with a defined number of degrees of freedom, and subjected to certain constraints." (Rao, 1996)

Optimization has been always a part of the design and an influence for the architects. It was also proposed as a decision-making model in building design by Wilson et al. in 1976, followed by a large (and still the most extensive) body of work by Gero et al. (1983) and Radford et al. (1988). Ironically, terms such as *optimal*, *optimum,* and *optimality* have become widely embedded in dialogues among design teams, but without any explicit definition of either the process or the end results they may represent. (Michalek et. al., 2005). In this thesis the term of optimization is not just used as a result, moreover the idea behind it, is studied to undestand its benefits and solution methods.

Optimization should be provided both as inputs and outputs. Without the optimum inputs, the derived outputs can not be counted as an optimal result. thats why designer should be careful with the parameters to satisfy the constraints and the optimized output. Below, optimization algorithms and the solution methods are disccused for a better view for computational optimization.

2.3.1 Optimization algorithms

Optimization algorithms can be divided into classical and evolutionary. Manzan and Pinto (2009) mentions these following for the two algoritms; classical techniques are not able to deal with multi-objective optimizations, instead they use the so-called utility functions. Namely, with the use of some criteria (weighting operations) in order to combine the objectives, a unique functional is created and optimized as a single objective. On the other hand, evolutionary (probabilistic) algorithms allow maximizing a function without any restriction imposed by functional constraints, as gradient-based algorithms do. Moreover, they can perform truly multiobjective optimizations. An other problem in using classical deterministic optimization has been highlighted by Wetter and Wright 2004 which carried out a comparison of deterministic (classical) and probabilistic optimization algorithms on non-smooth optimizations underlining the difficulty in reaching a good solution with gradient based algorithms.

2.3.2 Optimization solution methods

There are two methods that are applied when confronted with optimization problems. These are called gradient-based and derivative-free. Below, some brief explanation will be given for utilizing these methods. The selection of the method depends on the problem formulation and expected goals of the optimization.

-Gradient-based methods may be utilized to deal with the design problems involving variables from a continuous domain. These forms of methods opt out solutions one by one until the best solution is reached (Michalek et. al., 2005).

-In contrary, derivative-free methods provide better results when it comes to design problems that are disclosed, or that are caused by noisy function responses and unaffiliated domains. The reason for employing derivative-free methods in such cases is that they are not based on function gradients (Michalek et. al., 2005).

3. ENVIRONMENTAL CONCEPTS FOR USER COMFORT IN OFFICES

"*Nature can only be mastered by obeying its laws."* (Roger BACON; thirteenth-century English philosopher and scientist)

"Environmental design is not new. The cold environment of 350.000 years ago led our European ancestors to build shelters under limestone cliffs. More recently, English cob cottages and Doha homes, both built of earth, demonstrate vernacular responses to light and heat" (Thomas, 2006).

Environmental issues always have been the one of the base topics for architectural design. For having an efficient and environmentally satisfied building design, architects should have the knowledge of the environmental issues in detail. In this chapter, three different issues of the environmental design will be discussed. These issues have been chosen for the purpose of the thesis. A general brief about daylight, the thermal environment and energy saving will be given.

3.1 Daylight

When all buildings were designed around a single, fixed light source – the sun – the difference between great architecture and mere building could be measured to a large degree by the skill with which that source was used. The shapes and sizes of rooms, and the materials and details in them, were determined largely by the appearance the room would take on when rendered by daylight. Light was not always simply applied to structural innovations; more often, the structures themselves were developed to make possible desired lighting and spatial effects (Lam, 1977).

If it is asked why the daylight is crucial, there are many answers for it. For instance, Johnsen (1998) would answer as, daylight is an essential resource that is readily available – and unlikely to run out for thereforeseeable future. It also has the very special characteristic of having the ability to transform an internal space from uninspiring uniformity into a psychologically uplifting experience. Beside it is energy saving characteristic, it also bring a visual comfort for the occupants of the building

3.1.1 Daylight factor

Philips (1964) defines the Daylight Factor (DF) as following; the ratio between the horizontal illumination at a point in the interior, and the simultaneous horizontal external illumination from an unobstructed hemisphere of sky (excluding sunlight) is known as the daylight factor and is expressed as a percentage. DF is very common to measure for the subjective daylight quality in a room. Different percentages of the DF bring various daylight comforts for the occupants (See Table 3.1).

Table 3.1: Daylight factor, Appearance and Thermal comfort (Url-6).

Average DF	Appearance	Energy Implications
< %2	Room looks gloomy.	Electric lighting needed most of the day.
%2 to %5	Predominantly daylight appearance, but supplementary artificial lighting is needed.	Good balance between lighting and thermal aspects.
> %5	Room appears strongly daylight.	Daytime electric lighting rarely needed, but potential for thermal problems due to overheating in summer and heat losses in winter

A daylight factor can also be expressed as an average using experimental formulas. Several formulas for estimating the average DF in a room are in use today. Depending on the country and its legislation, one or the other might be more common: BRE formula **(3.1),** IES formula, Sumpner formula and Italian legislation (URL 1). In addition, components of the formulas can be seen in Appendix A in detail.

$$DF_{m,BRE} = \frac{(A_{window} \alpha \, M \, t)}{(A_{total}(1 - \rho m^2))} \qquad \textbf{(3.1)}$$

3.1.2 Daylight availability

All daylighting strategies make use of the luminance distribution from the sun, sky, buildings, and ground (Figure 3.1). Daylight strategies depend on the availability of natural light, which is determined by the latitude of the building site and the conditions immediately surrounding the building, e.g., the presence of obstructions. Daylighting strategies are also affected by climate; thus, the identification of seasonal, prevailing climate conditions, particularly ambient temperatures and sunshine probability, is a basic step in daylight design. Studying both climate and daylight availability at a construction site is key to understanding the operating conditions of the building's facade (Ruck et al., 2000). Moreover, daylight availability not only depends on latitude but also on a building's orientation and the building site and obstruction by the surrounding of it. That is why the daylight availability is one of the main parameters of the daylight design.

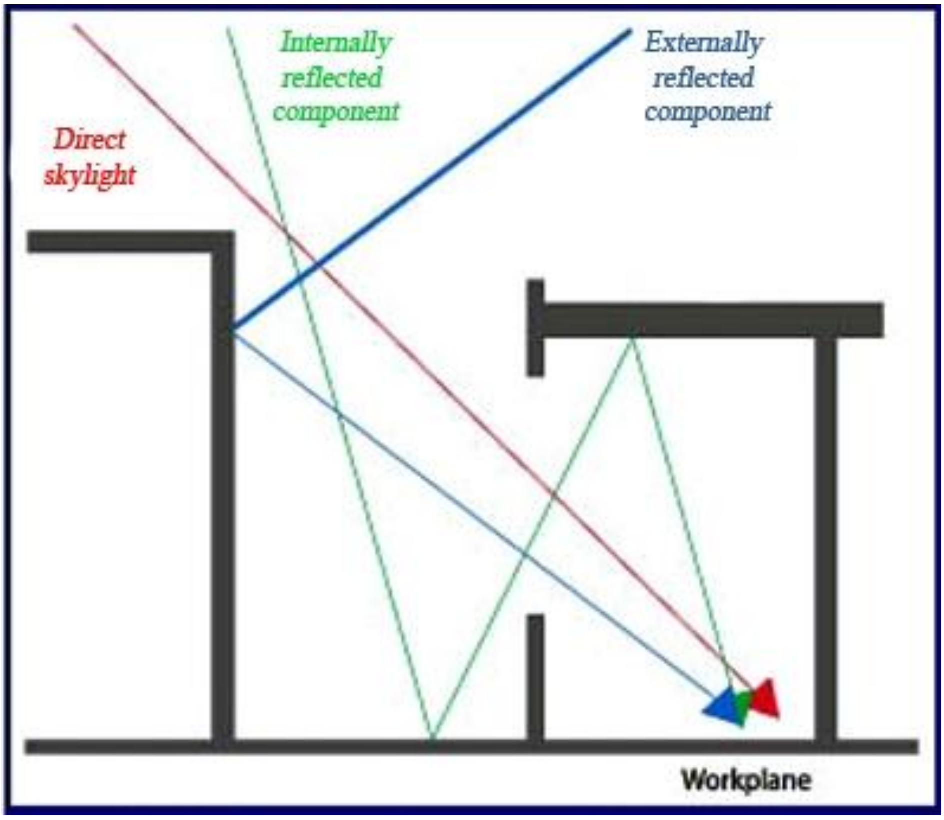

Figure 3.1 : Daylight resources diagram (Url-7).

There are several sources of information on daylight availability (Dumortier, 1995). For example, daylight availability data has been monitored every minute at more than 50 stations worldwide since 1991 and has also been monitored in the Meteosat satellite every half hour from 1996–1997 (under beta testing). Below the conditions of the sky is discussed in terms of the daylight availability. All the probabilities for the sky and climate should be taken into the count for an optimal design.

3.1.2.1 Diffuse skylight

The light received from the sun is the ultimate source of daylight, but it is the sunlight that is diffused in the atmosphere that, as skylight, serves as the primary source for the daylighting of interiors. The strength of daylight therefore varies with time, and, due to changes in the sun's position and to variations in cloud cover, the luminance of the sky neither constant nor uniform (Hopkinson et al., 1966).

Daylight design considers two basic stable conditions (Figure 3.2):

- The completely overcast sky
- The clear blue sky with sunlight

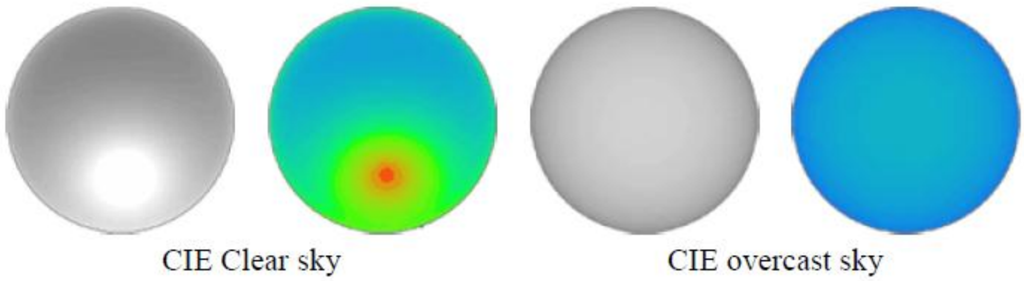

Figure 3.2 : CIE Sky Conditions (Kensek et al., 2011)

The cloudy skies

With completely cloudy sky (100% covered), this sky model has been widely used to calculate daylight factor. Many designers and users have used this model to calculate the worst-case scenario. Ecotect software uses this sky model as a default. (Kensek et al., 2011)

The clear skies

Clear sky is defined by having less than 30% of clouds covering the sky or no clouds. In either case, the sky is brighter towards the location of the sun, and the sun is visible. (Kensek et al., 2011)

3.1.2.2 Direct sunlight

In temperate climates, sunlight cannot be relied upon as a major source of illumination in buildings. Daylight design in such climates relies almost exclusively on the sky as the main source of light. Buildings, and particularly residential buildings and schools, are however often orientated to make use of the available sunlight as a welcome amenity (Hopkinson et al., 1966). On the other hand, indirect sunlight, which is result of reflection through ground and other buildings, can serve a useful purpose as the main source of illumination in a sunny climate. Still the thermal effect of the sunlight should be taken into count to prevent thermal discomfort, extra heat gain and extra energy consume for the cooling. Shading design is crucial for the south facing facades – for north hemisphere – because of the direct sunlight.

3.2 The Thermal Environment

According to Sodha et al. (1986) the internal environment within a building results from the response of the building fabric to the changing outdoor conditions of air temperature, solar radiation, humidity, precipitation or evaporation, wind velocity and direction and the clearness of the sky. Building elements with their specific orientation, thermal conductivity, absorptivity and emissivity react differently to the outdoor conditions. In typical desert cool climates, solar radiation can be intercepted and trapped into the building for providing heating, while in warm climates the interception, absorption and inward transmission of solar radiation can be reduce to minimize the cooling load demand. A building will be judged by the occupants according to its ability to satisfy the demand of thermal comfort. The thermal comfort, brands of the thermal transfer and thermal calculation methods will be discussed below in detail.

3.2.1 Thermal transfer

In nature heat transfers between matters and as law of nature heat always flows from hot bodies to cold ones. Direction of this flow depends on to the temperature of the materials itself and its surroundings. Moreover, the way of this flow depends on the material itself and its specification. Thermal energy can be exchanged in four ways. These include the three classic methods of thermal transfer (See Figure: 3.3), conduction, convection, and radiation, plus evaporation (Smith, 2011).

