A COMPUTATIONAL METHOD FOR THE DESIGN EXPLORATION AND OPTIMIZATION OF DAYLIGHTING PERFORMANCE OF MUSEUM BUILDINGS

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ABSTRACT

A COMPUTATIONAL METHOD FOR THE DESIGN EXPLORATION AND OPTIMIZATION OF DAYLIGHTING PERFORMANCE OF MUSEUM BUILDINGS

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Controlling and adjusting daylight for museum buildings is critical. The shortage of light in a space runs the risk of loss of vision, while excessive amounts of light causes visual discomfort, and especially in museums, can be destructive for art collections. The aim of this research is the development of a computational design method that supports control and adjustment of daylighting illumination level to satisfy both of the above-mentioned goals while ensuring indirect daylighting within the museum. For this purpose, Optimum Daylight Availability Method (ODAM) is proposed in this research, which aims to assist architects in controlling the interior daylighting more effectively. ODAM is a simulation-based method that is developed to satisfy interior daylighting criteria by supporting the design of dynamic shading devices. This method is integrated with an existing daylighting performance simulation tool that quantifies the daylighting metrics proposed as part of the method. The method is implemented as a parametric model definition and validated through a case study of the design of a museum building in The Hague.

Keywords: Computational design, Parametric design exploration, Performance based daylighting design, Optimum daylight availability, museum buildings.

ÖZ

MÜZELERİNİN GÜNIŞIĞI AYDINLATMA PERFORMANSININ TASARIM ARAŞTIRMASI VE OPTİMİZASYONU İÇİN SAYISAL BİR YÖNTEM

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Yüksek Lisans, Mimarlıkta Sayısal Tasarım ve Üretim Teknolojileri

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Müze binaları için günışığı kontrolü ve adaptasyonu önemlidir. Bir mekandaki ışığın azlığı görme kaybı riskini getirirken, aşırı miktarda ışık görsel rahatsızlığa neden olur ve özellikle müzelerde sanat koleksiyonları için tahrip edici olabilir. Bu araştırmanın amacı, müzelerde dolaylı gün ışığı sağlarken, yukarıda belirtilen hedeflerin her ikisini de karşılayacak şekilde gün ışığı aydınlatma seviyesinin kontrol edilmesini ve ayarlanmasını destekleyen bir hesaplamalı tasarım yönteminin geliştirilmesidir. Bu amaçla, mimarların iç aydınlatmanın daha etkin kontrol edilmesine yardımcı olmayı amaçlayan bir yöntem, Optimum Günışığı Müsaitlik Yöntemi (ODAM) önerilmiştir. ODAM, iç aydınlatma kriterlerini karşılamak üzere dinamik gölgeleme cihazlarının tasarımını desteklemek için geliştirilmiş bir simülasyon tabanlı yöntemdir. Bu yöntem, gün ışığı hesaplamalarını yapan mevcut bir gün ışığı performans simülasyon aracı ile entegredir. Yöntem, parametrik bir model tanımlaması olarak uygulanmakta ve Lahey'deki bir müze binasının tasarımına ilişkin bir vaka incelemesi yoluyla doğrulanmaktadır.

To my family

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CHAPTER 1

INTRODUCTION

"Architecture is the learned game, correct and magnificent, of forms assembled in light." ~ Le Corbusier

1.1 Background

1.1.1 Architecture and environmental consciousness

Human activities are the reason of climate change on the planet Earth. Not only they have been changing the nature and the ecosystems, but also they are endangering human's health and welfare by affecting forestry, agriculture, clean air, water supplies and substances that are vital for living. As an example of such activities the following graphs illustrate the level of carbon dioxide emission[1] , which formulates the majority of greenhouse gases[2] , has been rising critically mainly after the industrial revolution[3] (Figure 1Figure 2).

[1] Carbon dioxide can remain in the atmosphere almost for a century and therefore the planet will continue to get warmer in the following decades which increases the risk of severe climate changes on the planet.

[2] Greenhouse gases form a blanket around Earth which trap energy in the atmosphere to warm up the planet and support life on it. However, by increasing the level of greenhouse gases, excess amount of heat is trapped in the atmosphere which causes global warming and many other problems for the planet.

[3] For more information refer to https://climate.nasa.gov/evidence/

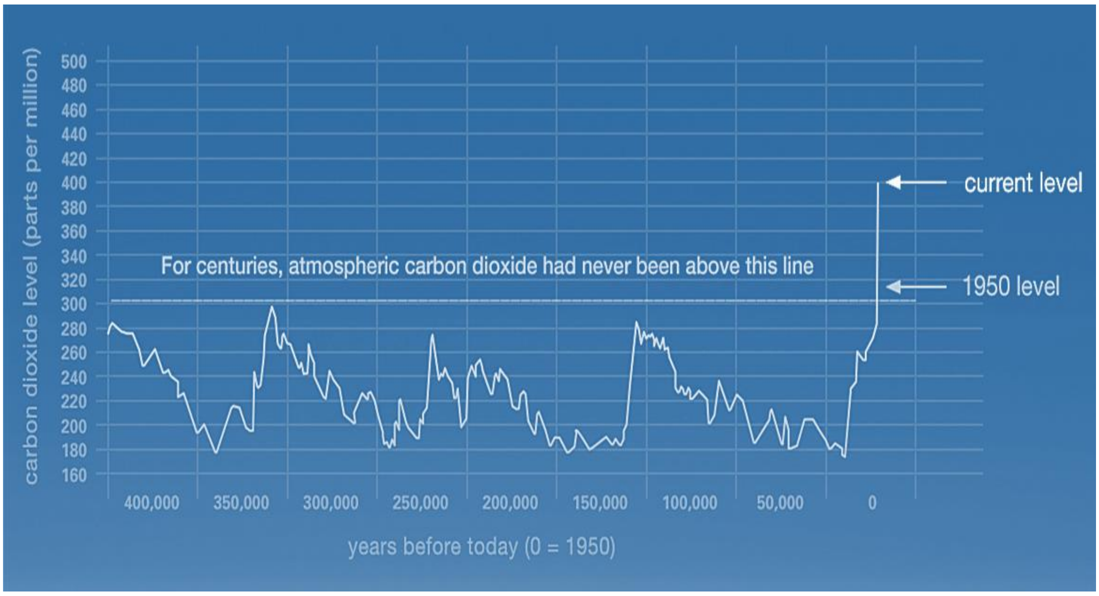

Figure 1. This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO2 has increased since the Industrial Revolution.

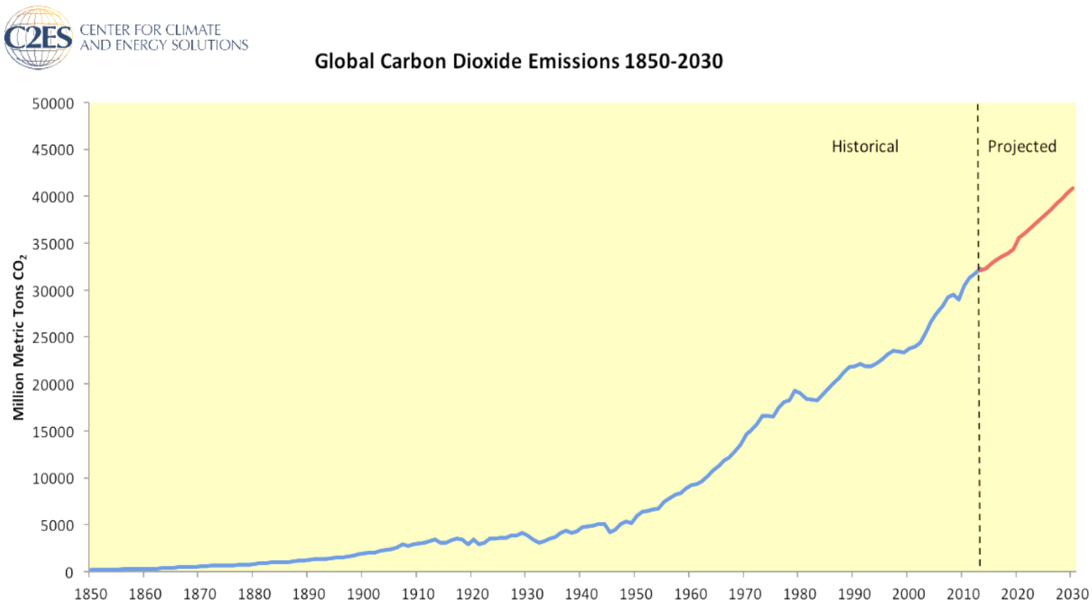

Figure 2. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory (2015). International Energy Agency, World Energy Outlook (2015)

The decisions that are made today play an essential role in shaping the planet wherein our next generations will live. In this realm, architects play a crucial role since their design choices directly influences the built environments. Recent research in the US has revealed that building industry involves in almost half of the energy consumption of the country and about 70% of the electricity consumption (Anderson, 2014). In addition, 40% of the total domestic carbon dioxide emissions and 26% of all non-industrial waste[4] are produced by building services (McArdle & Lindstrom, 2008).

> *"Since the beginning of the twentieth century, not only what we regard as the disciplinary discourse of architecture but also the techniques of design and construction have undergone rapid, extensive transformations in terms of sophistication as well as complexity. These transformations are linked to the rapid pace of industrial and technological development that has characterized the current age and its prevailing market economy model. These developments underlie many of the world's most serious environmental problems, and have greatly impacted our approach to the design of the built environment and its operations in ways that have moved us farther away from a sustainable position in nature."* ~ Sang, LEE. (2011)

If these industrial and technological developments are utilized intelligently, they can eliminate such negative impacts on the built environment. Therefore, there must be much more attention toward sustainable architecture through the implementation of smart and innovative design methods (Ahmed et al., 2016) which can save money, time and energy significantly (Hemsath, 2013).

1.1.2 Well-informed design decision-making

Currently, despite the excessive amount of data, yet only a small portion of it is informative and useful at the early stage of building design process while well-informed decisions can reduce future energy consumption without much additional

[4] Buildings and their Impact on the Environment: A Statistical Summary. Technical report, April 2009.

cost (Anderson, 2014). During this stage, there are many issues that architects consider to ensure high-performing buildings. This research tackles the fact that initial design is rarely associated with performative issues such as daylighting and shading. This thesis specifically proposes design method for architects, which supports better decision-making at the early design stages for spaces with strict daylighting requirements.

1.1.3 Performative design in architecture

Within the building industry, there is a growing demand for achieving high performance throughout the building lifecycle, from the very early stage of design process until its demolition (Dino, 2011). As a design approach, performance-based design aims to attain particular measurable or predictable performance requirements of a design object before it is built or manufactured (Luebkman, 2003). It is an alternative to the traditional and conventional prescribed codes [5], and allows for a dialogue among the clients, engineers and architects regarding appropriate performance objectives (Luebkman, 2003).

In performative design approach, neither of the form nor the function are treated separately, or followed by the other; instead, both of them are interrelated and interdependent (Hensel, 2010). Therefore, implementation of performance-based design does not mean neglecting the architectural qualities or the aesthetic aspects of a design, but if it is implemented correctly, it improves those qualities (Kolarevic & Malkawi, 2005). In this regard, Anderson believes that architects are required to increase their knowledge regarding building performance. He stated that "*One of the best strategies is to begin engaging in design simulation and becoming more knowledgeable about energy use and energy modeling"* (2014).

As the vast scope of performance based design, this thesis will only focus on daylighting performance as an essential factor that directly influences the living

[5] Prescribed codes are extremely constrictive and restrictive set of rules and dictate particular construction practices such as regulations about dimensions of the doors and corridors in a building.

environments. For this purpose, before proceeding any further there will be a brief introduction to various aspects of daylight and its vital role on living spaces. As a case study for this research an exhibition space of a museum in Netherlands has been selected.

1.1.4 Architecture and daylight

Daylighting is an essential factor in designing built-forms and shaping living spaces (Bell 1973). It is also a key factor in sustainable design since it is a free omnipresent source of energy, has a minimum effect on environment, and can also provide a maximum impact on the occupants of a built-form if controlled appropriately (Smith, 2011). Its correct utilization increases efficiency, productivity, occupant comfort, and health conditions (Kim & Chung, 2011). Daylighting also supplies the built-forms with energy saving during the day and minimizes electric consumption significantly (Hancock et al., 2009) by controlling solar heat gain and thermal loss and therefore decreasing energy demand for heating, cooling, ventilating and lighting purpose. According to U.S. Energy Information Administration, in the case of museums, lighting constitutes the highest amount of energy consumption after ventilation and cooling systems (Figure 3).