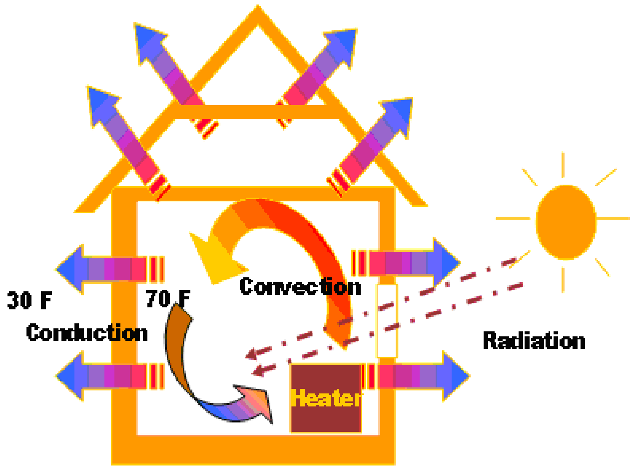

Figure 3.3 : Heat transfer diagram (Url-12).

3.2.2 Thermal comfort

"Thermal Comfort – that condition of mind which expresses satisfaction with the thermal environment." (ASHRAE, 1981).

Lechner (2009) explains the thermal comfort as following; certain combinations of air temperature, relative humidity, air motion, and mean radiant temperature will result in what most people consider thermal comfort. When these combinations are plotted on a psychometric chart, they define an area known as the comfort zone. It is important to note that the given boundaries of the comfort zone are not absolute, because thermal comfort also varies with culture, time of year, health, the amount of fat an individual carries, the amount of clothing worn, and, most importantly, physical activity. In addition, whenever possible additional controls should be made available for the occupants of a building so that they can create the thermal conditions that are just right for them.

Sodha et al. (1986) listed the most important parameters, which determine the state of thermal comfort as;

- activity level (heat production in the body)
- air temperature
- mean radiant temperature
- relative air velocity
- clothing

3.3 Energy saving strategies

With the over consumption of the fossil fuels, the impact of the energy saving projects got their places in architectural design. As a long term solution, energy efficient buildings are essential to deal with the problem of fossil fuels energy sources (Santos et. al., 2008). Buildings in the developed world consume about 40% of the world's energy, for heating, cooling, lighting and running equipment such as computers (Url-13). The energy used in the buildings mostly for the heating cooling and lighting (See Figure 3.4). Office buildings represent nearly one-fifth of all delivered energy consumed by commercial buildings, and are therefore an important focus for energy efficiency improvements (EIA, 2005).

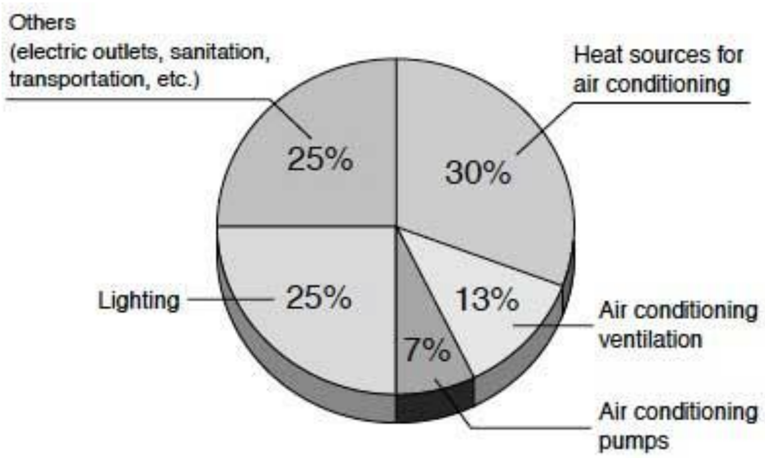

Figure 3.4 : Energy consumption of office buildings by usage (Sawai et. al.,2003)

With the building envelope is undergoing a revolution. It can now be designed to do more than just to keep the weather out and to provide an impressive appearance: it can make a positive contribution in reducing the energy consumption of the building. According to Glassman and Reinhart (2013) Energy use in buildings is a factor of the heat loss and gain through the opaque and glazed assemblies of a building envelope, internal loads from occupants, lighting, and equipment, and the performance of the building's mechanical systems that provide heating, cooling, and lighting. These factors are all interconnected and affect one another. Some of them reinforce each other, but some are inversely related. Moreover, the rates of energy consumption by buildings can be dramatically reduced with decreasing dependence on artificial systems of air conditioning and lighting. The comfort and energy demand of a building are influenced significantly by glazed area of the facade. There is an increase use of large window openings and curtain walls in today‘s architecture (Stegou-Sagia et. al., 2007). The glazed areas in the building are always challenging. Large glazing allows more daylight to get into the room but at the same time provides more heat gain and heat loss through the building envelop. Therefore, it has potential to cause thermal discomfort (F.Smith, 2001). To prevent the building from overheating and provide thermal comfort, shading devices are used frequently. Overheating protection has become important especially in office buildings; where internal heat gains and high occupant density occurs at the same time (Roetzel et. al., 2010). As it is seen from the previous researches done shading device has an important place in energy saving strategies. As much as saving the energy with the PV cells shading devices can produce energy for the Office buildings (See Figure 3.5).

Figure 3.5 : Aarhus Office Building façade design (Url-14)

4. SUN SHADING

"The sun control device has to be on the outside of the building, an element of the façade, an element of architecture. And because this device is so important a part of our open architecture, it may develop into as characteristics a form as the Doric column" (Breuer, 1955).

"The benefits of shading are so great and obvious that we see its applications throughout history and across cultures. We see its effect on classical architecture as well as on unrefined vernacular buildings ("architecture without architects")" (Lechner, 2009).

As it is said above, the history of shading devices is not something recent. For instance shading devices can be seen in ancient Greek architecture, they are not specifically shading devices but they function as one. Big overhangs supported by the columns define an outer space but at the same time, they prevent the sun going through windows. This kind of examples might be seen in Japan architecture also. Moreover, in modern architecture the examples of sun shadiers had started to being used with Frank Lloyd Wright and Le Corbusier. Wrights Robbie house (1909) was designed with overhangs to prevent over heating from hot and humidity climate of Chicago (Figure 4.1). Moreover, Corbusier had experienced the benefits of the sun shading in his project, Cité de Refuge (1932). The building was designed without any shadier and with large windows but this design did not work out during the summer time. Later he retrofitted the building with the sun shadiers, which are known as brise-soleil. Also in Anatolia shading louvers (Figure 4.2) are being used for many years. They are especially used on the west and south parts of the Anatolia because of the climate. They were easy to use and apply because they act like a second windows layer.

Figure 4.1 : Robbie house by Frank Lloyd Wright (Url-9).

Figure 4.2 : Louver systems used in Anatolian housing (Url-15).

Lechner (2009) in his book mentions that; although shading of the whole building is beneficial, shading of the windows is crucial. The total solar load consists of three components: direct, diffuse and reflected radiation. To prevent passive solar heating, when it is not wanted, a window must always be shaded from the direct solar component and often also from the diffuse sky and reflected components. Therefore, the type, size and location of a shading device will depend in part on the size of the direct, diffuse, and reflected components of the total solar load.

Further specifications of the sun shading, such as shading strategies, shading device types, shading coefficient will be researched on the next sections. Due to the details of this thesis subject, most of the following research refers to the shading of windows.

4.1 Shading strategies

Designing shading devices needs a detailed knowledge of environmental systems because designer has to analyze and then should have a strategy about it. While designing a shading device, designer has to work on some design criteria. This criteria are related with the building itself and its site. The surrounding is important because there might be no need for the shading devices if the surrounding already makes shade on the building. Moreover, orientation of the building also has a major effect on the shading devices i.e. mostly there is no need for a shading device on north facades. Nevertheless, if there is a huge glass façade building next to it, due to the reflection designer might design a shadier for the north façade. This shows the importance of the surrounding criteria. Buildings located on the north could experience the overheated period for a few months long however, a building located on the south could experience the overheated period for two or three times as long. Thus, the required shading period for and building depends on both the climate and the nature of the building. Shading periods and orientation of shading devices will be discussed below in detail.

4.1.1 Shading periods of the year

The summer season in Turkey roughly is defined as the period between April and November. This roughly is the time when complete shading is needed (See Figure 4.3). However, the study of the local climate of the area under consideration should determine the overheated period for that area more precisely. Cowan et al. (1980) mentions following ideas of him; the outdoor dry-bulb temperature reaches or exceeds a specified value during this period. It is assumed that this is also the period during, which the internal temperature of an unshaded building would exceed the comfortable level. Olgyay (1976) recommends 21 ^{o}C to be the limiting temperature for the temperate regions. For this limit of temperature the overheated season would start when the outdoor temperature around 26 ^{o}C. Moreover, these degrees of the temperature will define the span of the overheated and under heated periods.

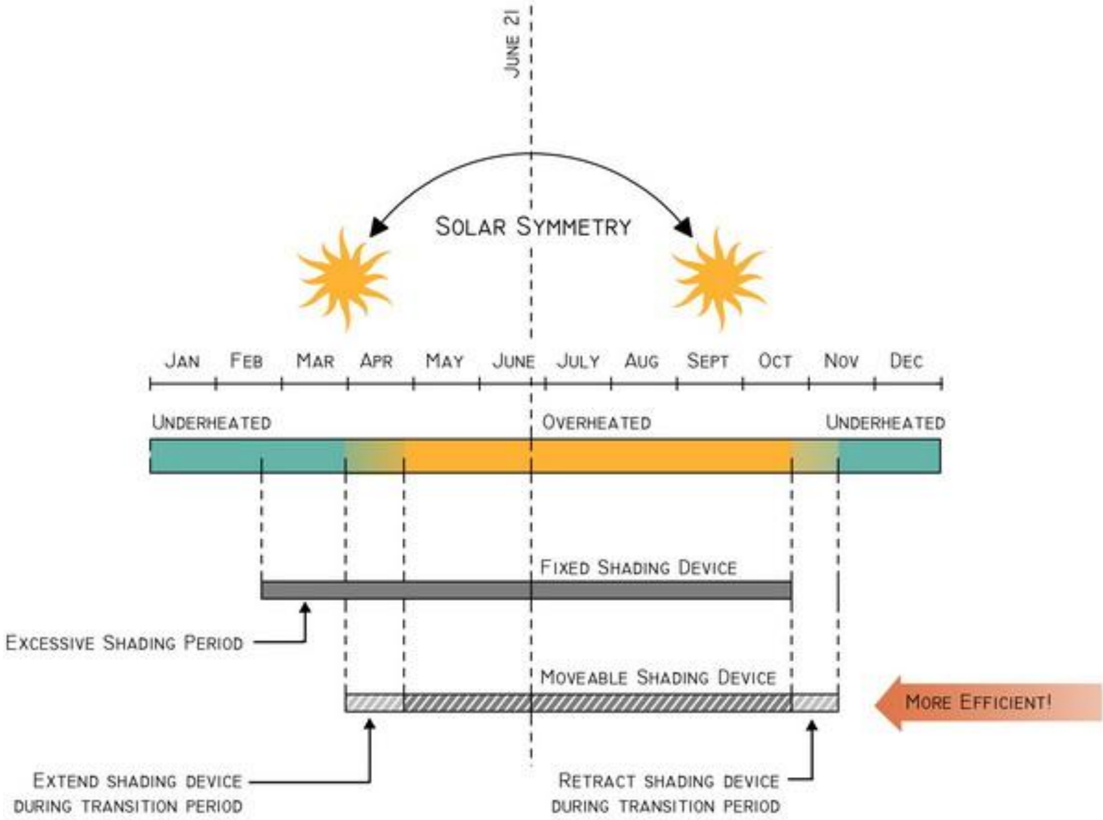

Figure 4.3 : The shading season for south hemisphere (Url-10).

4.1.2 Orientation of shading devices

One of the shading strategy criteria's is the orientation of the windows. It is also important that the site of the building, where it is located on earth, on which hemisphere. The strategies on the north hemisphere are the opposite of the ones on the south hemisphere. Below the north hemisphere will be taken as a reference. While Lechner (2009) suggesting horizontal overhangs as a quite effective shading device for the south facing windows, he mentions that that kind of shading devices might be used on the east, southeast, southwest and west facades. However, on these facades horizontal overhangs are not as effective as they are on south facades. In hot climates, north windows also need to be shaded because during the summer the sun rises north of east and sets north of west. Nevertheless, due to the altitude of the sun on these period is lower, horizontal overhangs are not efficient. For that reason, vertical fins can be suggested on north facades.

4.2 Shading devices

Cowan et al. (1980) described the most efficient way of maximizing management of the influx of solar heat gain through the building envelope as:

- To protect the glazing against both the direct and the diffuse components of solar radiation heat gain in summer; and
- To admit both direct and diffuse components in winter.

The above can be achieved with greatest efficacy by using shading devices. There are plenty types of shading devices have been developed. It is possible to categorize them in different ways but below they are categorized by the way they work. In addition, they are listed as following; moveable shading devices, fixed shading devices and special shading devices.

4.2.1 Movable shading devices

Lechner (2009) mentioned that it is not surprising that movable shading devices respond better to the dynamic nature of weather the do static devices. Since we need shade during the overheated periods and sun during the under heated periods, a shading device must be in a phase with the thermal conditions. Movable shading device can be very simple or complex like digitally automated ones. Nevertheless, at the same time they can be manually automated i.e. the movement of the shading device can be adjusted only twice in a year and it would be enough. These changes can be done in late fall and late spring at the beginnings of overheated and under heated periods (Figure 4.4).

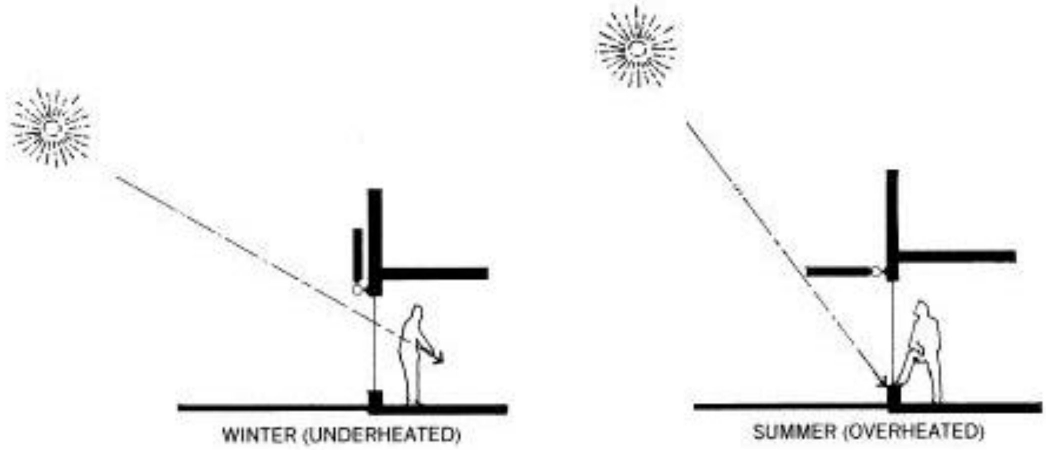

Figure 4.4 : Movable shading device with two simple adjustments (Lechner,2009).

4.2.2 Fixed shading devices

The first shading devices designed in the history was overhangs. They were basic and cheap to have on a façade. Then architects start having different versions of fixed shading devices because overhangs were not efficient for every façade. Instead of having horizontal devices, architects start using vertical elements such as fins. They were more efficient for east and west façades. Moreover, for some occasions, a mix of both horizontal and vertical elements was needed and it resulted in a shading device, which is now called as eggcrate. All these shading devices (See Figure 4.5) fulfill the need of shading but not still %100 efficient as the movable shading devices. However, as it mentioned at the beginning, it is much easier and cheaper to have fixed shading devices.

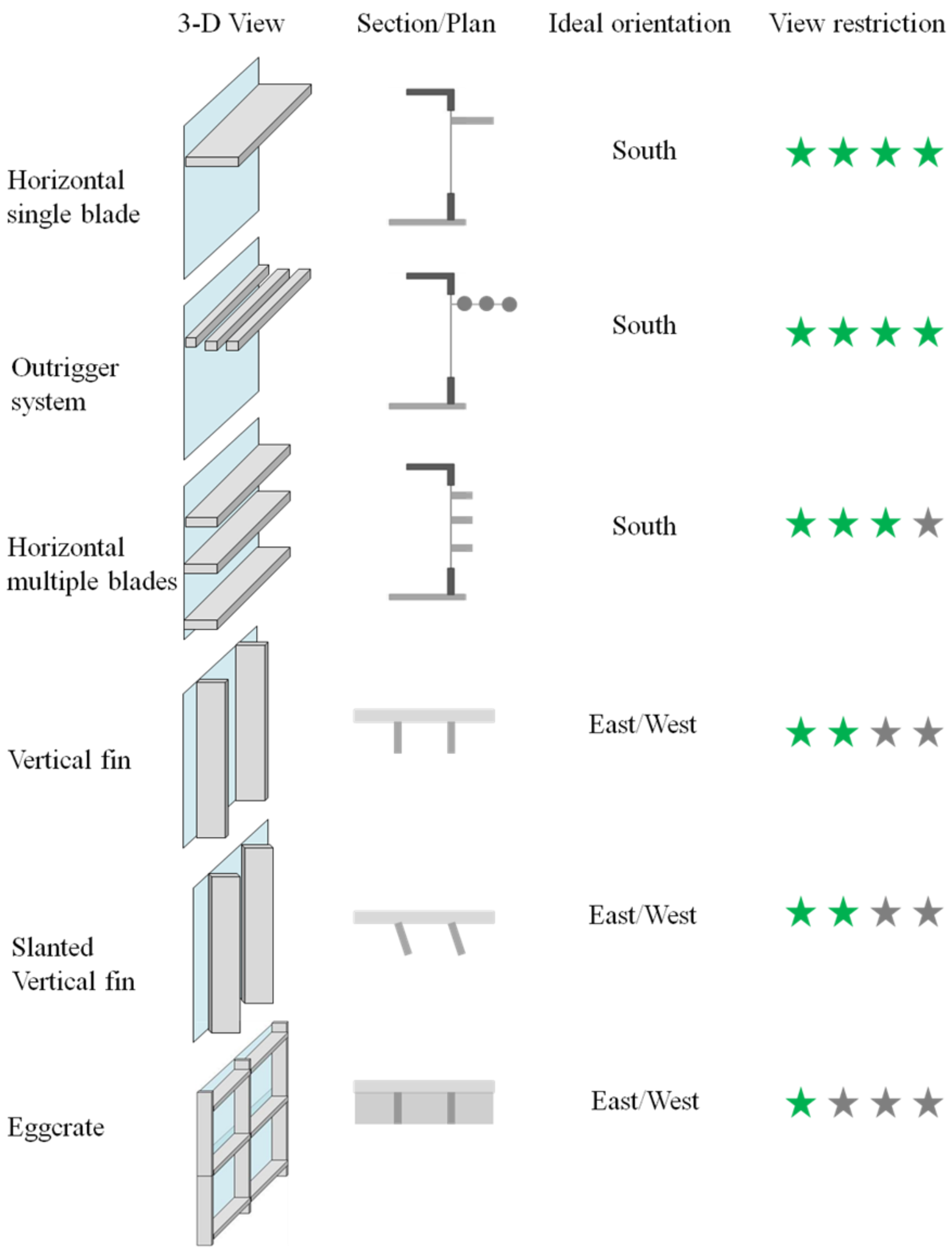

Figure 4.5 : Fixed shading device types (Url-11).

4.2.3 Special shading devices

Most external shading devices are simple variations of the horizontal overhang, vertical fin, or eggcrate. However, there are some interesting exceptions. For instance, One of these approaches is to create a separate shading envelope (see figure 4.6) around the building (Lechner, 2009). Moreover, another approach might me either rotate the building or the shading devices around building. These are can be count as an extreme approach for shading but still they can be applied for some specific projects.

Figure 4.6 : An interior view of shading envelope by Arhitektid Muru&Pere (Url-5).

4.3 Shading coefficient

Lechner (2009) defines shading coefficient as; SC is a number that varies from zero to one to grade the optimality of shading design. In addition, he makes this comment; the effectiveness of external shading devices depends on the specific design and therefore it is very difficult to assign a number to the generic type. Nevertheless, the table that he made can give us a clue about the effectiveness of the different various shading devices (See Table 4.1).

Table 4.1 : Shading coefficients for various shading devices (Lechner, 2009).

Device	SC[o]
Glazing	
Clear glass, 1/8 in. thick	1.00
Clear glass, 1/8 in. thick	0.90
Heat absorbing or tinted	0.50-0.80
Reflective	0.20-0.60
Interior Shading Devices	
Venetian blinds	0.45-0.65
Roller shades	0.25-0.60
Curtains	0.40-0.80
External Shading Devices	
Eggcrate	0.10-0.30
Horizontal overhang	0.10-0.60
Vertical fins	0.10-0.60
Trees	0.20-0.60

5. OPTIMIZATION MODEL OF A LOUVER SYSTEM FOR OFFICE BUILDINGS

Until this chapter, a brief research has been done on environmental design and computational design. In this chapter, some project examples will be explained and optimization of the louver systems via scripting will be applied to environmental design concepts such as solar heat gain and daylight factor. Parts of the optimization such as constraints, parameters and algorithms for this project will be given. Finally, a small example project will be proposed for testing the script and then the results will be evaluated.

5.1 Sun Shading & Daylight Optimization Examples

In the literature, there have been some research and some projects about optimization of daylight, thermal comfort and shading devices. In general, shading devices should have several functions: they can block direct sunlight to prevent glare and reduce overheating; they can still allow diffuse light into the space to reduce lighting energy consumption; moreover, motorized shading devices can be adjusted to changing outdoor conditions based on different criteria. For example, using daylighting to cut reliance on artificial light can reduce the electricity used to power the lighting, and additionally reduce cooling loads induced by the waste heat created by lighting fixtures (Bodart & De Herde, 2002). In addition, a healthy design should be so intelligent to provide comfort both inside and outside through the whole cycle of the year; so, the significance and complexity of optimizing the orientation and proportion of shading devices increases when the comfort factor outdoors is taken into consideration beside the comfort factor indoors. Below, five of the projects will be represented with the idea behind them and their technical specialties. After discussing these examples and doing the optimization project for the louver system, a comparison between them will be done in the conclusion part.

5.1.1 Shaderade

Shaderade is a new approach for designing a static shading device. Sargent et al. (2011) defines the approach of the project as the implementation of an eponymous tool based on Rhinoceros® and Energy Plus, and offers flexible, novel techniques for assessing the thermal desirability of solar transmittance through any potential shading volume or surface. Using simulated side-lit offices located in Anchorage, Boston and Phoenix, it is shown that SHADERADE is able to consistently generate shading systems with improved thermal performance vis-à-vis existing methods. In existing methods, the process consists of shading period selection and form finding. However, these methods have some limitations. Sargent et al. (2011) define one significant limitation of these methods as the problem of over shading. Instead of this process, Shaderade takes the following steps: valuation of the transmitted beam energy, resolution of shading conflicts, opaque shading surfaces, translucent shading surfaces and form finding. After trying different cases during the design, they came up with an optimized shading design in Phoenix in USA as shown in Figure 5.1 below. The conclusion Sargent et al. (2011) got to is that the SHADERADE method reliably matched or exceeded the load reductions and carbon savings of conventional approaches, and provided an efficient means of device size adjustment. In addition, they are planning to release the SHADERADE as an addition to the DIVA-for-Rhino plug-in (http://www.diva-for-rhino.com/).