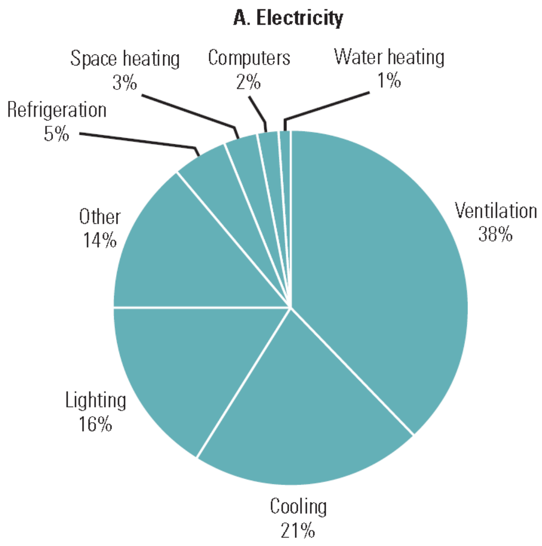

Figure 3. Energy consumption of museums (large, open gallery spaces) by end use. Source: U.S. Energy Information Administration, Public Assembly End Use, 2003

In comparison to artificial lighting, daylighting also provides various light qualities and better color rendering which is an essential factor particularly for museums and exhibition spaces where artifacts need to be observed more closely to their actual color (Kim & Chung, 2011).

1.1.5 Role of envelope in daylighting

The varying demands on quantitative and qualitative aspects of interior daylighting influence the form, orientation and especially the envelope of buildings. Building envelope, particularly, plays a significant role in connecting the interior environment and exterior conditions as a responsive and performative component (Shameri et al., 2011). To control daylighting performance, daylighting systems can be integrated with envelope either as static or dynamic. In the latter case, these systems can be operated either manually or automatically. Basically, these systems have two main tasks: Capturing and redirecting daylight into the building, and protecting the interior from excessive solar radiation (Garcia-Hansen 2006).

All interior spaces such as libraries, offices, hospitals, museums, classrooms, shops etc. require different amounts of interior lighting to fulfill the visual tasks and comfort of their occupants. However, it is a challenging task to maintain constant levels of daylight within a space because of the dynamic behavior of sun during the day, season and the year. The task of responding to such different solar conditions might be challenging in the design of shading devices.

1.1.6 Daylighting for museums

It is an essential issue for museums to provide a controlled interior lighting both for preserving the artifacts from damage as well as providing visual comfort for the visitors and the staff (Gay Hunt, 2009). As explained in the previous section, daylighting has many advantages compared to artificial lighting. While being a sustainable approach, it can increase efficiency, productivity, occupant comfort, and health conditions while decreasing cost and energy consumption significantly (Kim & Chung, 2011). Daylight also provides better color rendering in comparison to most artificial lights, which is an essential issue in exhibiting the artifacts (Kim & Chung, 2011).

In spite of all these advantages, integrating daylight within museums is a challenging task in comparison to other building types. Controlling daylight and providing a constant level of illumination is a problematic issue in museums**.** Such spaces require very strict illumination levels both for providing visual comfort for their occupants as well as protecting the artifacts from destruction. Moreover, the direct penetration of sunlight is required to be eliminated strictly throughout the year. However, such tasks are difficult to accomplish, mainly due to the changing behavior of daylight during the day, season and the year. This dynamic behavior of daylight results in a complex and unique design situation that is required to be solved by means of computational support.

1.2 Problem Statement

In spite of all the aforementioned benefits, daylighting is not a high priority in architectural design, since its qualitative and quantitative evaluation makes it not an easy task to cope with (Reinhart & Fitz, 2006). This difficulty is mainly due to the complexity of and the challenges in the effective use of daylight during the design process as well as the lack of tools specifically designed for this purpose.

An important issue in dealing with daylight is controlling the direct penetration of sunlight which might cause glare and visual discomfort for the occupants. Another problematic issue is providing a constant level of daylight illumination which is due to the dynamic behavior of sun throughout the day, month and the year.

Compared to other building types, controlling and adjusting of daylight for museums is much more critical. Shortage of light in a space causes loss of vision, while excessive amounts of light also causes visual discomfort, and especially in museums or galleries, it can become destructive for art collections (Littlefield, 2008). Moreover, unlike most building situations where direct sunlight can occasionally illuminate a surface, museums require that the UV exposure from direct sunlight be completely controlled, since it can cause permanent damage to valuable art collections. Therefore, proper daylighting can help to protect the integrity of the art and artifacts on display together with minimizing the glare and visual discomfort.

Building envelope is considered as the most essential components of a building for saving energy (Wang et al., 2007). As energy conservation has become a main concern, climate adaptive and dynamic envelope systems has been placed into the research agenda in architectural design.

The static facade systems are designed in response to many scenarios and objectives, which can be conflicting to each other: day- lighting versus energy efficiency, ventilation versus visual access and PV energy generation. Moreover, static façade systems, when designed to respond to the worst-case scenario, fail to address a wide range of daylight conditions. Dynamic systems, in contrast, it can respond better to the climatic conditions, improve occupant comfort, and lead to a more sustainable design. Dynamic envelopes respond to various environmental conditions by adjusting themselves in order to reach certain goals, such as reducing the need for mechanical and electrical systems in addition to improving occupant comfort. Moreover, such envelope can potentially be used to generate electricity when integrated with photovoltaic systems. These dynamic systems are not aimed to replace mechanical systems, but they can significantly reduce building energy demand.

While such dynamic systems are widely being used, they might have several disadvantages. First, the performance of such dynamic systems are rarely measured and evaluated for their energy efficiency at the early design stage, but after installation and becoming fully operational (Sharaidin & Salim, 2006). Another reason that makes dynamic systems less reliable than static ones is that they have higher levels of complexity due to their mechanical and electrical components. An operational dynamic façade is constantly in need of maintenance, to prevent malfunctioning, which can be costly and time-consuming (Loonen, Tr, Cóstola, & Hensen, 2013).

The design of dynamic envelope systems that respond better to different environmental conditions, specifically daylight, is an important issue that this thesis tackles. However, these potentials have not been entirely addressed by today's tools (Andersen et al., 2008). So far, there have been many attempts to control daylighting by adjusting and permitting adequate level of illumination in museums (Kim & Chung, 2011) yet there is not much works on how fine this illumination is entering and distributing inside the built-form. The main reason is due to the lack of suitable informative daylight performance tools and methods (Reinhart, 2010). Through the implementation of computational design tools, performance-based daylighting approaches can support architects, particularly at the early design processes.

1.3 Aims and objectives

The aim of this research is to propose a novel simulation-based computational method that support the design of dynamic shading devices in satisfying daylighting criteria in museum buildings. The proposed method, which is developed in this research, aims to assist the architects in controlling the interior daylighting of museums more effectively. In this respect, by implementing a parametric model, there will be an investigation on the evaluation and optimization of illumination level while ensuring indirect daylighting within the museums. The method is integrated with an existing daylighting performance simulation tool that quantifies the daylighting metrics proposed as part of the method.

As the main objective of this study, this method aids the designer in providing controlled daylighting by helping him/her in understanding and evaluating the effects of different envelope configurations through a parametric design approach. For this purpose, the design of an exhibition space, which is part of a museum designed by the author in Den Haag, Netherlands, was selected as a case study. Afterwards, the computational method, also proposed by the author, was validated through its application on the case study.

1.4 Research questions

- What method can support designers to effectively maximize daylighting performance of exhibition spaces through dynamic shading devices?
    - What are the daylighting performance requirements for museums?
    - What are the metrics of the daylighting performance?
    - What are the calculation procedures that quantify the daylighting performance metrics?
    - What design steps can be followed for effective design space exploration for performative design?
    - To which extent can this method support the design of dynamic shading devices?

1.5 Thesis methodology

Applied research methods are followed that involves:

a) an extensive literature review on daylighting performance assessment, computational tools and metrics that are commonly used for this purpose, and existing problems regarding the lack of methods and tools supporting performance-based daylighting design.

b) the development of a simulation-based computational method for exploration and optimization of interior daylighting performance in museum buildings.

c) the implementation of this method as part of a parametric model definition.

d) the application of the method on the design of dynamic shading devices of a museum building for the purposes of validation.

1.6 Thesis structure

In this chapter, a brief intro to the subject matter is presented, together with methodology, research questions, aims and objectives. The following chapters also cover literature review, methodology, case study analysis and discussion. At the end there will be the conclusion of this research and its potentials for the future studies (Figure 4).

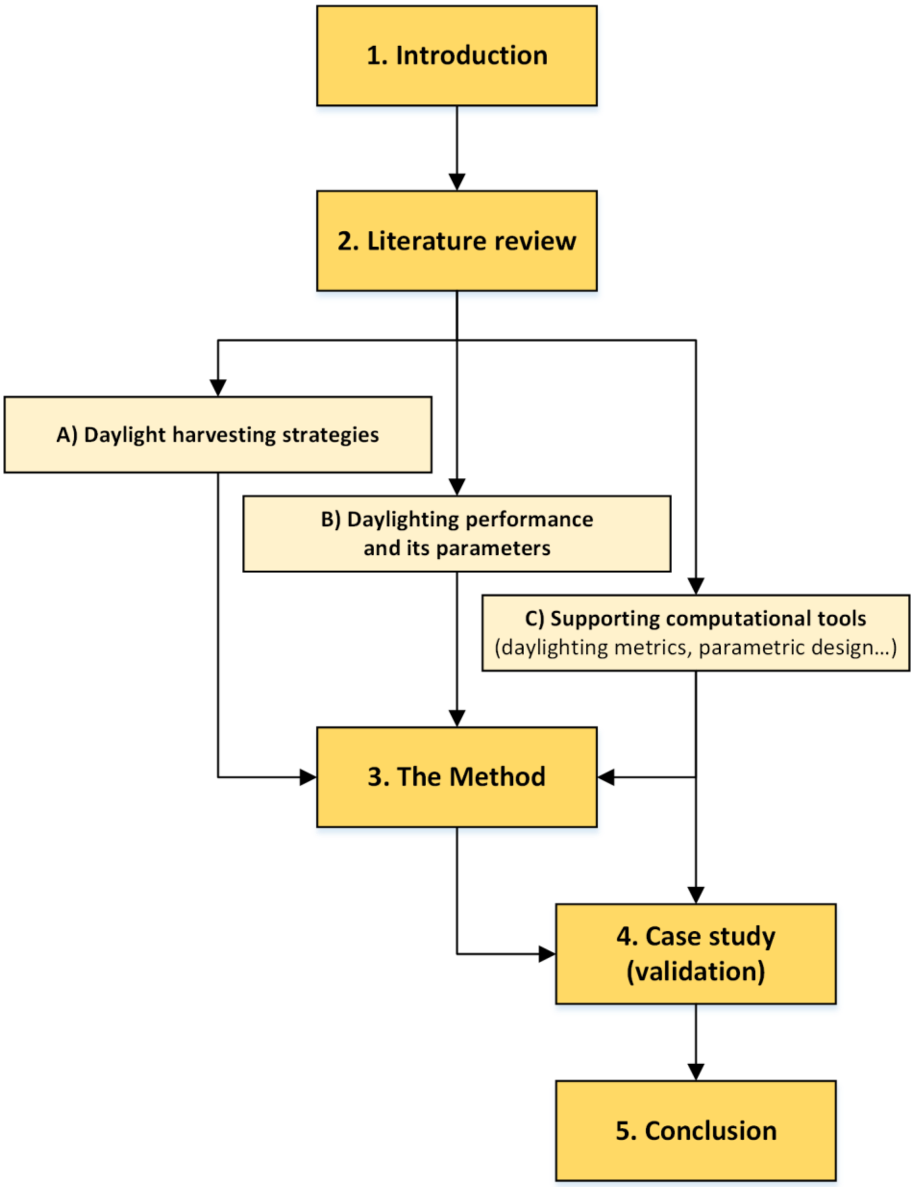

Figure 4. Research flow-chart

CHAPTER 2

LITERATURE REVIEW

"Form follows function - *that has been misunderstood. Form and function should be one, joined in a spiritual union"* ~ Frank Lloyd Wright

2.1 Daylighting

Daylighting has always been considered as an important issue in architecture, not only for its external expression through façade but also for providing qualities for the interiors, where most people spend up to 90% of their activities (Bougdah and Sharples, 2010). Good daylighting of any space can be achieved by fulfilling the particular demands of that space, such as minimum or maximum illumination levels, hours of occupancy, benefiting from side-light or top-light, desired views, and sensitivity to direct sunlight etc.. Effective design for daylighting requires early design decisions that can be informed by experience and analyses (Anderson, 2014).

2.2 Daylight harvesting strategies and devices

The orbit of the earth around the sun results in dynamic behavior of daylight throughout the day, month, season and the year. This dynamic behavior of sunlight varies depending on the geographical location on the planet. In this regard, the northern hemisphere is expose to daylight from the south throughout the year, while the southern hemisphere receives direct sunlight from the north direction. The exposure time of direct sunlight also varies depending on the geographical location and its distance from the celestial equator. As an example, Ankara, the capital city of Turkey, is situated on the North hemisphere at latitude 39.90° North and longitude 32.85° East, which receives direct sunlight mostly from south direction throughout the year. As illustrated in Figure 5, city of Ankara approximately receives sunlight for 15 hours and 9 hours relatively during summer and winter solstices.