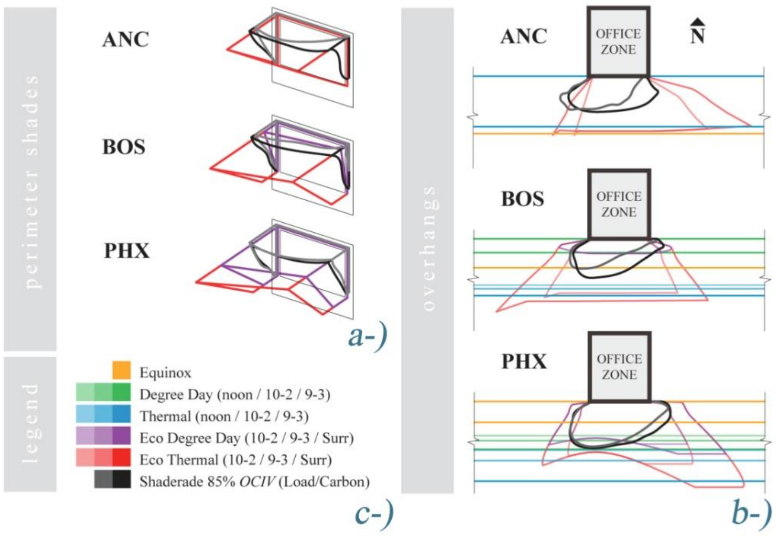

Figure 5.1 : a- Axonometric view of perimeter shades, b- plan view of overhang shades, c- Color code of thermal environment.(Sargent et al., 2011)

5.1.2 Animated building performance simulation (ABPS)

This project is mainly about the link between the three-dimensional CAD modeler, Rhinoceros, and advanced daylight simulations using Radiance and Daysim. Lagios et al. (2010) described their project as follows: A new, highly effective design workflow within Rhinoceros is presented that directly exports scene geometries, material properties and sensor grids into Radiance/Daysim format and calculates a Series of performance indicators including monthly or seasonal solar radiation maps as well as daylight factor and daylight autonomy distributions. The simulation results are automatically loaded back into the Rhinoceros scene using false color mappings. Using the Grasshopper plug-in for Rhinoceros, key design parameters such as window size and material descriptions can be changed incrementally and the simulation results can be combined into an animated building performance simulation, i.e. a dynamic visualization of the effect of these design parameters on the daylight availability within the scene. For their approach to the project, one of the main issues is the passing from single variant design solutions to multiple variant solutions (Figure 5.2). They achieved fast simulations for a variety of levels and stages of design by simplifying the process of performance analysis. As a conclusion, Lagios et al. (2010) mention that the creation of a new type of workflow such as this also presents several new questions about the benefits and costs of widely available tools and the use of parametric performance analysis in design. While it is not possible at present to forecast the implications of this tool on the use and dissemination of the understanding of daylight in buildings, its development represents a significant step towards the production of tools which seamlessly unite the parametric design process with performance analysis.

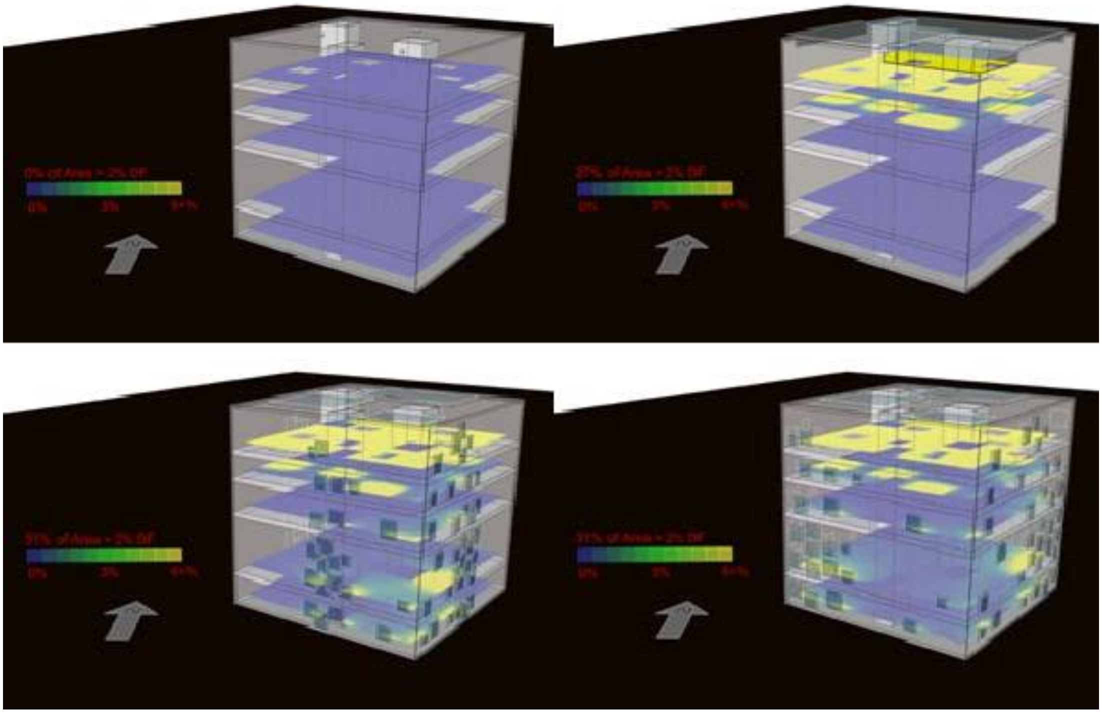

Figure 5.2: Multiple Variant Results – Series of standstill images of a parametric daylighting study of the Zollverein Essen (Lagios et al., 2010).

5.1.3 Computer-optimized shading design

Marsh (2003) explains his project as follows: the project demonstrates how solar position calculations can be used to automatically generate quite complex optimized shading devices and quickly determine the solar envelope of developments given even the most stringent of overshadowing restrictions. The project consists of two types: the simple case and more complex cases. In the simple case aims at defining a shading device for a vertical rectangular window. The generation of the shading device's shape is basically a four-step process, based on a number of basic parameters. These parameters specify the planes that are to form the device as well as the times and dates for which shading is to be provided. Nevertheless, in the more complex cases the designer can use both the location and color of the point cloud to shape the required shading device. Areas of high solar intensity obviously require shading coverage, whereas lower intensity areas allow the designer to make a judgment call based on other constraints. In addition, Marsh (2003) mentions that, the case shown in Figure 5.3 illustrates applications with different post-processing requirements. For example, the situation in Figure 5.3 would be more accurate if the transmission characteristics of the window glazing were fully considered and used to moderate the relative intensity of each displayed point.

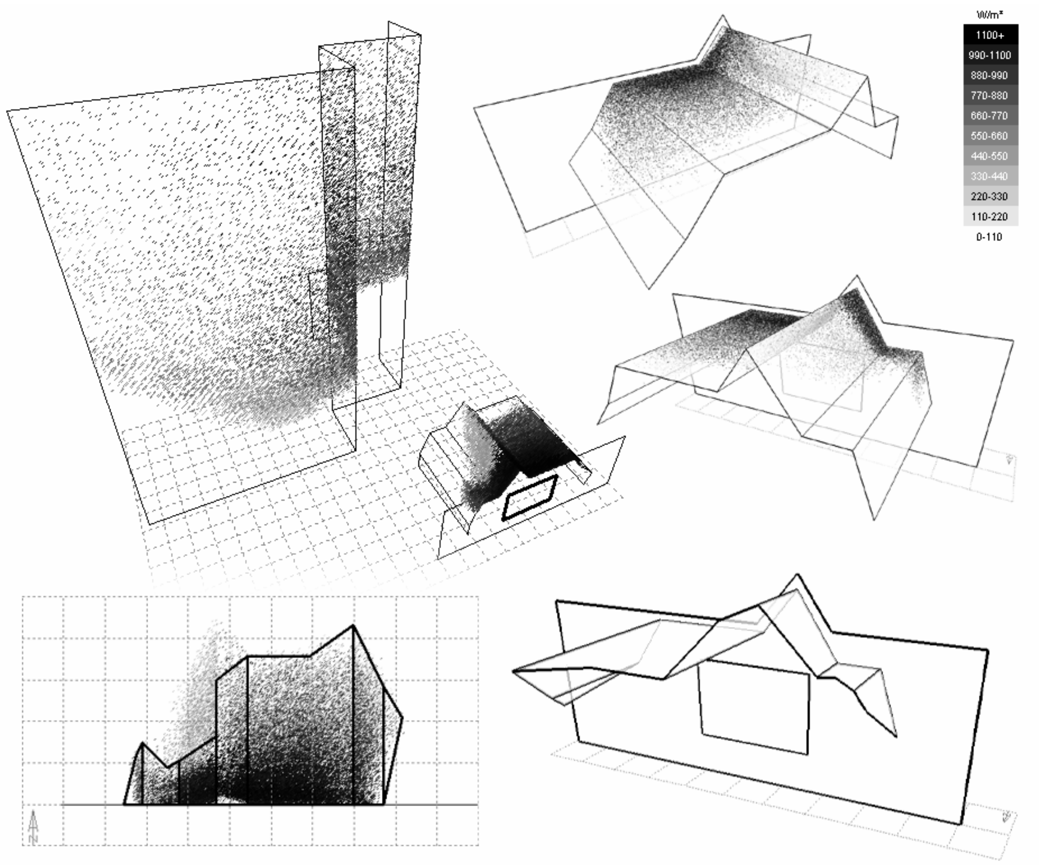

Figure 5.3: An example ray-tracing analysis showing the effect of external obstructions on the distribution of solar intensity over the shading surface and the optimized shape of the device (Marsh, 2003).

5.1.4 Facade optimization using parametric design and future climate

Glassman and Reinhart (2013) define the methodology they followed during the project as follows: the method presented optimizes a set of variables in a building facade to find the most suitable solution for a favorable energy balance. The study then explores how the most optimized solution may change in future climate scenarios. They used Rhinoceros and Grasshopper as working tools. When doing the research on the future climate scenarios, they defined five different time frames, which are 'Current', '2020', 2050', '2080', and '2010-2080'. They made the optimization for two different criteria, one of them is cost-based optimization and the other one is carbon based optimization. Glassman and Reinhart (2013) explain their approaches for these two optimization criteria as follows: the cost-based optimization model sought to find the least costly solution as a total of the initial cost of the facade assembly and the ten years of energy costs resulting from its performance. On the other side, the carbon optimization model found the solution that produced the lowest total of kg/CO2 between the embedded carbon in the materials and the carbon emissions produced from the generation of electricity used in the building. Figure 5.4 shows the results for the southern zone and western zones in the Boston climate over time, optimized once for cost and once for emissions. The results were indicative of the general trends found in all the locations for all orientations.

Figure 5.4: Sample of optimized results from study, the south and west facades in Boston, MA (Glassman and Reinhart, 2013).

5.1.5 Genetic optimization of external shading devices

In this project, to examine the effects of the different glass characteristics a genetic optimization is applied to a shading device for an office room. With the project, primary energy consumption such as that caused by heating, cooling and lighting is minimized. After Manzan and Pinto (2009) making the problem description, different cases are defined to investigate. These cases are about the kinds of glass used in the office windows. Cases can be listed in the table 5.1 as following:

Table 5.1: The cases investigated (Manzan and Pinto, 2009)

DESCRIPTION	CASE
Standard glass without reveal	1.1
Standard glass with reveal	1.2
Standard glass without panel	1.1.0
High performance glass without reveal	2.1
High performance glass with reveal	2.2
High performance glass without panel	2.1.0

To investigate these cases the shading device is optimized with four parameters: shading height, width, angle and distance from the wall. ESP-r, which is a computer simulation tool, is used for the energy simulation and daylight simulation. After this simulation process, a general optimization tool, which is Mode FRONTIER, is used for the optimization process. As a result, the identified optimal configurations are reported graphically for case 1 in Figure 5.5 and for case 2 in Figure 5.6.

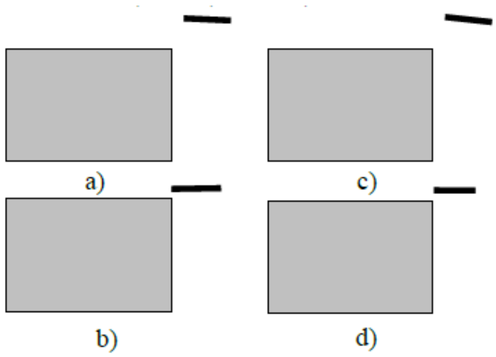

Figure 5.5: Case-1 shading geometry for cases a) 1.2, b) 1.1, c) 1.2.1, d) 1.1.1(Manzan and Pinto, 2009).

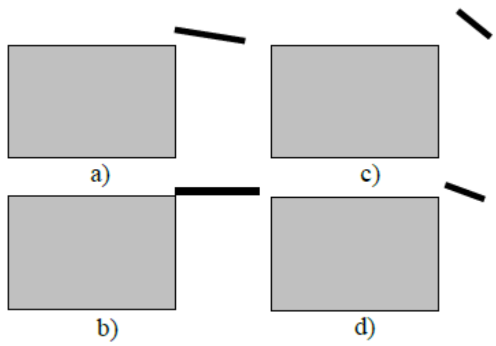

Figure 5.6: Case-2 shading geometry for cases a) 2.2, b) 2.1, c) 2.2.1, d) 2.1.1 (Manzan and Pinto, 2009).

5.1.6 Example projects evaluation

Above five different example projects from the literatüre are explained in detail. As it is seen the Table 5.2 all of the projects only deal with an optimization case. That's why one project which focuses on both daylight and thermal optimization is needed to see how they work together. Because it is crucial to have an optimization for both thermal and visual comfort. A good design should deal with all the environmental issues in once. Otherwise the term optimum or optimal can not be used while speaking about a well-designed project. While optimizing these two cases using shading devices are the most common technic. With a movable shading device it is possible to have an optimum comfort area inside the office buildings.

Table 5.2: Optimization cases used in example projects

	Daylight Optimization	Thermal Optimization
Project 1		+
Project 2	+	
Project 3		+
Project 4		+
Project 5		+

5.2 The System, Design & Design Parameters

This thesis proposes an optimization script that optimizes the louver systems under certain environmental circumstances. As the environment brings a physical comfort to the office rooms, it also brings a psychological comfort with daylight and thermal effects. Maximization of daylight usage is desired because visual quality is ensured, occupants' productivity is increased and electricity consumption for lighting is reduced (Tzempelikos and Athienitis, 2007). The window size, orientation and shading device type mainly affects these two factors. In literature, a number of papers can be found which deal with the problems of the impact of shading devices on energy consumption. However, they mostly consider climate and lighting as separate problems. For office spaces, it is suggested that direct sunlight is not allowed to enter the room, to avoid overheating and glare problems. Shading provision is therefore necessary in order to prevent thermal and visual discomfort.The shading devices created in this thesis, are aimed to be optimized in a digital space with consideration of both climate and light together. Therefore, an optimized shading device would be sized to exclude the direct solar gains when they are not wanted, but permit them when they would be advantageous (Jorge et. al.,1993). Moreover, new links between parametric design tools, energy analysis tools and optimization algorithms give an opportunity to customize the design or it components to prevent the anticipated energy use. To achieve variability with efficient time and cost control, a script has been written for the project. The process flow of the project starts the evaluation of the data for the occupants' comfort. This data gives the designer the opportunity of setting the limitations for the design. After this process, the user defines the parameters for the desired project and then the script creates plenty of outputs that cover the limitations. Finally, an optimization tool finds optimal designs for the louver systems. Users are free to choose one of these optimum results while considering aesthetic and technical concerns.

5.2.1 Choosing the Working Environment and Application Interface

There are many software solutions which allow the user to write scripts or draw in 2D & 3D. Therefore, for the purpose of this thesis, a software product which can work both on 3D models and scripting is needed. The data coming from the 3D model and numerically-entered parameters should be editable by the script, written through the design algorithms & constraints, and a 3D output should be available. For these reasons, Rhinoceros NURBS © has been chosen since it has VB Script base that is capable of processing algorithms quickly.

5.2.2 Environmental Design As a Optimization Problem in Computational Design

Optimization in environmental design is an interesting point of study because of the integrated nature of energy performance (Glassman et al. 2013). There are two kinds of parameters affecting the environmental performance of a building. The first type is the unsteady climatic excitation that the building is subject to, such as solar radiation, air temperature, daylight availability and wind direction. The second type is that of the design variables under the control of the architect. Those are the design parameters, which are related to the building and which determine its environmental control response to the climatic conditions (Bouchlaghem, 2000). To deal with the environmental design problem there are two alternatives. One of them is to test a number of design alternatives by computing their daylight and thermal performance. To obtain these design alternatives, all parameters except for one are fixed. These fixed ones are on reasonable values to determine the effect of this single parameter on the design. Finally, design guidelines can be generated through an analysis of the results. However, there is a disadvantage to this method, since some quality design can be missed out on during the analysis. The other alternative for dealing with this problem, is synthesizing the daylight and thermal design by combining an optimization method and a thermal analysis technique and daylight analysis for buildings. In this method, all the solutions can be checked to determine the optimal environmental design for daylight and thermal comfort. This optimum solution will be the best combination of the design variables to achieve the most effective environmental performance of the building. In this thesis, the second path is chosen, to make this alternative work required constraints and parameters are specified. Moreover, with the help of these components the optimization algorithms are designed systematically.

5.2.2.1 Constraints

Gross (1985) describes a design as a set of constraints, or relations on a set of variables. Each variable has a value, that the designer may set, or fix. Some variables the designer may fix directly; others are calculated as consequences of those fixed. There are user requirements and choices that should be taken into consideration. That is why there must be some rules which guarantee that these requirements and choices are considered. These rules can be defined as limitations and they will draw the borders for the algorithms. The first one is for daylight comfort, since, as previous research mentioned, the DF inside a room should be between certain ratios. If the DF ratio goes out of the limits that means the optimization model does not work. The second one is about the angles of the sunbeams. In different periods of the year, sun is needed for heating. In these periods, shading device angles have to be positioned to get the light in and not block the sunbeam. Nevertheless, for overheated periods angles have to be in a position that get the light in but prevent the sunbeams, which cause a heat gain.

5.2.2.2 Parameters

There are nearly ten parameters in the model. Almost all of them can be counted as adjustable on the other hand for focusing on the results for specific results a few of them are set constant. Some of the more critical variables affecting the character of the louvers as well as aspects of the model workflow are explained below. In addition, they have all different types of inputs and these inputs can be seen in Table 5.3 below.

Table 5.3: Parameters details for script.

Parameter	Type
Window size	Square Meter
Louver size	Centimeter
Numbers of louver	Integer
Solar angles	Degree
Angle of visible sky from the window	Degree
Maintenance factor of the window	Rational
Transmission factor of the glazing	Rational
Average reflection factor of all internal surfaces	Rational

Window size

Windows are the tools to get the light and air in, so their sizes are have major effect for office designs. However, having bigger windows to get more daylight in can cause an extra heat gain in overheated period and heat loss in under-heated periods. Still, users have the chance to have windows whose dimensions are limited only by the dimensions of the outside wall (figure 5.7). Changing the dimension of the windows will bring variety to the outputs for the louver design. Beside the sizes of the window material of it also has an effect for the reflecting and keeping the heat inside or outside. But for now it is not taken into account for this project.

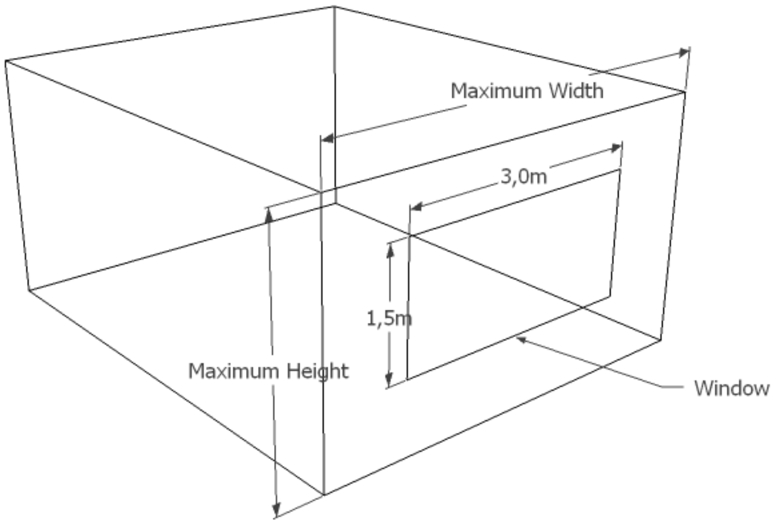

Figure 5.7: A diagram showing the window size.

Louver size

Dimensions of the louver have a major effect on shading design. With the change of the dimensions, the numbers of the louvers also changes. However, the length of the louver is connected to the window size; the user can decide the depth of the louver. In our project, the louver depth is limited to four different options. That is because of the manufacturing of the louver. The user can choose one of the choices between 20cm, 30cm, 40cm & 50cm (Figure 5.8).

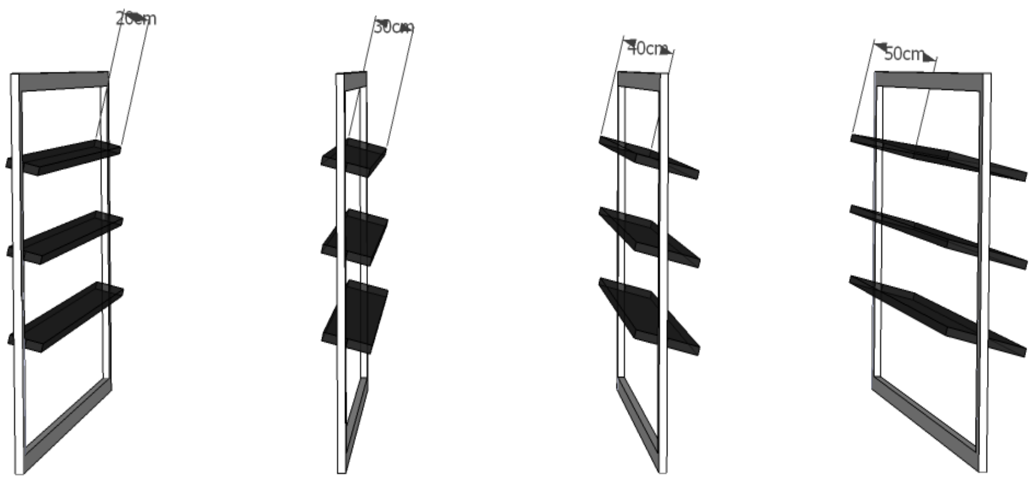

Figure 5.8: Louver types by their dimensions.

Numbers of louver

Shading design has an impact on view comfort for architectural space. The number of louvers is directly related to the view. As much as the size of louver, the number of louvers should be taken into account so as not to obstruct the view. There is an inverse proportion between the number of louvers and the dimensions of the louver. This parameter is left for the user to define, to challenge the optimization. When the size gets smaller, more louvers are needed for the shading. If the user gives a smaller number to the count, optimization will be more difficult to achieve. Nevertheless, to evaluate the various outputs this kind of challenges should be integrated in the design.

Solar angles

This parameter is one of the environmental ones and subjected to solar radiation. Due to the movement of the sun, sunbeams do not come to a building in the same angle all the year. Because of this change in solar angles, the louver angles are also affected. In different periods of the year, the occupants of the building will or will not want to allow the sunbeams to go inside the space. In figure 5.9, the path of the sun can be seen clearly for a specific location in the northern hemisphere. The red line is for summer, the yellow one is for spring and fall and last one is for winter.

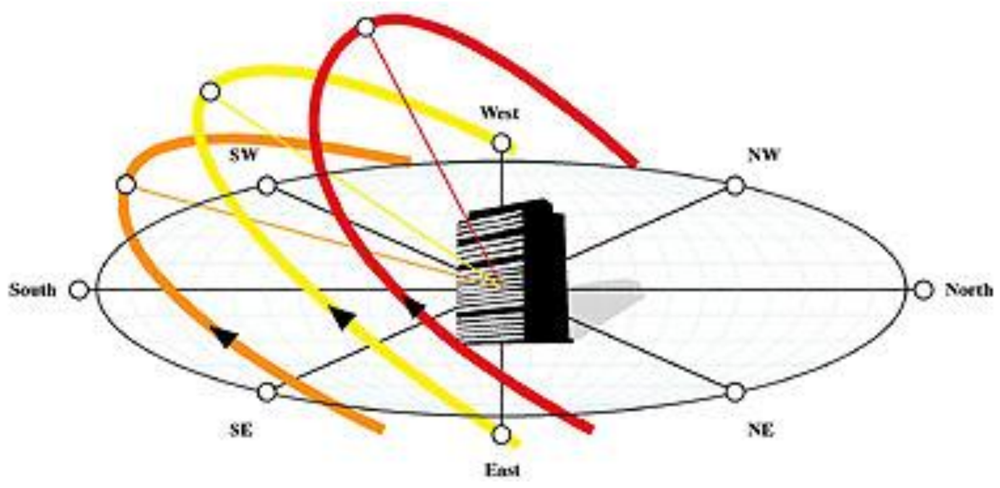

Figure 5.9: Solar geometry path

5.2.2.3 Design algorithms

Research shows that without an algorithm it does not make sense to have parameters or constraints. A detailed algorithm is a crucial tool for applying constraints and parameters properly to an optimization model. In the thesis there are three different algorithms designed with the limits of the constraints according to desires of the users. The first two of them are designed to analyze the environmental issues and the third one is a combination of both of them to optimize the results.

As it mentioned before, for the occupants of an office room a certain amount of light is needed. It can be both natural and artificial light; however, natural light has an added psychological visual comfort. That is why a certain amount of daylight should be used inside the office room, also for preventing energy loss. Big windows can be designed for having efficient daylight inside the room but that would cause extra heating inside it during the overheated period. Shading devices are the tools for preventing those extra heat gains. Still they have to be in an angle to optimize the glare inside, to evaluate this, an algorithm that calculates the DF factor is designed (Figure 5.10). The algorithm guarantees that the ratio of DF stays between given numbers. When it is out of the ratio, it starts the algorithm again. We can call this algorithm a control mechanism.