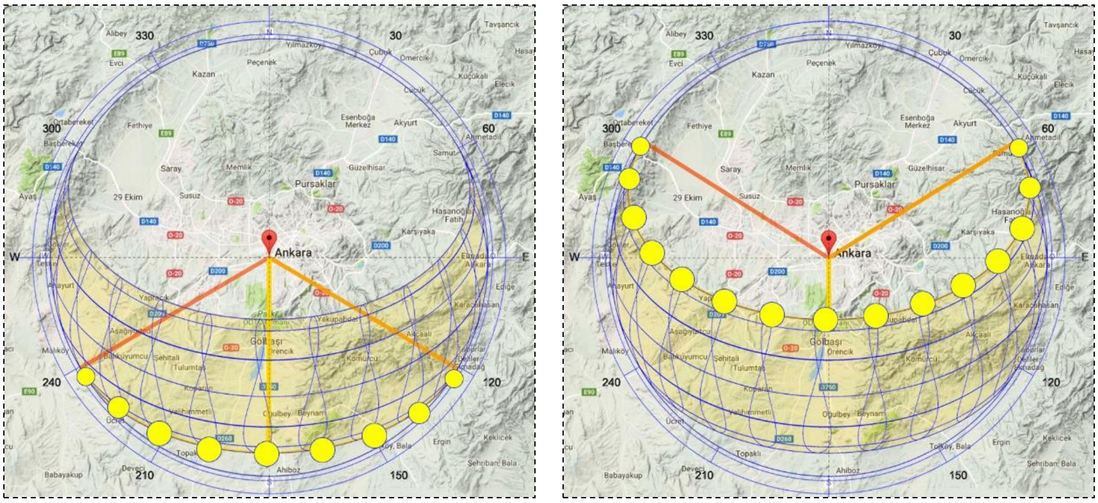

Figure 5. Ankara sun path during winter and summer solstices

Daylighting systems are generally designed based on daylight components which are sunlight and skylight. Daylight harvesting strategies can be divided in two main groups, side-lighting and top-lighting (Anderson, 2014). These strategies can be integrated with daylighting devices[6] to increase daylight performance and system delivery as well as minimalizing glare (Garcia-Hansen, 2006).

2.2.1 Side-lighting systems

Side lighting systems are directly in relationship with the sun path throughout the day and year. Their aim is harvesting daylight for interior spaces from the vertical envelope elements. In this type, the illumination levels are indirectly proportional to their proximity to the opening (Figure 6). For this reason several problems can be

[6] Generally, main daylighting devices are classified as: light shelves, light guiding systems, louvres and blind systems, prismatic systems, laser-cut panels, sun directing glasses, holographic optical elements, and light transport systems (Rahimzadeh, 2015).

encountered such as uneven illumination of spaces, lack of sufficient daylighting for deep spaces and glare due to directivity of sunlight. The illumination levels are further dependent on other factors such as opening's size, orientation, shading or reflection through building elements, neighboring structures or trees, building integrated shading systems, glazing properties, interior design, furnishing as well as time of day, season and climate (Huang, 2010).

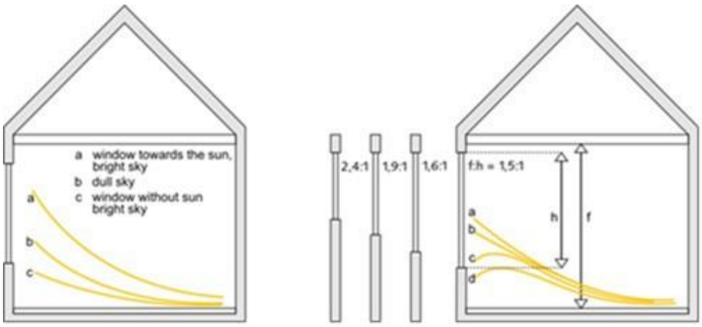

Figure 6. Iso-contour curves of daylight penetration (Frankel and Lyles, 2013)

2.2.2 Top-lighting systems

Since sky is brighter near the zenith than the horizon, top-lighting provides higher amount of daylight than side-lighting (Anderson, 2014). Although this type can provide sufficient daylight levels with more ease, controlling solar radiation becomes difficult when sun is directly on top. Also top-lighting systems have more tendency to gain or lose heat by convection and conduction than the other types (O'Connor et al., 1997). The use of simulation tools and intelligent design approaches makes it possible to achieve the right quantitative and qualitative aspects of daylighting (Anderson, 2014).

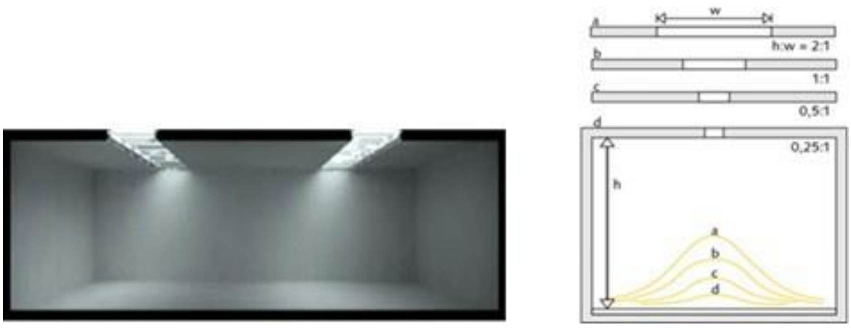

Figure 7. The impact of top-lighting on daylight distribution (natural frequency 1994- 2011; Architecture 2011).

2.3 Daylighting performance and its parameters

Generally architects initiate the design process by generating simple and abstract models and representations of what would be constructed later in the future. These representations, which contain low-resolution early-design information, are gradually developed step by step. Typically, performance simulation takes place at the end of the design process however, at this phase, applying any modification becomes unfeasible and expensive (Jabi, 2104). Therefore performance simulation needs to be embedded within the design process, and preferably the early stage of design (Brahme et al., 2001).

Creating well and constant illuminated spaces is challenging task, since daylight has a changeable behavior that varies broadly depending on location as well as different hours, days and seasons throughout the year. Proper control of daylighting plays a crucial role in decreasing the building's environmental impact (U.S Department of Energy, 2006) as well as increasing the efficiency, productivity, occupant comfort, and health conditions (Kim & Chung, 2011). However, the key characteristic of daylighting is the way it offers a space to be perceived and discovered by its users (Guzowski, 2000), (Andersen et al., 2008). Shortage of light causes loss of vison, while its excessive amount results in visual discomfort as well as destruction of artifacts in museums and galleries (Littlefield, 2008).

Therefore, the main challenge in design is to deal with many interrelated parameters of daylighting performance altogether. These parameters are expected to reach the required amount of illumination levels, to balance light levels within a space, to prevent glare, to control solar heat gain and thermal loss (Anderson, 2014). It is crucial that all the parameters should be integrated and evaluated at the early stage of design process to achieve building performance (Andersen et al., 2008). Although an integral approach is necessary to tackle such a high amount of objectives. This research particularly focuses on the first two parameters, reaching the required amount of illumination levels, and balancing light levels within a space. In order to evaluate these parameters, designers use different metrics[7] (Boyce & Smet, 2014) that will be described later in this chapter.

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[7] *"A metric is a well-defined measure that a designer can use to evaluate a design"* ~(Boyce & Smet, 2014)

2.4 Daylighting requirements for museums

Museums require suitable interior environmental quality (IEQ) for artifacts as well as visitors throughout the exhibition areas. There are several parameters—such as humidity, temperature, pollution (noise and chemical), and lighting—that must be considered carefully in order to provide a suitable IEQ for preserving the artifacts within the museums (Pavlogeorgatos, 2003). Previously, IEQ of museums were mainly designed with respect to the convenience of the visitors and the staff. However, a more contemporary approach is the conservation of artifacts and collections as the most essential factor in ensuring the IEQ of museums (Pavlogeorgatos, 2003).

2.4.1 Interior light quality of museums

Among the parameters of IEQ, illumination plays a crucial role in museums. It is through the light that visitors can discover and explore the museum and interact with the artifacts. On the other hand, light can also be destructive for collections and artifacts. Therefore, providing a controlled interior lighting is the central issue for museums both for preserving the artifacts from destruction and providing visual comfort for the visitors and the staff (Gay Hunt, 2009).

Typically, there are two different approaches for illuminating an interior space: artificial lighting and daylighting. As it was explained previously, daylighting has many advantages compared to artificial lighting. While being a sustainable approach, it can increase efficiency, productivity, occupant comfort, and health conditions as well as decreasing cost and energy consumption significantly (Kim & Chung, 2011). However, compared to artificial lighting, daylight is rather destructive to exhibited objects.

2.4.2 Light spectrums

Light is a form of energy and it is expressed in wavelength. Light, both natural and artificial, can have a significant impact in deterioration of the artifacts. Sunlight has a wide range of wavelengths starting from 300 nanometer (Wavelengths shorter than 300 nm cannot penetrate the atmosphere) that can be classified in three main spectrums (Bouwmeester & Hill, 2005):

- ***Wavelengths between 300 to 400 nm*** which are defined as ***Ultraviolet radiation*** (UV) and cannot be seen by human eye. UV radiations are the shortest wavelengths, and therefore it is the most destructive one.
- ***Wavelengths between 400 to 760 nm*** which are defined as ***Visible light*** and can be seen as the colors of the rainbow.
- ***Wavelengths longer than 760 nm*** which are defined as ***Infrared radiation***. This range of radiations are also invisible, but it can be felt as heat.

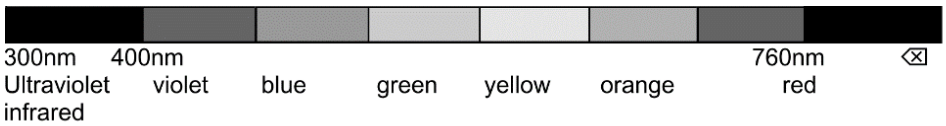

Figure 8. Sunlight spectrum

2.4.3 Conservation of artifacts

These three light spectrums can be found in all types of light; however, their amount may differ. In addition, there is no light level below which the materials does not damage. Therefore, the damage cannot be eliminated completely; however it can be decreased as much as possible by:

- Eliminating unnecessary invisible radiation.
- Reducing the level of illumination (intensity of visible light) that is received by the artifacts.
- Reducing the exposure time that the artifact is exposed to light.

Daylight is much more destructive in comparison to artificial light, since it contains Ultraviolet (UV) rays and high level of illumination (Armas, 2011). Therefore, unlike most building types wherein sunlight can directly penetrate inside the spaces, invisible radiation (particularly UV radiation) must be eliminated completely from direct sunlight in museum buildings (Wood, 2009). In addition to invisible rays, the radiant energy within the visible light spectrum can also be potentially harmful for materials (Oksanen & Norvasu, 2005). The damage from visible light depends on the combination of both light intensity and the time of exposure (Bouwmeester & Hill, 2005). Therefore, while integrating daylight within the exhibition spaces it is very crucial to consider the intensity level of illumination together with its exposure time as well.

2.4.4 Material sensitivity toward light

The intensity of visible light is measured by light meter, and its unit is lux. In this sense, 50 lux is the minimum level of illumination that is required for recognizing the color and shape of objects correctly (Bouwmeester & Hill, 2005). Therefore, 50 lux is admitted to be the maximum recommended illumination level for sensitive materials. According to the Illuminating Engineering Society of North America (IESNA), the artifacts in museums can be classified into four groups based on their sensitivity toward light (IESNA, 2000), which is illustrated in the following table:

Table 1. Material classification based on their sensitivity toward light (Armas, 2011)

Material classification	Example of material	Limiting illuminance	Limiting annual exposure
a) High sensitivity	Silk, newspaper, sensitive pigments	50 lx	150 000 lxh/a
b) Medium sensitivity	Watercolor, pastel, various paper	50 lx	150 000 lxh/a
c) Low sensitivity	Canvas, frescoes, wood, leather	200 lx	600 000 lxh/a
d) Intensive	Metal, stone, glass, ceramic	No limit	No limit

2.4.5 Challenge of daylighting in museums

As previously discussed, museums require strict lighting conditions for protecting the artifacts from damage as well as providing visual comfort for the visitors and the staff. However, in museums, shortage of light results in loss of vison, whereas excessive amount of light also causes damage to artifacts and visual discomfort for the occupants (Littlefield, 2008). Therefore, improving the daylighting performance of museums relies on a careful balance of the two above mentioned factors which are in contradiction with each other and therefore makes it a complex design task. Here the main difficulty is to provide a constant level of daylight illumination which is a result of the dynamic behavior of the sun as well as the changing climatic conditions during the day, season and the year.

2.5 Supporting computational tools

With the increasing use of computer-based tools and methods in architectural design and the growing connectivity of the digital programs, many new potentials have emerged such as simulation, optimization, parametric design and etc. (Luebkeman, 2003).