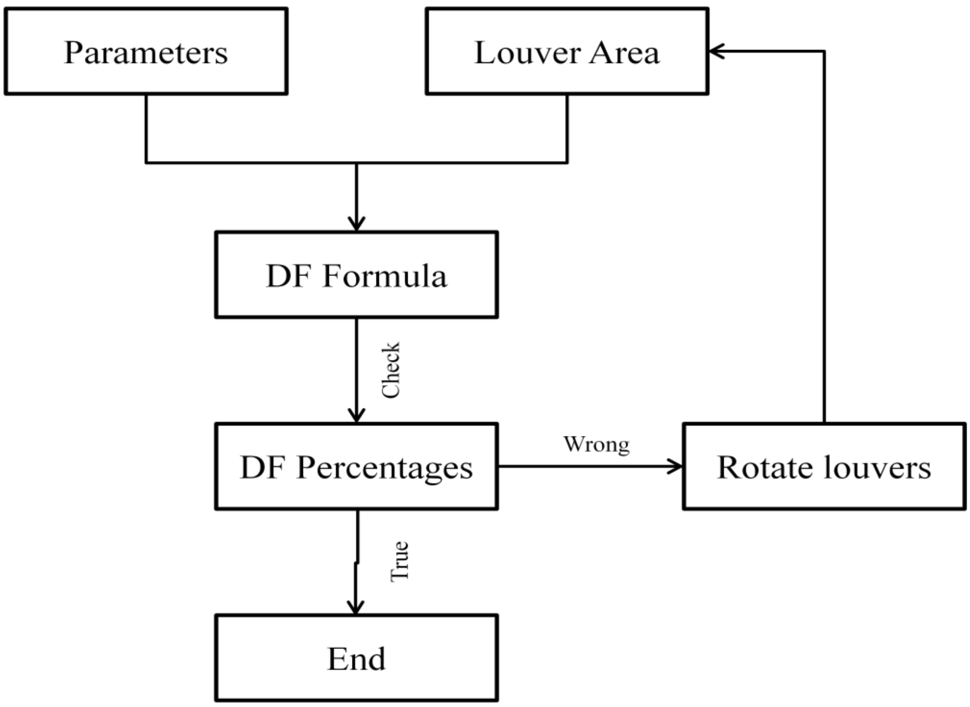

Figure 5.10: Daylight factor algorithm diagram

The other base algorithm is about the thermal comfort (Figure 5.11). For the thermal comfort in the overheated period, sunbeams should be blocked for shading inside the place. To achieve this, season should be checked to find out the sun path. With this sun path, the angles of the sunbeams are obtained. To block sunbeams angles are matched with the louver angles. If the louvers do not let the sunbeams enter the room, they stay stable. If not, they start rotating until they block the sunbeams. Whenever it start entering the room algorithm starts over again for checking.

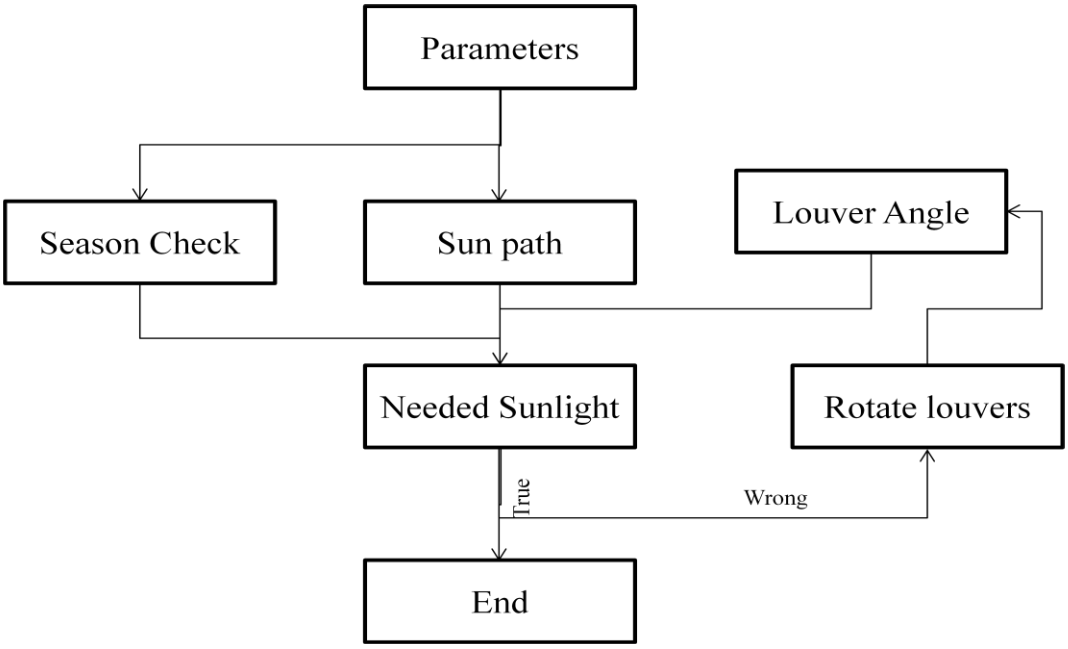

Figure 5.11: Solar heat gain algorithm diagram

The first two algorithms are working successfully. However, a more efficient solution should be found, rather than checking both algorithms for optimal outputs. An algorithm than can make two of these algorithms work together should be designed (Figure 5.12). With that method, the best combination of two can be found easier and faster. Moreover, there will be no missed-out results that can cause a problem later.

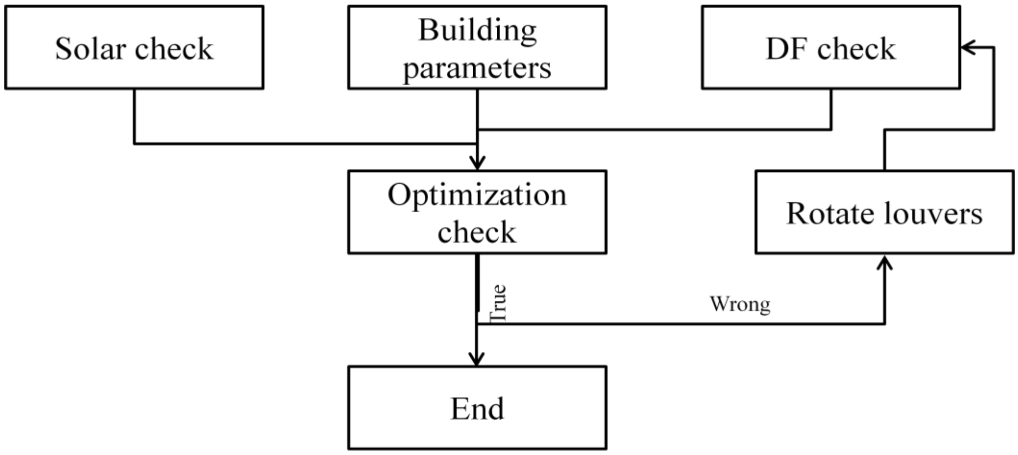

Figure 5.12: Optimization model algorithm diagram

5.3 Optimization Model

The purpose of the thesis is to evaluate the effects of the computational design on optimization methods. While doing this, it is also aimed at examining which parameter has the biggest effect on shading design. Therefore, the office room is adjusted with fixed dimensions. In the present model, an optimization has been carried on an office room with a floor area of 30 square meters and a south-facing window. The office, to be considered at the third floor of a multistory building is 3m high, 5m wide and 6m deep. Figure 5.13 shows the geometry of the room with the shading device. Shading devices are not fixed but the user should choose one of the specified ones. The louvers are flat panels with a width of 5 cm and whose length is defined by the size of the window. The depth of the louvers is defined as 20cm, 30cm, 40cm and 50cm. The other parameters are set by the user to control their effect.

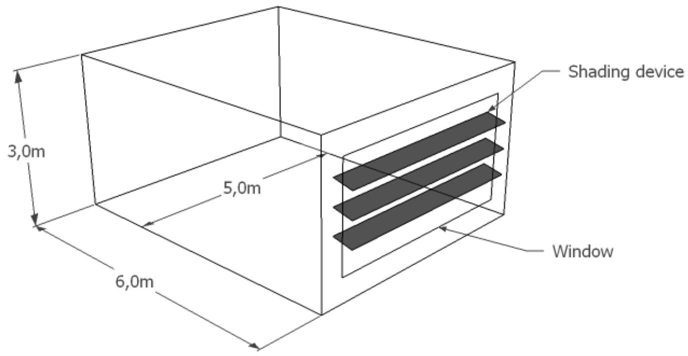

Figure 5.13: Office room with shading devices

5.3.1 Script design and optimization

Script design is the phase in which all the information is brought together and computerized. All the constraints and formulas are redefined in script lines. Monkey script editor for Rhinoceros has been chosen for the reasons mentioned before. It has an easy user interface (Figure 5.14) and shows the help options directly in the interface without taking the user to another window. The results are taken as a 3D drawing because of its VB background. Moreover, different user interfaces are created for the user to make the use of the program easier (Figure 5.15).

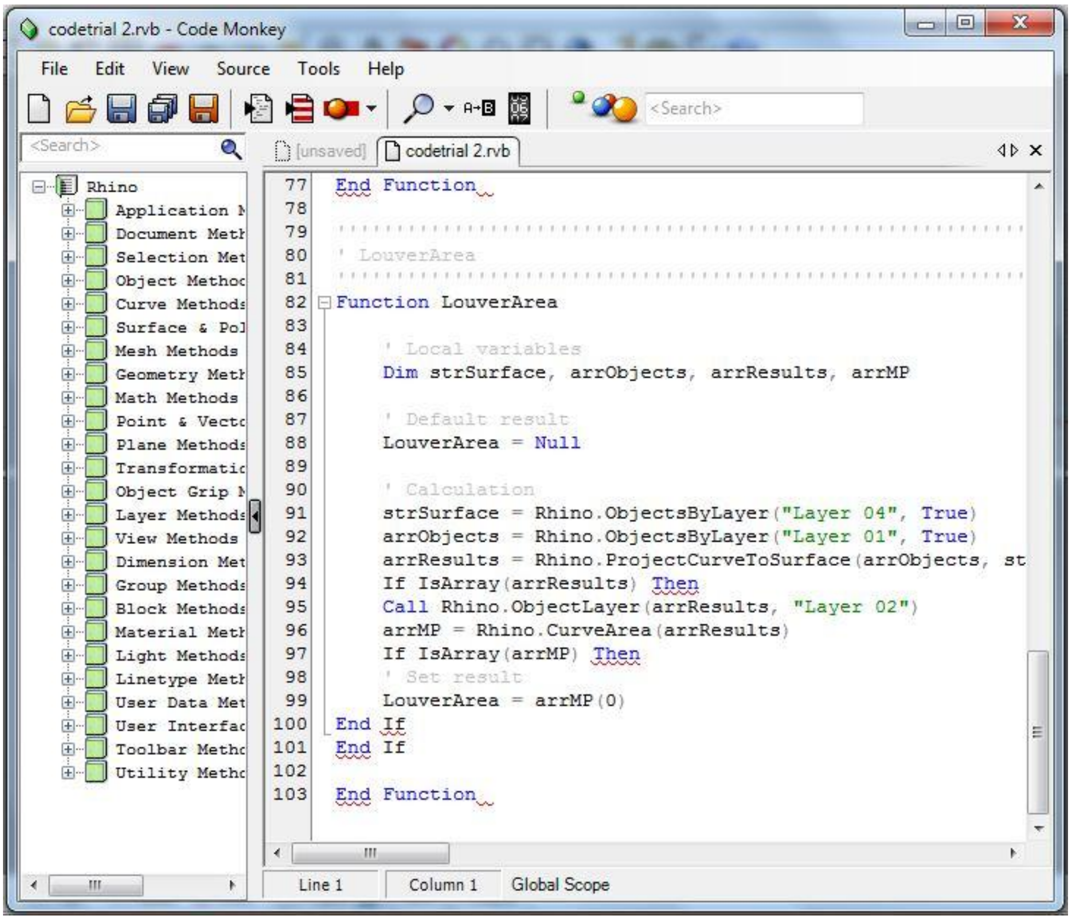

Figure 5.14: Monkey script editor user interface

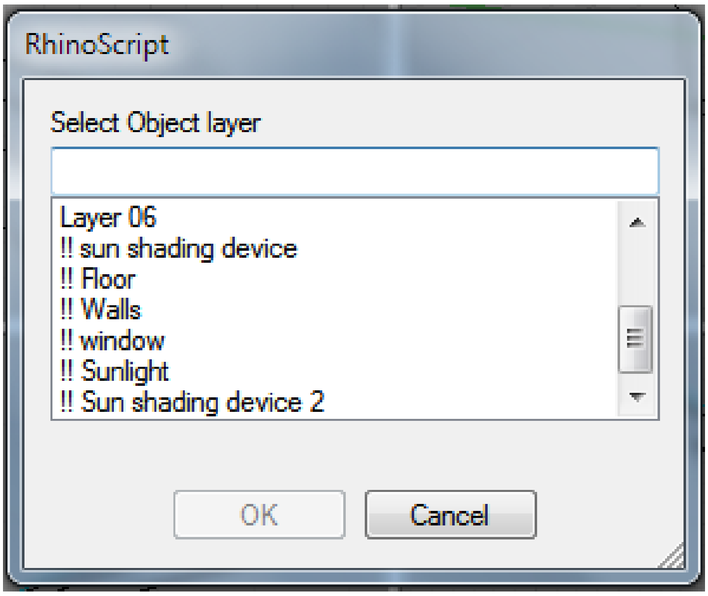

Figure 5.15: User interface for object layer selection

There are two factors affecting the optimization process, one of which is the DF. For DF calculations different formulas are given in chapter 3, BRE formula is chosen amongst the others. The factors of the formula are defined in the script in detail. The total area of the room is fixed so it is taken by the geometry. The others factors such as: Surface area of the window, Angle of visible sky from the mid-point of the window, Maintenance factor of the window, Transmission factor of the glazing, Average reflection factor of all internal surfaces, are set by the user via the designed user interface. After the calculations with these parameters and the given formula, the script checks the DF ratio. If the ratio is either smaller than two or bigger than five, the louvers starts to rotate 5°. Then it calculates the ratio again, and this loop goes on until the results catch the given interval. The algorithm which calculates the DF can be seen below (figure 5.16). When these conditions obtained, it means that the occupants have visual comfort from daylight. Nevertheless, there is another factor that also affects the optimization, and that is thermal comfort. Its results can be achieved by the calculation of solar heat gain and examination of the solar beam angles. The angles for the examination are obtained with the declaration of building site. For now, these angles are taken to the script as numbers from the tables.

```
.
Do
    ' Window area
    A = WindowArea
    ' Louver area
    L = LouverArea
    ' Validate results
    If IsNull(A) Or IsNull(L) Then Exit Do

    ' Calculate daylight factor
    A = A - L
    Df = (A*d*t)/(Stot*(1-Rf*Rf))
    Call Rhino.Print("Daylight factor " & CStr(Df))

    ' Rotate objects
    arrObjects = Rhino.ObjectsByLayer("Layer 01", True)
    If IsArray(arrObjects) Then
    Call Rhino.EnableRedraw(False)
    For Each strObject In arrObjects
        If Rhino.IsCurve(strObject) Then
        arrPoint = Rhino.CurveMidPoint(strObject)
        Call Rhino.RotateObject(strObject, arrPoint, -5.0)
End If
Next
Call Rhino.EnableRedraw(True)
End If

Loop Until (Df < 5.0)
```

Figure 5.16: DF calculation algorithm for the louver design.

Finally, inside the script the combination of these two algorithms is supplied. First, it checks for the DF and stops when it is achieved, then starts checking for the thermal conditions. If the thermal comfort cannot be achieved, it changes the angle of the louver without disturbing the DF ratio then checks again for thermal comfort. This loop goes between the essential DF ratios. If still the thermal comfort is not achieved then it starts checking for the 180° opposite angles. Because of the DF calculations, the contrary angles would be sufficient also.

5.3.2 Model outputs and evaluation

There are plenty of parameters and it is a big opportunity to have this script to evaluate them according to their effectiveness. For the evaluation of the project five different cases will be examined (Table 5.4). These cases are chosen due to understand the logic behind the shading design. All these cases are here to investigate certain parameters and constraints.

Table 5.4: The cases examined and their properties.

Case Number	Evaluation Parameter
C-1	Solar angles
C-2	Average reflection factor of all internal surfaces
C-3	Louver size
C-4	Numbers of louver
C-5	Window size

In C-1, the effects of the Sunbeams are analyzed. The window dimensions are set as 3m width and 1.5 m height and the angle of visible sky from the mid-point of the window is obtained as 150°. Transmission factor of the glazing is set to 0.65 and Maintenance factor of the window is set to 1.0. The room walls are treated like white plaster and the average reflection factor of all internal surfaces is set by 0.40. After fixing all the parameters, the angles of the sun are changed a number of times. As a result, an impressive impact of the solar angles for the louver design is experienced. The figure 5.17 reports the four results, which are chosen by the user up to the seasonal changes. Results show that the impacts of the solar angles are clearly observable. For the overheated periods such as spring and summer, louvers are nearly %100 closed, also to prevent glare inside the room. On the other side in winter, it is not blocking the view and opens to get the sun inside the room.

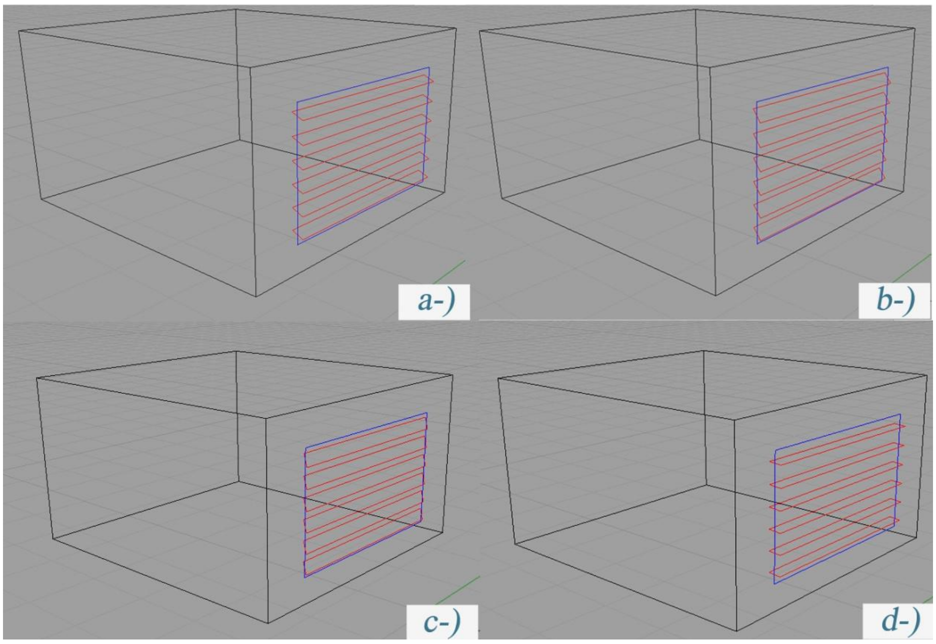

Figure 5.17: Outputs for fixed DF, changing solar angles a-) fall (Sept 23), b-) spring (March 21), c-) summer (June 21), d-) winter (Dec 21).

In C-2, the impacts of Average reflection factor of all internal surfaces are tested. The window dimensions are set as 3m width and 1.5 m height and the angle of visible sky from the mid-point of the window is obtained as 150°. Five of the 20 cm depth louvers are placed on the window. The transmission factor of the glazing is set to 0.65 and 1.0 is set for the Maintenance factor of the window. To have the thermal effect in minimum the date is set to the 21st of March. Different materials have the variety of the reflectance factor; even with white color the reflectance factor changes slightly. The average reflectance factors of the different materials are shown in Table 5.5. Some of these materials are chosen to experiment their effect on DF and lighting demand of the office room.

Table 5.5: Reflectance factors of the materials.

Type of the material	Reflectance F.
Plaster	0.45
Paint (white, matte)	0.80
Paper (white)	0.75
Paint (light green)	0.50
Paint (dark blue)	0.15
Marble (polished)	0.40
Aluminum(polished)	0.70
Aluminum Coatings(matt)	0.55

Plaster, paint (white, matte), paint (dark blue) and aluminum coating (matte) are chosen for the testing of the DF and louver angle. After entering all parameters and changing the Average reflection factor of all internal surfaces, the results, shown in Figure 5.18, are taken. Results show that as much as other parameters the material of the interior affects the louver orientation; while the material colors are darker and not too reflective, the louvers are open to get the daylight in. On the other side, while the materials are shiny or reflective the louvers are more closed to avoid extra brightness inside the room.

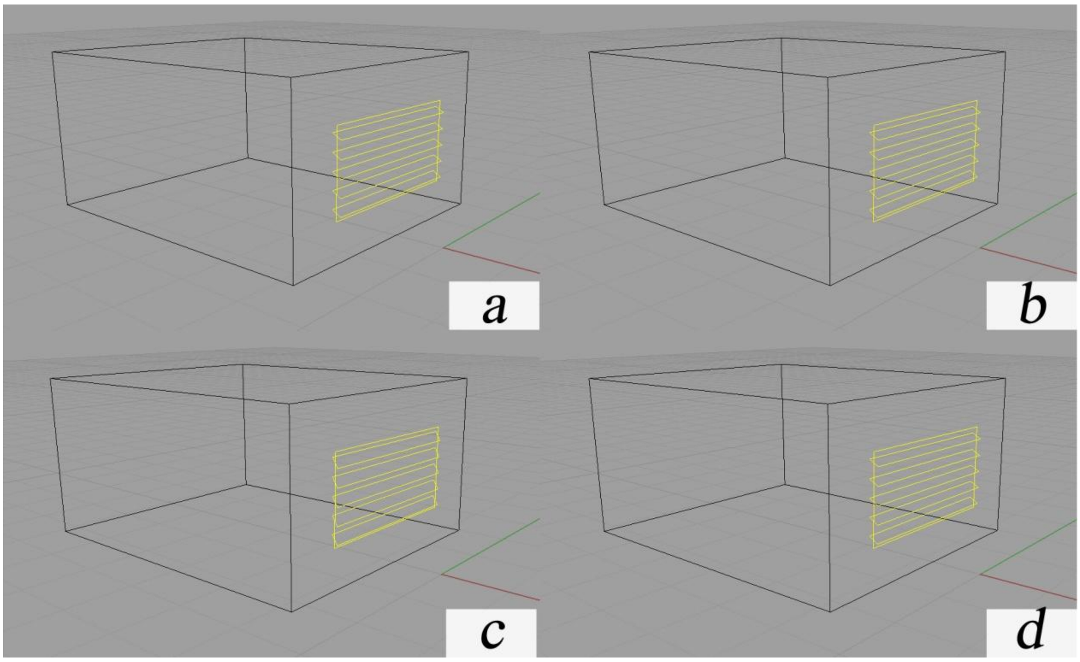

Figure 5.18: Louver positions up to the interior materials. a-) aluminum coatings (matt), b-) paint (dark blue), c-) paint (white matte) d-) plaster.

In C-3, louver sizes affect the view as much as they affect the visual and thermal comfort. Moreover, the wind load also affects the size of the louver. Therefore, designer can choose the size of the louvers according to the building site and climate scenarios. Wide ones are those most affected by the wind. That is why it is important to examine the impacts of the louver size on the daylight availability and thermal comfort. For this reason, the window dimensions are set to 3m width and 2 m height and the angle of visible sky from the mid-point of the window is obtained as 160°. Three of the louvers are placed on the window. The transmission factor of the glazing is set to 0.65 and 1.0 is set as the Maintenance factor of the window. To have the minimum thermal effect, the date is set to March 21. The average reflection factor of all internal surfaces is set to 0.45, like plaster. After all the parameters are set, the five different louver sizes are examined with the optimization algorithm (Figure 5.19). With the results, designers will be able to make decisions about the louver sizes more easily. Because from the outputs, it is clearly seen that the size do not affect the louver angle hardly. However, the wind power and other environmental loads affect louver sizes. So it is more effective to use smaller louver systems on a high-rise project. Moreover, the 50 cm and 40 cm louvers block the view for the occupants of the office room.