> *"Architects are no longer constrained by the limits of traditional construction techniques; designs can now be fully conceived in three dimensions. More profoundly, architecture can be guided by the same laws that control and shape the world around us — an organic approach to design based on exploring solutions through performance."* ~ Branko Kolarevic, 2005

These tools and processes are developed to predict the behavior and the performance of a building from a very beginning stage of design process up to its demolition. There have been a development in a variety of computational simulation tools as well, mainly to predict the performance of a build-form more specifically in areas such as structures, lighting, energy, acoustics, thermal flows, and etc. (Kolarevic & Malkawi, 2005).

2.5.1 Daylighting simulation techniques

Illuminance can be defined as the total luminous flux per unit area that falls on a surface (CIE, 1932). It is an extensively used measurement of light and it is the basic metric for evaluating daylight performance. It is the most common measurement that is referred by codes and standards on a work plane to define the recommended amount of light for different tasks (IESNA, 2000). In this respect, most metrics have been developed to evaluate minimum threshold of illuminance levels within a task-oriented space such as offices, libraries and schools. By aiming these thresholds, it can be guaranteed that sufficient amount of illumination is provided for a given activity (IESNA, 2000). For evaluating daylight performance in a building, different methods can be used such as Daylight factor, Climate-based models and visualization (Rahimzadeh, 2015).

2.5.1.1 Daylight Factor

The metric that is most commonly used for simulating and measuring daylight performance is the daylight factor (DF). Daylight factor, which is usually expressed as a percentage, is the ratio of interior illuminance received at a given point to the exterior horizontal illuminance under overcast sky (Moon and Spencer 1942). However, this metric has major limitations that doesn’t take into account some basic daylighting parameters such as orientation, latitude, climate, and direct sunlight (Ibarra & Reinhart, 2009).

2.5.1.2 Climate Based Daylight Modeling (CBDM)

Since DF limits understanding of daylight as a dynamic source of illumination, alternative solutions are developed to quantify daylight performance on an annual basis. Climate-based daylight modeling (CBDM) provide statistically accurate results of quantifying internal illuminance levels (Mardaljevic 2000). The key characteristic of this approach is that their performance are based on irradiance and illuminance data files that are provided by both sun and sky for almost any location throughout the world over the whole year (Boyce & Smet, 2014). There are four metrics that are associated with CBDM.

2.5.1.2.1 Daylight Autonomy (DA)

Daylight Autonomy (DA) is commonly referred as dynamic daylight metric. DA can evaluate the specified illumination level by considering building orientation and climate-driven sky types (Rahimzadeh, 2015). It represents the percentage of occupied time over the year in which the minimum illuminance levels at a given point inside a space met by daylight and does not require supplemental artificial lighting (Reinhart & Walkenhorst, 2001). Implementing this method for multiple points produce a contoured area which assists particular minimum DA to be explored for further improvements. The larger contour enclosing an area means that the space is considered to receive more daylight (Boyce & Smet, 2014).

2.5.1.2.2 Continued Daylight Autonomy (CDA)

As a modification to DA, Continued Daylight Autonomy (CDA) is a method that assigns a weighted value for the illuminance levels that fall below the minimum threshold, implying that some daylight is superior to no daylight (Rogers 2006). For instance, if the required amount of illuminance for a point is 500 lux but it receives 350 lux, then a weighted value of 0.7 (350/500 = 0.7) is considered for that time step (Wienold 2007).

2.5.1.2.3 Useful Daylight Illuminance (UDI)

Useful Daylight Illuminance (UDI) was initially introduced by Nabil and Mardaljevic (2005) as an adjustment for Daylight Autonomy (Frankel and Lyles 2013). This metric indicates the total percentage of time over a year in which the illuminance level at a given point inside a space falls within a defined range (González & Fiorito, 2015). For this purpose 4 ranges of illuminance scale has been developed (Mardaljevic et al., 2012). The first range is illuminance levels with less than 100 lux which are highly ignored. The second range is between 100 lux to 300 lux which is considered as supplementary to electric lighting. The third range is between 300 lux to 3000 lux which is considered as primary since artificial lighting is likely to be dimmed or turned off. The last range is more than 3000 lux which is neglected since it provides visual discomfort for an indoor space. Therefore, according to this approach only illuminances in the range of 100 lux to 300 lux are counted as useful (Boyce & Smet, 2014).

2.5.1.2.4 Daylight Availability (DA_V)

Daylight Availability (DA_V) is the combination of Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). This metric benefits from local weather data and evaluates illuminance profiles based on hourly and sub hourly time series (Reinhart & Wienold, 2011)

2.5.2 Parametric / algorithmic design

Parametric designing as a computational method has received significantly attention in practice, research and education during the last decade. It assists the designers in generating a variety of alternative design solutions (Turrin et al., 2011). Parametric tools are based on algorithmic principles, and there is strictly a reciprocal relation between them. An algorithm is a set of finite and well-defined instructions or rules (using logical if-then-else operations) for dealing with problems (Terzidis, 2006).

"Algorithms can computationally generate and manipulate design entities such as geometric form, design variables, data structures that contain numeric or geometrical entities, mathematical expressions and operations, and logical operations. This level of control over design in a 3D modeling environment allows the designers (or in this case developers) extend functionality, or evaluate certain conditions and respond appropriately."[8]

Algorithms are basically operated by parameters and similarly the main components of parametric systems are algorithms. However, unlike the algorithms, parametric systems give more emphasis to the direct manipulation of the parameters in implementing the changes of the design geometry, while searching for the optimal design solutions (Dino, 2012). Also, their essence in adapting and responding to design alteration provide design exploration in complex and dynamic design settings (Henriques et al., 2012).

In addition, parametric control of form is considered as valuable attribute in performance based design, since it offers an integration of performance analysis into design synthesis (Dino, 2012). Parallel to this approach, this thesis proposes a parametric model to be integrated with simulation tools to evaluate daylight quality of museum buildings.

2.6 Current approaches to performance based daylighting design

Previously a literature review regarding daylighting, daylight harvesting strategies, interior daylighting performance assessment in museums and simulation based metrics that are commonly used for this purpose is presented. In this final section, recent approaches that attempt to evaluate daylighting performance of different building types with different daylighting requirement by means of computational tools will be presented.

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[8]) Dino, 2012. creative design exploration by parametric.

Existing approaches, as presented in Table 2, address the need for performance based daylighting design through the application of simulation based computational methods. For this aim, metrics such as Daylight Factor (DF), Daylight Autonomy (DA), Daylight Availability (DA_V) and Useful Daylight Illuminance (UDI) have been used. The building typologies considered in these works include museum, library, office, classroom, laboratory and theatre buildings. These approaches aim to control daylight by adjusting and permitting adequate levels of illumination (to save energy and provide visual comfort), yet strict control of daylight illumination while satisfying indirect sunlight (on hourly, daily, monthly and annual basis) has not been addressed in these works.

Table 2. Current approaches to performance based daylighting design

Case	Year	Design/modeling firm:	Building type	Project name (Location)	Analyzed space	Harvesting strategy	Objectives of daylighting performance analysis	Methodology	Schedule type	Schedule period	Daylighting Metric	Sky Type
A	2008	Arup & Partners	**Museum**	Miami Science Museum (Florida, United States)	1 Gallery (level 3) 1 Gallery (level 4) 1 Administration (level 4) 1 Entertainment (level 4)	Side-lighting	Visual comfort + Energy saving	Balancing interior daylighting by applying shading system and modifying glass type	**Annual**	—	**DA + UDI**	**Climate-based**
B	2010	Christopher Meek & John Breshears	**Laboratory**	Health Science Research Laboratory (California, United States)	Laboratory	Side-lighting	Visual comfort + Energy saving	Balancing interior daylighting by applying dynamic shading system	**Daily**	Mar. 21 (whole day) Jun. 21 (whole day) Sep. 21 (whole day) Dec. 21 (whole day)	**DF (Radiance)**	**Clear sky**
C	2012	Chang Sung Kim & Kyung Wook Seo	**Museum** (three story)	Seoul Museum of Art (Seoul, Republic of Korea)	Duplex exhibition space (level 2 & 3)	Top-lighting	Visual comfort + Artifact conservation	Balancing interior daylighting of the exhibition space by modifying the shape of Top-light	**Hourly**	Jun. 21 (at noon) Sep. 21 (at noon) Dec. 21 (at noon)	**DF (Radiance) + Physical model**	**Intermediate sky**
D	2012	Mahlum Architects	**Elementary school**	Wilkes Elementary (Bainbridge Island, Washington)	Classroom	Side-lighting	Visual comfort + Energy saving	Exploring daylighting performance criteria for two different space allocation options of two different classroom type	—	—	**DF (Radiance) + DAv**	**CIE Overcast sky (DF) + CIE Sunny sky (DAv)**
E	2012	**Design**: Lake Flato & Shepley Bulfinc + **Modeling:** UW IDL	**Library** (six story)	Austin Central Library (Austin, Texas)	4th floor of the library	Side-lighting	Visual comfort + Energy saving	Balancing interior daylighting through dynamic translucent shading systems	**Annual**	—	**DA + UDI**	**Climate-based**
F	2013	Harley Ellis Devereaux	**Library** (single story)	West Berkeley Library (Berkeley, California)	Single-story library	Top-lighting	Visual comfort + Energy saving	Optimizing interior daylighting by modifying the shape of skylight apertures and dynamic shading system	**Hourly**	Dec. 21 (4 pm) Mar. 21 (whole day) Jun. 21 (at noon)	**DA + DAmax (Radiance + Daysim)**	**Clear & Overcast sky**
G	2015	**Design:** Michael Wilford & Partners + **Modeling:** Shahab din Rahimzadeh &	**Theatre**	Esplanade - Theatres on the Bay (Singapore)	Theatre	Top-Lighting + Side-lighting	Visual comfort + Energy saving	Finding the optimum interior daylighting performance through the changes in building orientation and parametric shading system measurements	**Annual**	—	**DA + UDI**	**Climate-based**
H	2016	Lemonia Karagianni & Michela Turrin & Ulrich Knaack & Truus Hordijk	**Office**	Office (Delft, Netherlands)	Office	Side-lighting	Visual comfort	Exploring interior daylighting performance assessment through the changes in the measurements of a parametric shading device	**Daily**	Jun. 21	**UDI**	**Climate-based**

2.7 Requirements of ODAM

As previously discussed, this thesis aims to deal with the problem specific to spaces that require strict control of daylight. In this regard, as a novel computational approach, **Optimum Daylight Availability Method (ODAM)** is proposed by the author for controlling and adjusting daylighting performance of museum buildings more strictly and effectively.

ODAM responds to the requirements that are needed for performance-based daylighting assessment approaches, specifically those that necessitate strict illumination control:

- Initially, ODAM should be integrated with climate based weather data to provide accurate results of daylighting illumination levels (on hourly, daily, monthly or annual basis) compared to metrics such as Daylight Factor (DF) which does not take into account some basic daylighting parameters such as orientation, latitude, climate, and direct sunlight.
- In addition, ODAM requires to be built upon mathematical frameworks in order to deal with direct sunlight and therefore controlling glare and indirect daylighting illumination within the spaces.
- Moreover, ODAM needs to be developed based on Fuzzy logic which provides the soft computation of the thresholds, as opposed to metrics such as Useful Daylight Illuminance (UDI) that use crisp thresholds for evaluating daylighting performance assessment of spaces,
- Finally, this method should be integrated with appropriate search algorithm methods based on the requirements of the design to decrease the computational effort during the parametric design exploration.

Based on these requirements, there is a need for computational methods to support the design and evaluation of daylighting performance of interior spaces which have strict daylighting requirements such as museums. Also there is a need for the development of daylighting metrics and tools as well as smart strategies to answer the needs of such spaces that are particularly less tolerant to daylight.

The following chapter presents the development of ODAM that aims to assist architects in controlling the interior daylighting more effectively by optimizing the level of illumination while ensuring indirect daylighting within the museums. The proposed method will support the design of dynamic shading devices that respond to the internal daylighting conditions hourly, daily, monthly or seasonally based on the user's preferences.

CHAPTER 3

THE METHOD / APPROACH

"Design is not just what it looks like and feels like. Design is how it works." ~ Steve Jobs, 2003

In the previous section, a brief literature review on daylighting, daylight harvesting strategies and devices, daylighting performance, daylighting requirements for museums and computational tools and simulation based metrics that are commonly used for this purpose was presented. Consequently, problems regarding the lack of methods and tools supporting performance-based daylighting design are identified. Also the requirements for performance-based daylighting assessment approaches were identified which are as follows:

- The need for climate based weather data in order to provide accurate result of daylighting performance.
- The need for mathematical frameworks in order to deal with direct sunlight.
- The need for Fuzzy logic in order to provide the soft computation of the thresholds.
- The need for appropriate search algorithm method in order to decrease the computational effort during the parametric design exploration.

In this section, a novel approach, Optimum Daylight Availability Method (ODAM), will be presented which is developed for the exploration and optimization of interior daylighting performance in museum buildings.

3.1 Method requirements

The proposed method aims to support museum shading design by optimizing the geometric parameters of dynamic shading devices. Dynamic shading devices respond to the internal daylighting conditions hourly, daily, monthly or seasonally based on the user's preferences. Daylighting performance requirements include:

- To ensure sufficient illumination levels, as defined by the user
- To eliminate direct sunlight entering the exhibition space that is defined by the user

This requires that several parameters of the shading devices are pre-set in advance, and their angular position is optimized by the proposed method. Therefore, multiple simulations that quantify the hourly daylighting performance and generalize the hourly data into weekly, monthly or seasonal aggregate data are performed. The proposed method then applies a fuzzy Gaussian function to quantify the eventual performance.

3.2 The proposed design process

This chapter presents a novel method for optimizing daylighting performance inside museums and exhibition spaces through parametric shading system. This method is embedded in a proposed design process that is executed in four main steps (Figure 9):

- Modeling the building
- Parameterizing the shading system
- Analyzing daylighting performance through simulation
- Implementing Optimum Daylight Availability Method (ODAM)
    - Generating solutions
    - Design space exploration

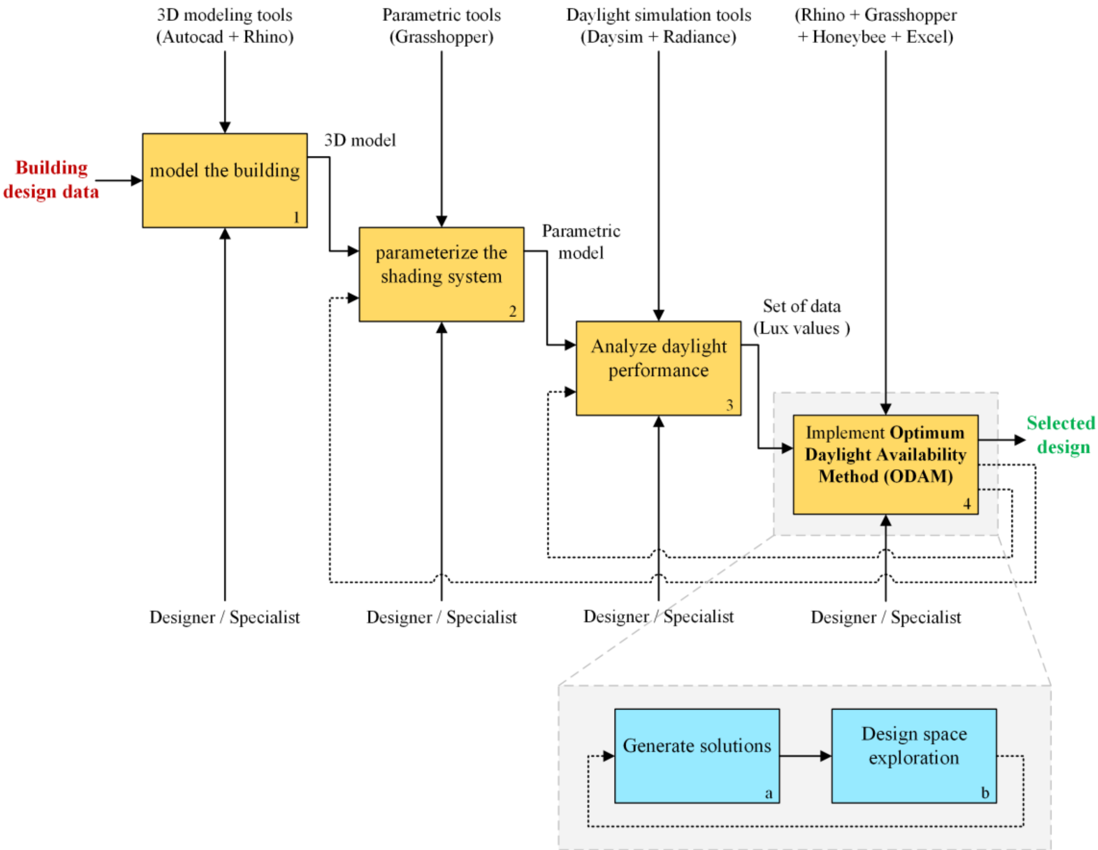

Figure 9. IDEF0 diagram of the design process

3.2.1 Modeling the building

In this phase, the 3D model of the museum building and its surrounding context is required to be prepared by the assist of 3D modelling tools. For this aim, Rhinoceros (often abridged as Rhino) was used in this research which is capable of creating geometries ranging from simple lines, curves or shapes to complex NURBS[9] geometries and free-form modeling (Reinhart and Wienold 2011).

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[9] Non Uniform Rational Basis Spline (NURBS) is a mathematical representation of 3D geometry that can accurately describe curves and surfaces. Robert McNeel and Associates. Rhinoceros features. http://www.rhino3d.com/ features/, April 2014.

3.2.2 Parameterizing the shading system

In this phase a parametric shading system is required to be designed with respect to the requirements of the built-form and its surrounding environment. As the shading device, this research benefited from a Horizontal Louvered Shading (HLS) system that was defined parametrically in Grasshopper (GH) (Figure 10). Grasshopper is a plug-in of Rhino which utilizes generative algorithms and associative modelling techniques to assist designers and engineers in creating geometries in a flexible way (Tedeschi 2011). GH plug-in not only provides controlling the design process but also it allows the development of script without any programming knowledge (Tedeschi 2011).

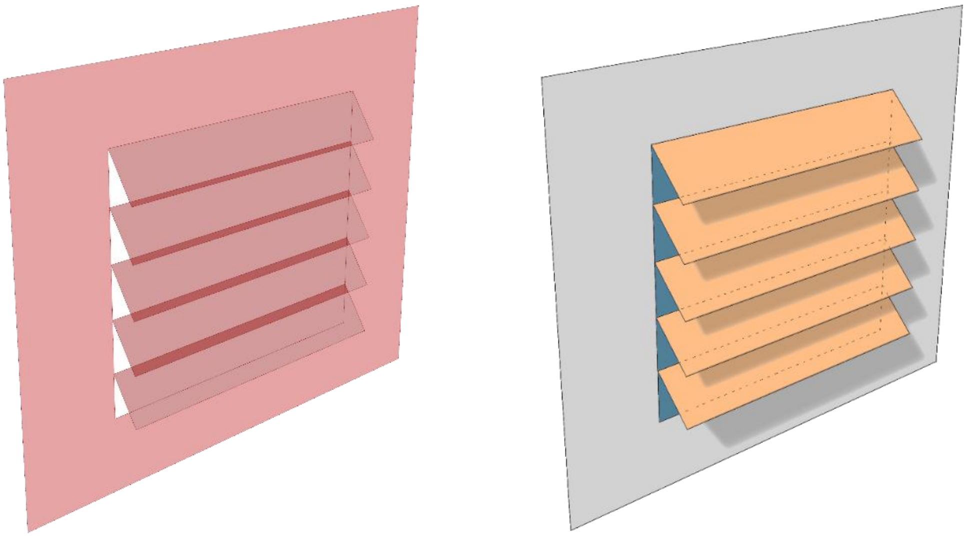

Figure 10. Horizontal louvered shading system that is designed parametrically in grasshopper.

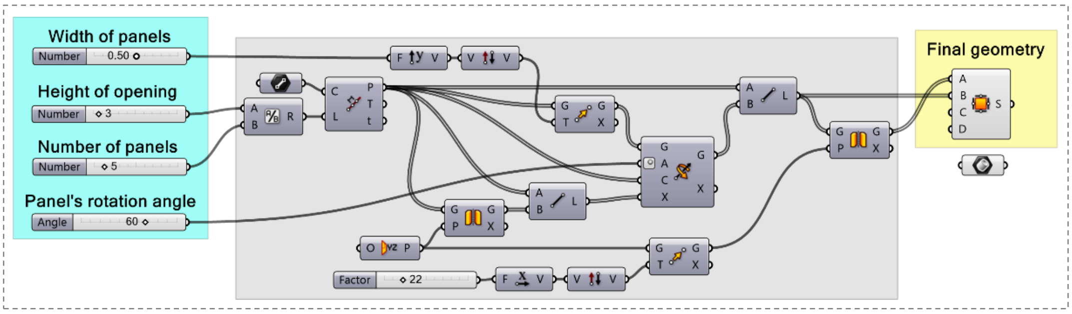

Figure 11. The design process of the horizontal louvered shading system in Grasshopper

3.2.2.1 Design parameters

While designing the parametric HLS shading system, a set of parameters was defined as follows (Figure 12):

- ***h***: height of the opening
- ***n***: number of panels
- ***s***: spacing between panels
- ***w***: width of panels
- ***β***: rotation angle of panels
- ***α***: altitude of sun

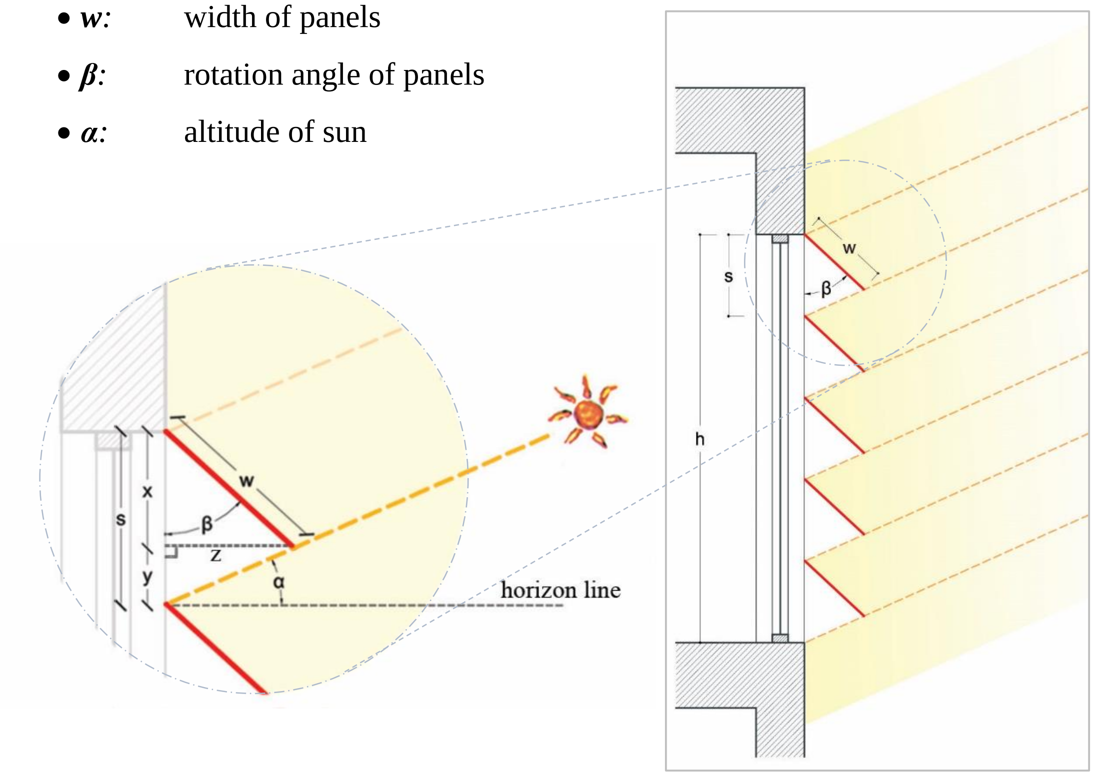

Figure 12. Design parameters of the horizontal louvered shading system

It should be noticed that some of these parameters are dependent and some are independent. For example, since height ***(h)*** of the opening, number ***(n)*** of panels and the spacing ***(s)*** between them are in a direct relationship therefore, by defining two of the parameters the third one just arises dependently.

3.2.2.2 Constraints and assumptions

The **design parameters** defining the shading devices are determined in two steps: fixed parameters and variable parameters. In order to simplify the complexity of the simulation process during the next phases, only *"$\boldsymbol{\beta}$"* (rotation angle of the panels) was defined as the **variable parameter** in this research. Other parameters were accepted as **fixed parameters** and were defined at the early stage of the design process with respect to designer's choice and the requirements of the project. During the design process also the thickness of the panels are neglected and thus they are modeled as simple planes.

As it was explained beforehand, it is an essential issue for the museums to protect their interior spaces from direct sunlight. Therefore, considering in**direct daylight** played an important role as a constraint while designing parametric HLP shading system.

For satisfying indirect lighting, what comes first to the mind is that width *"$\boldsymbol{w}$"* of panels and its direct relationship with the rotation angle *"$\boldsymbol{\beta}$"* of panels and the *spacing "$\boldsymbol{s}$"* among them. However in order to find exactly which parameters and to what extent they are involved in such relationship, requires a mathematical framework. Here, minimum panels' *width "$\boldsymbol{w}$"* that is required to obstruct direct sunlight can be derived from the following equations with respect to the *Altitude of Sun "$\boldsymbol{\alpha}$"*, *rotation angle "$\boldsymbol{\beta}$"* of panels and the spacing *"$\boldsymbol{s}$"* among them.