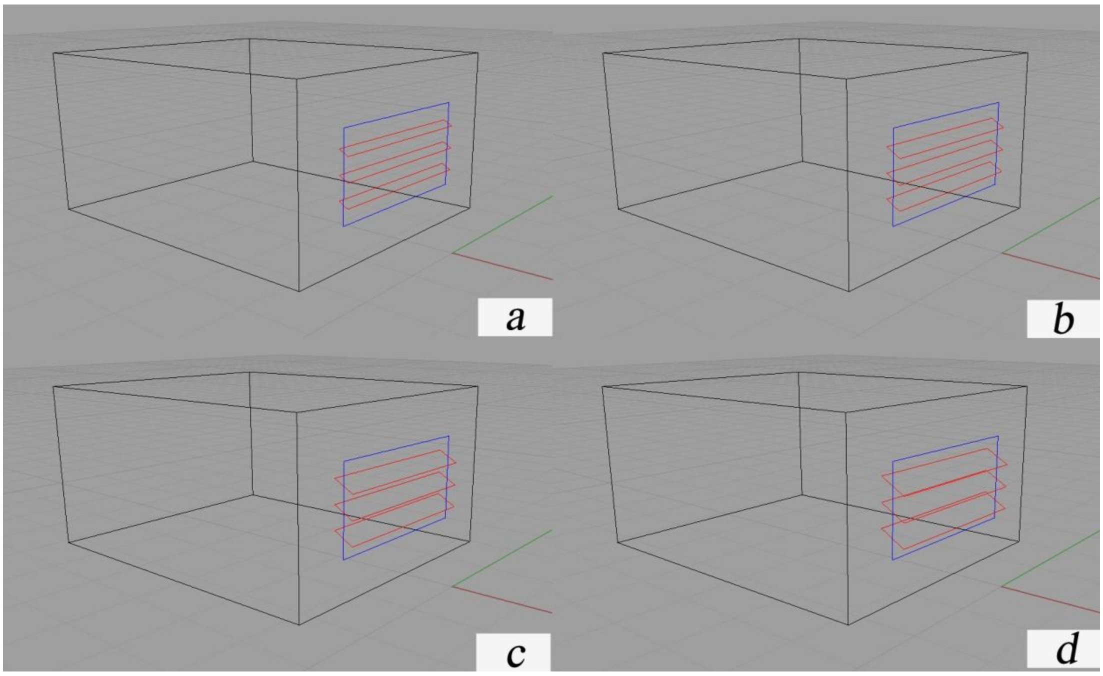

Figure 5.19: Louver positions up to the louver size. a-) 20 cm, b-) 30 cm, c-) 40 cm, d-) 50 cm.

In C-4, another parameter for the louver optimization is the louver number. Certain numbers of louvers are used in the project. Moreover, different numbers are tested to understand the impact of louver numbers. Louvers are spread on to the windows with equal spans. Three, five, seven and nine are the numbers of louvers tested in the optimization process. The windows dimensions are set as 3m width and 1.5 m height and the angle of visible sky from the mid-point of the window is obtained as 150°. 20 cm depth louvers are placed on the window. The transmission factor of the glazing is set to 0.65 and 1.0 is set for the Maintenance factor of the window. To have the minimum thermal effect, the date is set to the 21st of March. The average reflection factor of all internal surfaces set to 0.80, as white paint. After the examination of the louver sizes, the results shown below are received (Figure 5.20).

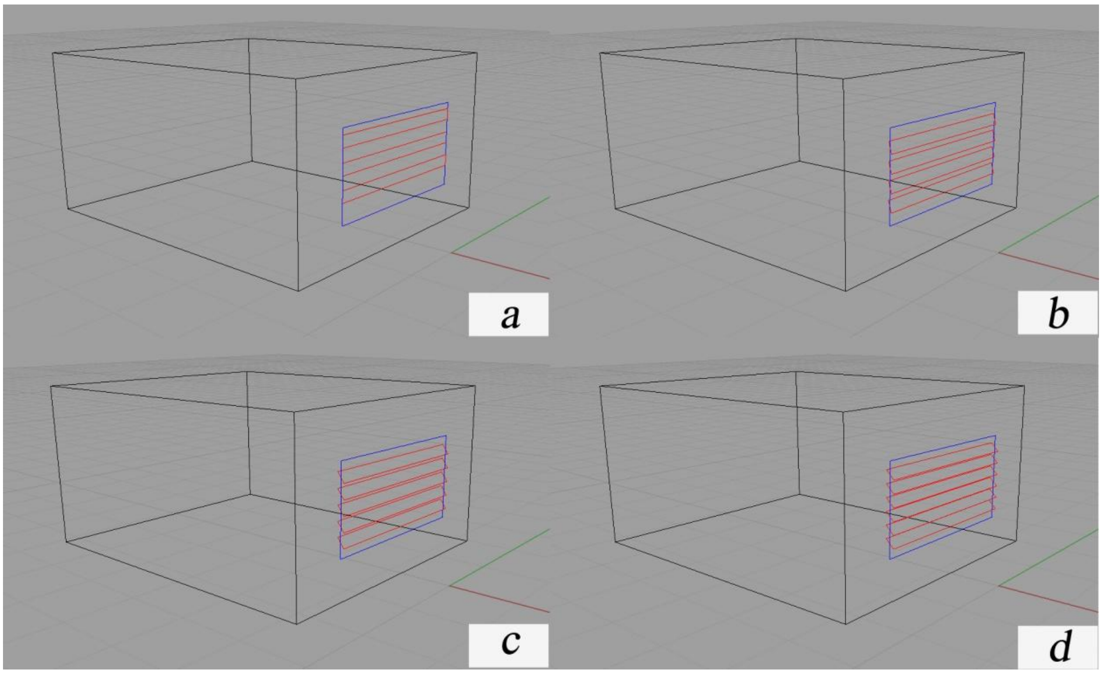

Figure 5.20: Louver positions up to the louver number. a-) 3, b-) 4, c-) 5, d-) 6.

Louver size has a big impact on the daylight factor optimization. For example with the given properties and three louvers, expected percentages could not be achieved even it was fully closed. The closest number for the DF was % 5.8 and it was not at the span that it should be in. On the other examples the expected numbers are reached. While the number increases the louver angles decrease. Nevertheless, that does not mean the louver numbers should be higher because when there are more and more of them they affect other criteria such as view of the room.

In C-5, one of the most effective parameters is examined. Window size affects all the room in terms of daylight, thermal comfort and view zone. While examining this parameter, another parameter, which is the angle of visible sky from the mid-point of the window, will be changing according to the window size. For the experiment, the parameters shown below are fixed. Five of the 20 cm depth louvers are placed on the window. The transmission factor of the glazing is set to 0.65 and 1.0 is set as the Maintenance factor of the window. Average reflection factor of all internal surfaces set by 0.80 as white paint. To have the thermal effect in minimum the date set as 21 of March. The results of the algorithm with the given parameters are shown below(Figure 5.21).

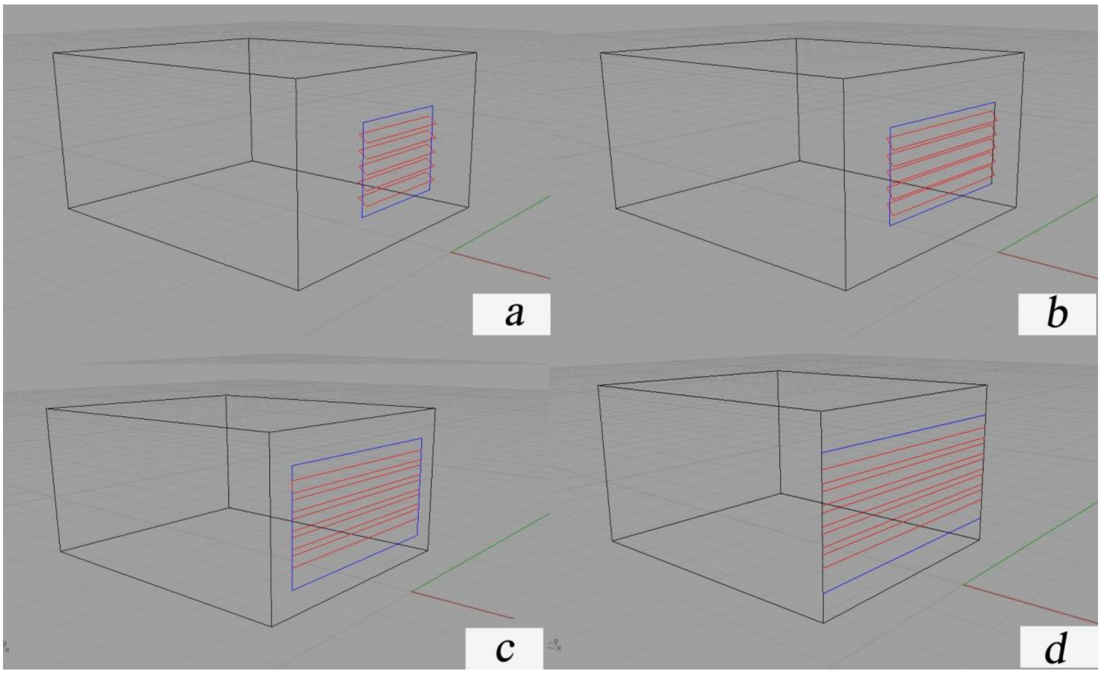

Figure 5.21: Louver positions up to the window size. a-) 200*150 cm, b-) 300*150 cm, c-) 400*200 cm, d-) 500*200 cm.

While the dimensions of windows increase the louvers close to protect interior of the room from glare. However, the minimum DF obtained for the 400*200 cm windows was %8.6 and for 500*200 cm windows it was %12.3 even when they were totally closed. Therefore, that means while the windows are getting bigger, the number of the louvers should decrease in proportion. That will bring an optimal louver positioning to the project.

6. CONCLUSIONS

The integration of the computational design tools and environmental control systems offers the possibility of building itself and its components optimized for environmental comfort performance. Moreover, this study and the researches have shown that the subject of environmental responsive design optimization is more complex than how it is usually presented by architects. For that reason instead of just “when to shade?” question, “when and how much?” questions should be asked. The quality and the efficiency of the shading design have a great importance for staying still optimized over the seasons. If the shadier has been designed just for a particular scenario, it would not remain as an optimum shadier during the years. The static parameters of the building are hard to change while the environmental parameters are changing over time. Any design that claims to be ‘optimized’ for any environmental criteria will not be optimized for long if it is just design with one current condition. Although there are still limitations to predict the future climate scenarios, this evolutionary algorithm based optimization still performs better over the time instead of a design only optimized for custom conditions. There are two main advantages of optimization through computational design. The first one is the time issue, normally examination of environmental issues are time consuming. However, feedbacks are much faster with optimization methods. The time of response takes less than a second instead of minutes. The second one is infinitive realm of possibilities for the resulting form. It is impossible to evaluate all these results with out computationally optimized method.

In the thesis model part, an optimization of external louvers has been performed for maximizing the overall primary thermal and visual comfort in an office room. The coupling of shading devices with different interior conditions, solar angle chart, DF, etc. have been analyzed. For each configuration, a different solution is obtained with optimized angles of louvers. The obtained results show how much powerful the evolutionary algorithm based optimization can be as a tool for the architects.

Movable shading devices are very suitable for providing shade throughout the day. They are able to provide optimized shading with respect to the sun position. The results of this study comport with other similar studies. Generally, solar radiations are obstacled via shading devices. Thus, they decrease cooling demand in summer and increase heating demand in winter. By providing shade inside the room, Shading devices help to protect the interior from glare. Those also provide an increase in electricity consumption. This impact gets more important in office buildings.

More research and development regarding shading devices are still necessary. For future studies, there are some suggestions as follows. In this study, only a few parameters are studied and more cases and variables need to be investigated. Some of variables are different colors and materials for the louvers, different windows materials, different combinations of louver places and mixed sizes, etc. Only horizontal louvers are studied in this thesis but also vertical ones should be examined. Moreover, the view contact is one of the considerable issues in evaluating shading systems. This problem is not addressed in detail in this research, so it can be one of the possible future work criteria. All the cost problems are ignored during the study but on the design phase, it has a major impact. That is why a cost assumption section can be added to the study. Daylight evaluation is carried out only based on Daylight Factor (DF). Further studies can be done in terms of other analysis methods, specifically Daylight Autonomy (DA). Daylight Glare Probability (DGP) can be studied for glare evaluation. Finally, shading systems have a very important impact on the facade in terms of their expression as an architectural element. This attribution enforces itself with external shading devices regarding their functionality and their potential of improving aesthetics of a building. As a further research topic, necessity in using, aesthetics and advantages of shading devices can be discussed.

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APPENDICES

APPENDIX A: Daylight factor formula components

A_{window}
: Surface area of the window, excluding frame, bars and other obstructions [m²]

A_{floor}
: Floor area of the room [m²]

A_{total}
: Total internal surface area of the room [m²]

ε
: Factor to account for external obstructions

U
: Utilization factor

α
: Angle of visible sky from the mid-point of the window [°]

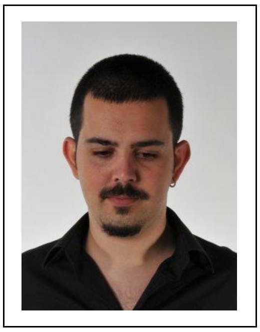
M
: Maintenance factor of the window

t
: Transmission factor of the glazing

ρ_m
: Average reflection factor of all internal surfaces

ψ
: Factor to account for thickness of the window wall

CURRICULUM VITAE



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