It is known that *"$\boldsymbol{h}$"* is directly related with *"$\boldsymbol{n}$"* and *"$\boldsymbol{s}$"* as:

$$s = \frac{h}{n} \qquad \text{(Eq. 1)}$$

And from trigonometry rules these 3 equation can be derived (Figure 12):

$$x = w\, cos(\beta) \qquad \text{(Eq. 2)}$$

$$z = w\, sin(\beta) \qquad \text{(Eq. 3)}$$

$$y = z\, tan(\alpha) \qquad \text{(Eq. 4)}$$

Then from 2nd and 3rd equation we can obtain 4th equation:

$$y = w\ sin(\beta)\ tan(\alpha) \tag{Eq. 5}$$

Since

$$s = x + y \tag{Eq. 6}$$

Then 5th equation can be derived as:

$$s = w\ cos(\beta) + w\ sin(\beta)\ tan(\alpha) \tag{Eq. 7}$$

Finally *"**w**"* can be obtained as:

$$\boldsymbol{w = \frac{s}{cos(\beta)+sin(\beta)\ tan(\alpha)}} \tag{Eq. 8}$$

As previously mentioned, *"**w**"* and *"**s**"* are considered as fixed parameters and are defined at the early stage of the process. Since direct sunlight needs to be avoided throughout the day for the case of museums, *"**α**"* can also be defined as a fixed parameter by considering the worst-case scenario of the sun position. This means that, the only variable parameter in the 6th equation is *"**β**"*. Therefore the equation can be reformed based on the function of *"**β**"*as following:

$$\frac{s}{w} = cos(\beta) + \sin(\beta) tan(\alpha) \tag{Eq. 9}$$

And since it is known that

$$tan(\alpha) = \frac{sin(\alpha)}{cos(\alpha)} \tag{Eq. 10}$$

Then the equation can be rewritten as:

$$\frac{s}{w} = cos(\beta) + \sin(\beta)\ \frac{sin(\alpha)}{cos(\alpha)} \tag{Eq. 11}$$

And therefore,

$$\frac{s}{w} = \frac{cos(\alpha)\ cos(\beta) + sin(\alpha)\ sin(\beta)}{cos(\alpha)} \tag{Eq. 12}$$

And since it is known that

$$cos(\alpha)\, cos(\beta) + sin(\alpha)\, sin(\beta) = \; cos(\alpha - \beta) \qquad \text{(Eq. 13)}$$

Then the equation can be rewritten as:

$$\frac{s\ cos(\alpha)}{w} = cos(\alpha - \beta) \qquad \text{(Eq. 14)}$$

And therefore

$$\cos^{-1}(\frac{s\ cos(\alpha)}{w}) = \cos^{-1}(cos(\alpha - \beta)) \qquad \text{(Eq. 15)}$$

Finally β can be derived as

$$\boldsymbol{\beta = \alpha - \cos^{-1}\left(\frac{s\ cos(\alpha)}{w}\right)} \qquad \text{(Eq. 16)}$$

In this equation *"**β**"* indicates the maximum angle that panels can have in order to ensure indirect lighting. For example, if *"**s**"* and *"**w**"* take values of **35** and **40** centimeter accordingly and "***α***" take value of **14°**, therefore in order to satisfy indirect lighting the maximum angle *(β_{max})* that panels can take will be **46°.**

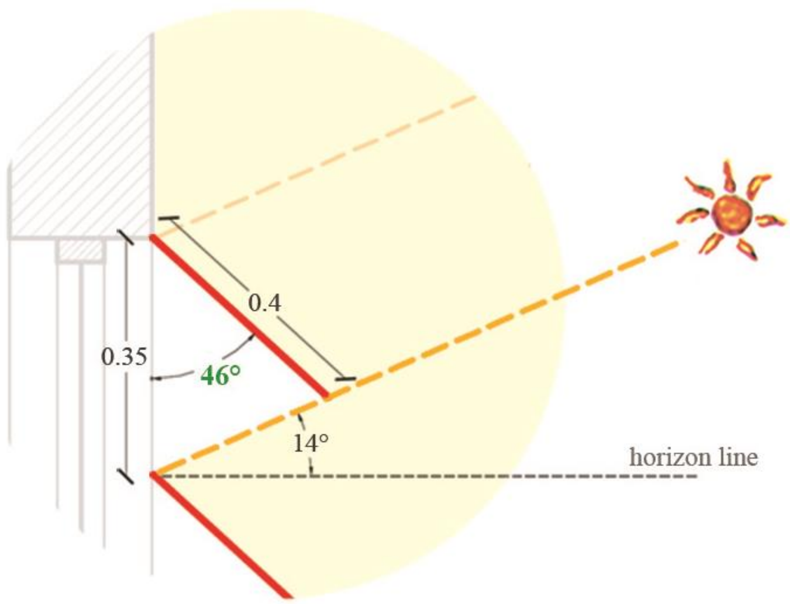

Figure 13. Parametric louvered shading system

3.2.3 Analyzing daylight simulation

In this phase, for each panel instance (different rotation angles for ***β)***, daylighting simulation is performed. This simulation can be daily, weekly, monthly or seasonally, depending on the building's capacity to change its shading angles. For simulations, a number of computational tools were used.

3.2.3.1 Simulation tools

- **Honeybee:** is an open source and free plugin of Grasshopper which assists in exploration and evaluation of environmental performance. It also provides the users with creating geometries and generating variety of radiance based materials[10] and skies (Erlendsson, 2014). Honeybee links Grasshopper with four validated simulation engines such as Daysim, Radiance, EnergyPlus and OpenStudio for evaluating building energy consumption, comfort, and daylighting (Roudsari et al., 2013). Since this plugin benefits from Radiance and Daysim, static simulations can be done with Radiance for one sky condition on a single point at a time, or dynamic daylight simulations can be performed by Daysim based on specific geographic locations and climate files[11].
- **Daysim:** is a Radiance-based daylight simulation software that is used vastly to model and analyze daylighting inside and outside of buildings. Daysim provides the ability for calculating annual luminance and illuminance level of daylighting for interior spaces based on weather data files which can be implemented to obtain further information regarding user behavior model for predicting daylight performance indicators (Reinhart et al., 2013).

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[10] Radiance-materials are materials with user defined characteristics which define how a surface reacts to light. Characteristics such as reflectance, light transmittance, roughness and specularity can be easily define (Erlendsson, 2014)

[11] M.S. Roudsari. What is Honeybee? http://www.grasshopper3d.com/group/ ladybug, March 2014.

- **Radiance:** is considered as an advanced, a state of the art, backward ray-tracer which simulates indoor illuminance and luminance distribution of daylight for complex building geometries with a great variety of material surface properties for one sky condition at a time (Erlendsson, 2014).
- **OpenStudio[12]:** is open-source and cross-platform collection of software tools that provide whole building energy modeling using Radiance.

3.2.3.2 Development of the simulation model

During modeling for daylighting performance of an interior space in Honeybee, a set of criteria are required to be met which are as following:

- **Building components:** As an essential part, the 3D model and parametric shading system that were modeled previously, are introduced to simulation model with required level of details together with their material properties. For this aim, Honeybee provides Radiance-materials which have user-defined characteristics that determine how it reacts to light. The user can define various characteristics of the material such as reflectance, transmittance, roughness and etc.
- **Contextual shading elements:** In this phase, all contextual elements such as buildings, trees and any other objects that influence interior daylighting by blocking or redirecting it, are introduced to the model.
- **Sky type:** In this phase, with respect to the daylighting simulation type, a suitable sky model needs to be selected. In general, there are two types of daylight that is received by a building: direct daylight from the sun, diffused daylight from the atmosphere. Therefore, the light that is received by the building depends on the sky condition. In simulations, a sky model is defined by an algorithm that maps luminance levels onto an imaginary hemisphere which is called a sky dome. Then, from a set of points on sky dome, light rays are projected onto the 3D model (Anderson, 2014). International Commission on Illumination (CIE, from the

[12] for more information refer to https://www.openstudio.net/

French acronym) defines three types of skies that are generally used for the purpose of daylighting simulation (Anderson, 2014).

- *Uniform sky:* It is the simplest sky condition in which luminous distribution is uniform over the whole sky dome.
- *Clear sky* (sunny sky): This sky type represents a sky with less than 30% of cloud cover. Approximately, clear sky has the luminance transition of 10:1 ratio from sun to the rest of the sky which drops sharply near the sun. Among the existing sky types, the clear sky is used for daylight availability calculations.
- *Overcast sky* (cloudy sky): This sky type represents a sky with more than 70% of cloud cover. Approximately, overcast sky has the luminance transition of 3:1 from zenith to the horizon. Generally, to simplify calculations sun position is not considered in most overcast skies. This sky is used for daylight factor calculations.

Daylighting conditions typically take into account two extremes, completely clear and completely overcast skies. Each of the sky conditions represent a particular moment of time during the simulations. Therefore, they can provide better results for Static simulations done by Radiance. However, for Climate Based daylight simulations, all sky conditions are required to be included with respect to the schedule of the simulation. For this aim, Daysim utilizes *weather data* to model all sky conditions throughout the year (Erlendsson, 2014).

Weather data: Weather data files are provided in "epw" format which contains hourly based weather data for all the year (8760 hours of the year). They provide all required weather information for Climate Based simulations such as, geographical location, temperature, humidity, enthalpy, wind and solar radiation[13] data. For each daylighting simulation Daysim uses EnergyPlus weather files based

[13] Solar radiation data that are provided by epw files are: direct normal radiation, diffuse horizontal radiation, global horizontal radiation, horizontal infrared radiation, direct normal illuminance, diffuse horizontal illuminance, global horizontal illuminance and total sky (cloud) cover.

on the specific geographical location of the project to model all sky conditions of the year (Reinhart, 2010).

- **Working plane:** Generally, in order to find the illuminance level due to daylighting with related simulation metrics, a horizontal working plane is set with a specific height over the floor (Figure 14). Generally, this height is considered as 80 centimeter since the visual task of most activities such as reading, writing, cooking and etc. are performed at this approximate height (Anderson, 2014). The working plane illustrates the resulting data by a series of sensor points in a grid format. The gird size demonstrates the amount of sensor points that take part within the simulation. Therefore, by decreasing the grid size, it is expected to obtain a more accurate result. However it should be considered that, by decreasing the grid size the simulation time also increases relatively. Both of the plans illustrated in Figure 15, are exposed to same daylight condition. Both of them illustrate the level of daylight illumination in false color for 9 a.m. on 21st of July at a working plane with 80 cm height over the floor. However, they differ only in having dissimilar gird sizes.

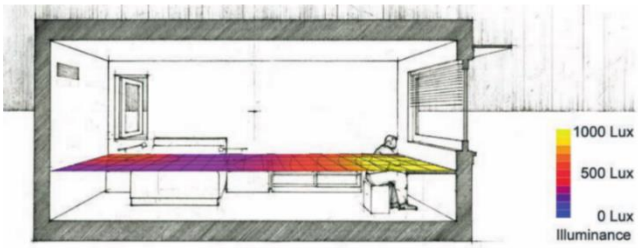

Figure 14. Illumination level on a working plane that is illustrated in false color. The simulation was performed for 2p.m. on March 21 at a workplain with 76 cm height over the floor (Anderson, 2014).

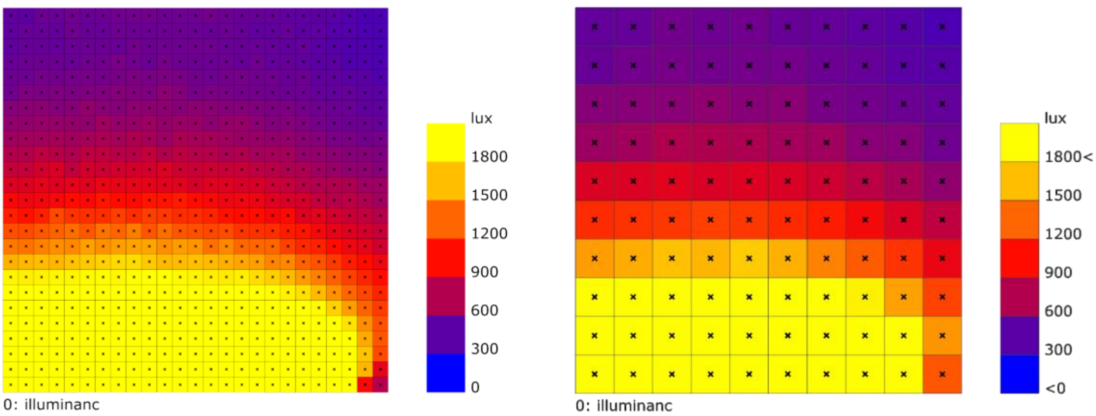

Figure 15. working plane of an instance simulation with different grid sizes. The working plane on the left has a grid size of 20 cm, while the one on the right has a grid size of 50 cm.

- **Ray-tracing parameters:** (Backward) ray-tracing is a method that is utilized by simulation engines for calculating the luminous distribution in a room. It simulates individual light rays in space that are emitted from the point of interest and goes through a user-defined number of bounces and diffusions until they either hit a light source or another object. A ray is aborted by reaching the required number of reflective bounces or by falling below the required weight of the threshold value (Reinhart, 2010). The correct definition of ray-tracing parameters plays a crucial role in the result and time of the simulation models. The ray-tracing parameters[14] that are used in all simulations are as follows (Reinhart & Wienold, 2011):
    - ***ambient bounces (ab):*** This parameter indicates the maximum number of diffuse bounces that will be calculated before the ray path is discarded. The ab-value of *"0"* implies no bounces and thus no calculations while the ab-value of *"2"* gives a reasonably accurate rendering. By increasing the ab-value, the accuracy of the render increases too. However, it should be noticed that doubling this value can double the time of calculation.
    - ***ambient divisions (ad):*** This parameter defines the number of sample rays that are emitted from a surface point during an ambient calculation. The ad-value of *"0"* implies no calculations while the ad-value of *"512"* gives a reasonably accurate rendering. Doubling this parameter can quadruple the rendering time.
    - ***ambient super-samples (as):*** as-value indicates the number of extra rays that are sent in sample areas with high brightness gradient. This parameter is applied to ambient divisions, therefore it has a direct impact on accuracy and time of rendering. The as-value of *"0"* implies no extra rays added to ad parameter while the as-value of *"256"* gives a reasonably accurate rendering
    - ***ambient accuracy (aa) and ambient resolution (ar):*** ambient resolution indicates the maximum density of ambient values that are used in interpolation. The combination of this parameter together with ambient accuracy and

[14] For more information refer to these websites that are recommended by the developers of Honeybee:
http://daysim.ning.com/
http://radsite.lbl.gov/radiance/refer/Notes/rpict_options.html

maximum scene dimension defines how well the luminance distribution in a scene is calculated. The aa-value of *"0.15"* and ar-value of *"128"* gives a reasonably accurate rendering. Depending on the scene, doubling either of the values quadruples the rendering time.

3.2.4 Implementing Optimum Daylight Availability Method (ODAM)

In this phase, the data from daylighting simulations of parametric building instances are collected, evaluated and utilized through the "*Optimum Daylight Availability Method (ODAM)"* to find the best value for *"**β**"* (rotation angle of the panels) and consequently, finding the best daylighting illumination for analyzed interior space.

In more general terms, ODAM indicates the optimum percentage of the space that is illuminated within a user-defined threshold [15] during a specific period of time (hourly, daily, weekly, monthly, seasonal or yearly). For example, if the result is 58% for an exhibition space analyzed during a day in January and within the range of 100 lux to 300 lux, then it means that the best solution provides the space with 58% of daylight illumination within the required range during the specified day. This necessitates that the rest of the space is to be illuminated by artificial lighting during that day.

Rhino, Grasshopper, Radiance, Daysim, and Excel (as an interface to the simulation engines, Ladybug and Honeybee were used) are the main tools that took part during this process. Specifically, ODAM is composed of two main steps:

- Generating solutions
- Sampling and evaluating data and finding the best solution

[15] This threshold is defined with respect to requirements of the space and the visual task in there.

3.2.4.1 Generating solutions

As previously discussed, for panel rotation angle ***(β)***, a daylighting simulation is performed. The result of each daylighting simulation contains a set of daylight illumination values (Lux) indicating the amount of illuminance that is received by the sensor points on the working plane (Figure 16).

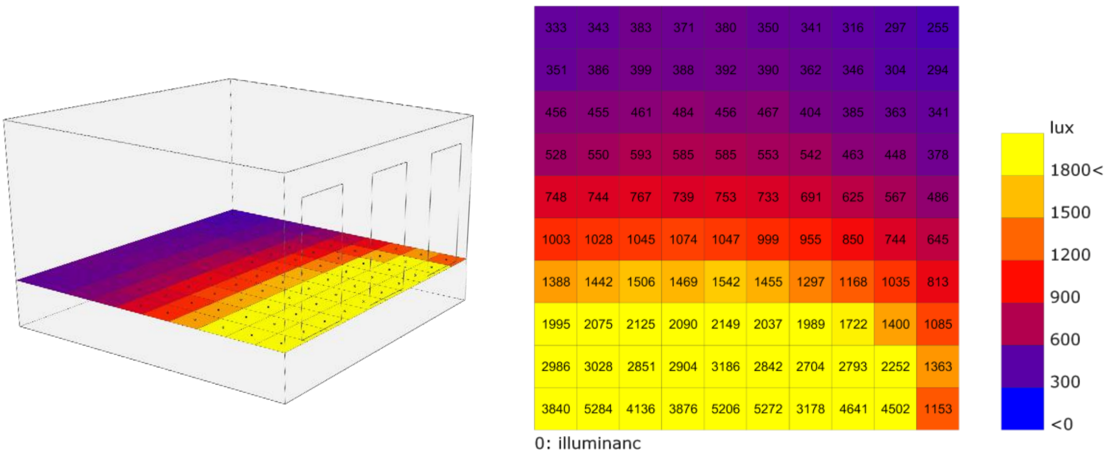

Figure 16. Daylight illumintion values (in lux) that are recieved by grid cells.

The simulation results that indicate daylighting illumination level for each grid cell is in the format of Lux. To be able to calculate a cumulative/ total daylighting performance value, this metric is not directly usable. This is because:

- It cannot be aggregated.
- The goodness to Lux values is of fuzzy nature.

Therefore a fuzzy Gaussian membership function is formulated (Figure 17). Through the implementation of this function, all lux values that are received by the sensor points are given a membership value between “0” and “1”. In this regard, “1” indicates that the cell has completely obtained the required level of illumination (or has obtained required amount of lux) and similarly, the cells that have taken the attribution of “0”, either have not received enough illumination or have received excessive amount of illumination.

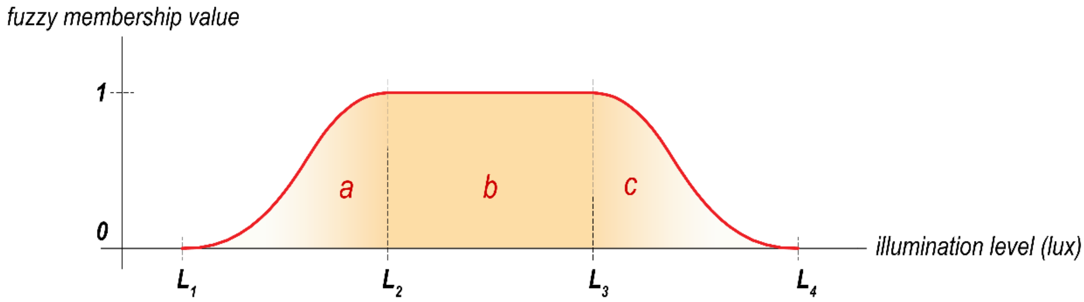

Figure 17. Graph of fuzzy Gaussian membrship values

In this graph, region *"b"* can be described as the "desired range" of grid cells (the range between the minimum threshold of "L_2" and maximum threshold of "L_3") receiving the required amount of daylighting illumination and therefore attributed value of "1". Benefiting from Gaussian function, membership values between "0" and "1" are assigned to those cells with the illuminance levels that fall into a close distance of the desired range *"b"*, implying that some daylight is superior to no daylight or unwanted daylight. For example, if the required amount of illuminance for a grid cell is between 500 to 700 lux but it receives 450 lux, then a weighted value[16], for instance 0.85 is considered for that cell.

In this regard, "L_1", "L_2", "L_3" and "L_4" also can be described as four input variables or "set-points" of the function through which the desired range of lux values (grid cells) can be changed with respect to the amount of daylighting illumination that is required for the performance of the visual task within the space.

The Gaussian function is composed of three parts. If "I" defines the amount of daylight illumination (lux value) that is received by a grid cell, then the three parts of the function can be derived from the following formulas:

- ***Range "b":*** each lux value that falls in this range is weighted as "**1**". Therefore, the formula can be written as:

$$\boldsymbol{G(I) = 1} \qquad \text{if;} \qquad \boldsymbol{L_2 < I < L_3} \qquad \text{(Eq. 17)}$$

[16] It is not a constant value and it depends on the user's decision, so it can be changed while adjusting the amount of "L_1", "L_2", "L_3" and "L_4".

- ***Range "a" and "c":*** each lux value that falls in these ranges is weighted between "0" and "1" which can be calculated through the Gaussian function. Its formula can be written as:

$$\boldsymbol{G(I)} = \boldsymbol{e}^{\frac{-(\boldsymbol{I}-\mu)^2}{2\sigma^2}} \qquad \text{(Eq. 18)}$$

  - For range *"a"*: $\boldsymbol{\mu = L_2}$, $\boldsymbol{\sigma = \frac{L_2 - L_1}{3}}$
  - For range *"c"*: $\boldsymbol{\mu = L_3}$, $\boldsymbol{\sigma = \frac{L_4 - L_3}{3}}$

After calculating the membership values, their average is calculated, which is the *Desired Daylight Availability (DDA)* for the shading system's daylighting simulation and is expressed by the following mathematical equation:

$$\boldsymbol{f(h)} = \frac{\sum_{i=1}^{n} \boldsymbol{G(I_i)}}{\boldsymbol{n}} \times \boldsymbol{100} \qquad \text{(Eq. 19)}$$

- ***h:*** a specific hour of a day (i.e. 10:00 am on 30 June).
- ***f(h):*** the percentage of *DDA* for a shading instance of *"**h**"*.
- ***I:*** the level of daylight illumination (lux) that is received by a grid cell.
- ***G(I):*** the Gaussian membership value of ***I***.
- ***n:*** the total number of grid cells in the analysis space

Two examples are illustrated here to provide a better understanding of the subject (Figure 19). Both of the examples are evaluated based on a daylighting simulation that was performed for a single room (Figure 18). The simulation is performed for the 21st of July, 9:00 am. The grid height is assumed as 80cm over the floor, and the size of grid cells are 20 cm. There is a total number of 625 grid cells (sensor points) on the working plane.

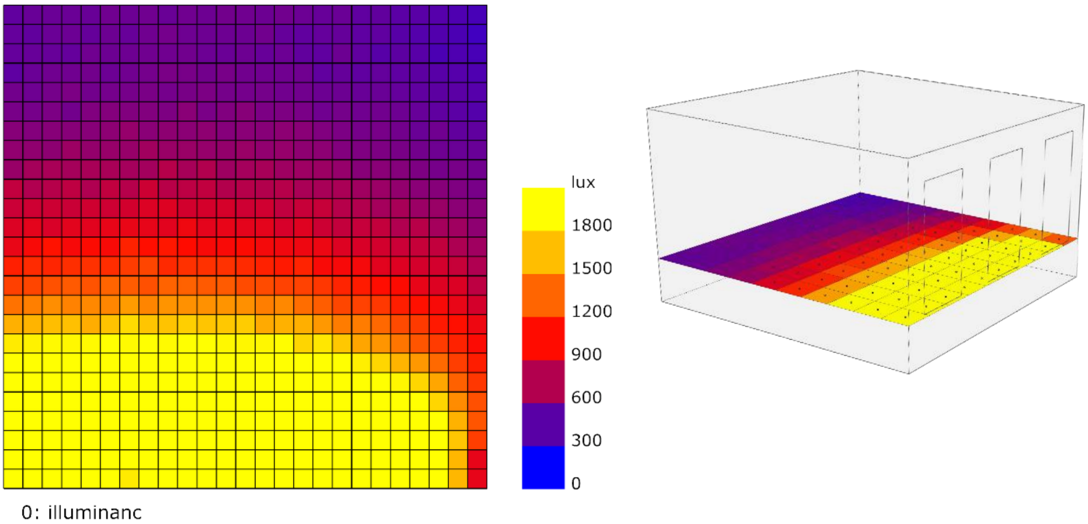

Figure 18. Sample room for evaluating daylighting performance, illustrating the level of illumination recived by all gird cells on the working plane.

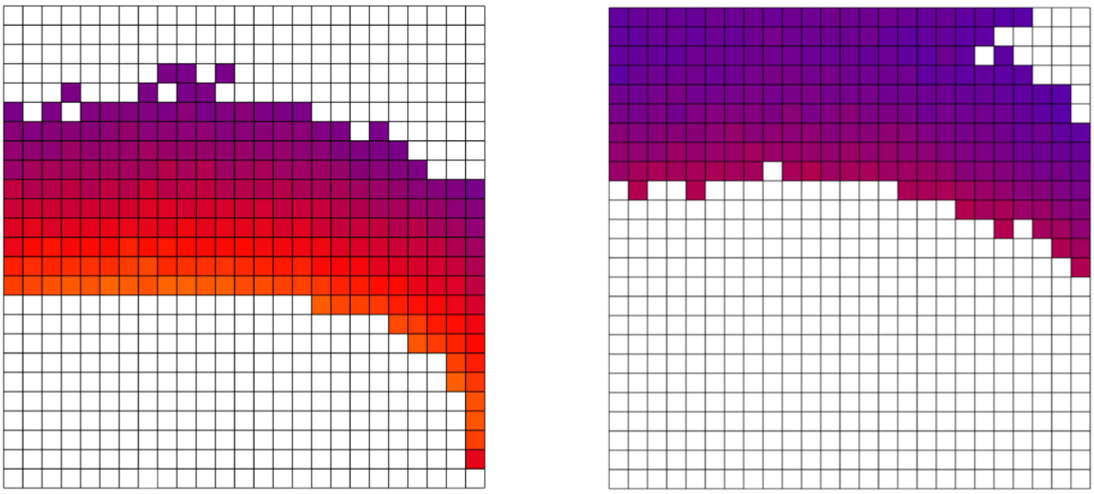

Figure 19. Two different ranges of ilumination values (lux) that are selected from an instance daylighting simulation, illustrated in Figure 18. Developed by the author in Grasshopper and Honeybee.

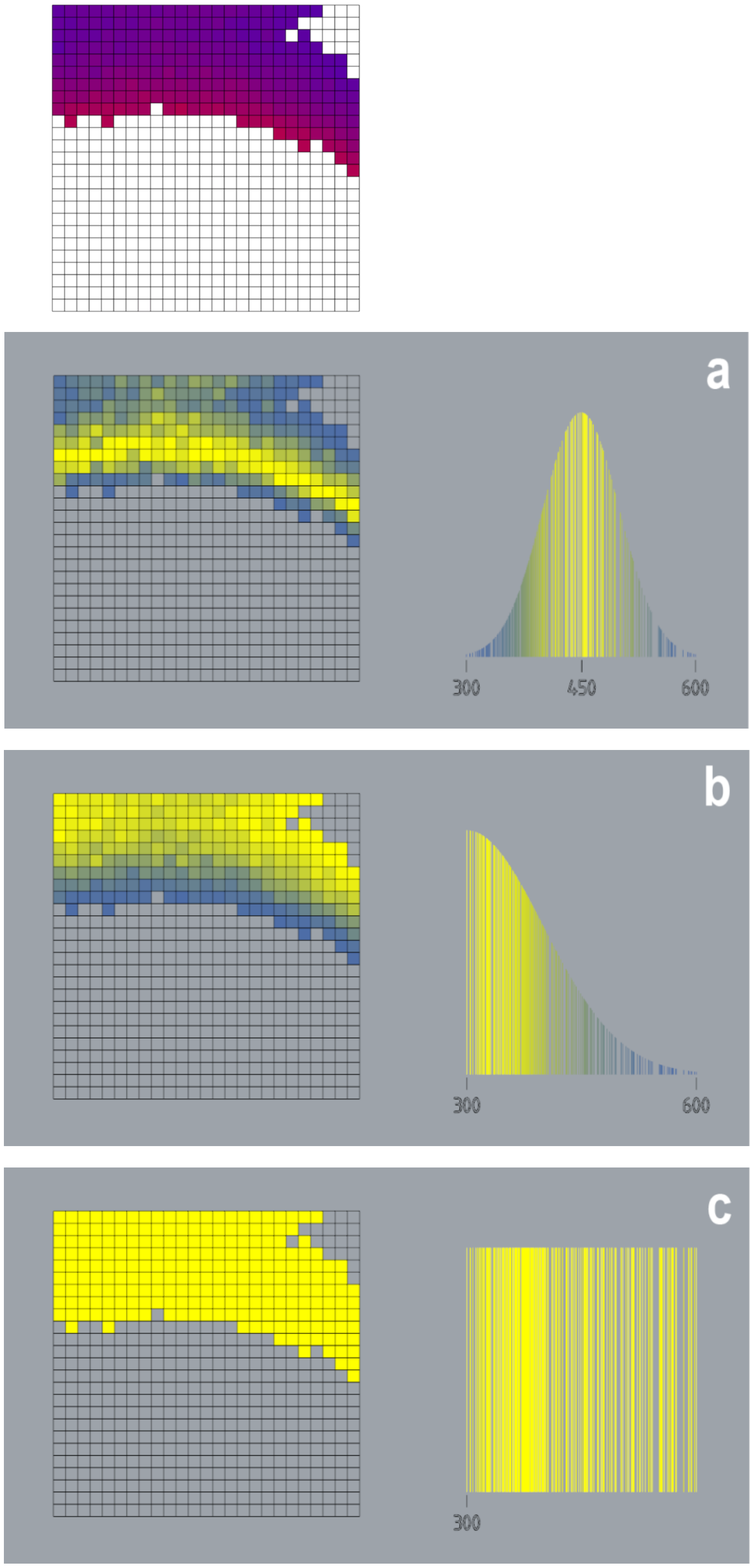

Figure 20. Fuzzy Gaussian membrship values, assigned to the range of 300 to 600 lux in 3 different ways wih respect to the desired visual task. Developed by the author in Grasshopper and Honeybee.

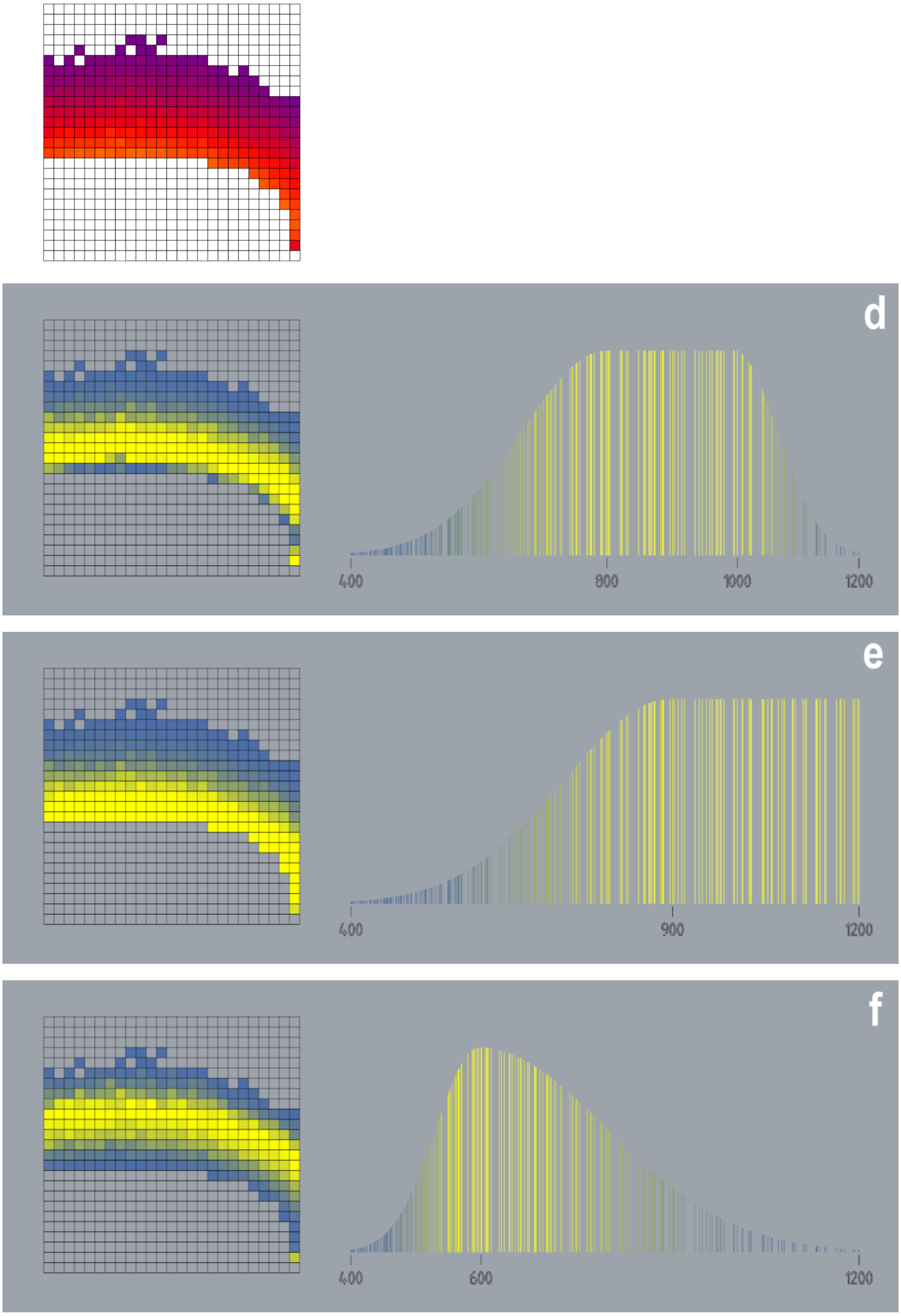

Figure 21. Fuzzy Gaussian membrship values, assigned to the range of 400 to 1200 lux in 3 different ways wih respect to the desired visual task. Developed by the author in Grasshopper and Honeybee.

Two working planes that are illustrated in the Figure 19, represent two different ranges of illumination values that have been selected from the instance daylighting simulation (Figure 18). In this respect, Figure 20 represents a selected range between **300** to **600** lux on the working plane, while Figure 21 represents a different range selected between **400** to **1200** lux on the same working plane. Each of the two ranges have been selected in three different ways and accordingly led to three different results. For example, if the percentage of Desired Daylight Availability is calculated for the three similar cases of ***"a"***, ***"b"*** and ***"c"*** then the results will be **15.6%**, **31.7%** and **37.8%** accordingly. Also these results for the three similar cases of ***"d"***, ***"e"*** and ***"f"*** will be **35.2%**, **14%** and **23.6%** subsequently. The reason of such differences in the results is due to the changes in the weights that are assigned to each gird cells.

Up to now, the process of calculating the percentage of Desired Daylight Availability was presented. However, in this thesis, for each panel instance (each rotation angle of ***β)***, a daylighting simulation is required. Consequently, a series of solutions are generated that will be utilized in the following step.

3.2.4.2 Design space exploration

In this step, the generated solutions are sampled in Excel spreadsheets. This sampled data is evaluated through the process of visualization and comparison, and consequently the best solution is selected by the user from all possible candidates. This process can be defined in three parts that is illustrated in the following figure. This phase is exemplified in detail in the following section as part of the case study.

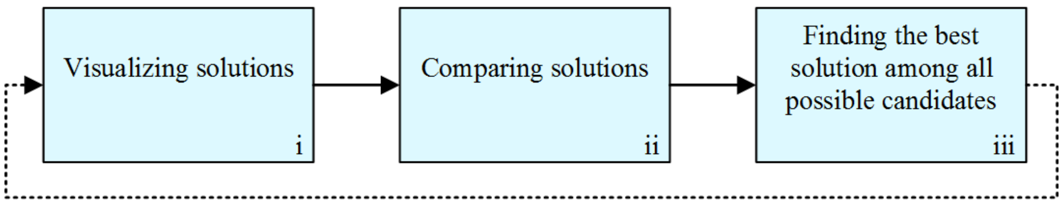

Figure 22. Design space exploration scheme.

CHAPTER 4

CASE STUDY

"While artists work from the real to the abstract, architects must work from the abstract to the real" ~ Steven Holl, 2013

In the previous chapter, the development of ODAM as a novel method for the exploration and optimization of daylighting performance of museum buildings was presented. In this research, Optimum Daylight Availability Method (ODAM) is developed to assist architects in controlling the interior daylighting more effectively by supporting the design of dynamic shading devices.

This chapter aims to validate the proposed method by means of its application on the design of a museum building designed by the author during his Graduation Project as part of his master's study at TU delft, Department of Building Technology, Computation and Performance Chair, between 2012 and 2014. In this chapter, the proposed method will be implemented in the Elevated Exhibition Space of the building that has strict daylight requirements. The daylight conditions of the site, including the building's exposure to direct daylight during summer, posed particular challenges that motivated the application of the method

4.1 Background

The museum site is situated in the coastal city of The Hague, which is the 3rd largest city (in population) in the Netherlands after Amsterdam and Rotterdam. As the government town and seat of the monarchy, the historic city of The Hague has been attracting many embassies and so it has become famous as an international city. It is known as the city with many national heritages and more than 100 ethnic groups living together alongside, which has brought it the name ‘International City of Peace and Justice’. It has always been welcoming many visitors from all over the world for its touristic attractions such as museums, galleries, cultural heritages and etc. among them there were many famous people visiting or residing in the city such as Van Gogh, Erasmus, Spinoza, Mozart and etc.[17]

The site of museum is located at the central part of the city of The Hague with many activities taking part around it, and it is very conveniently accessible from different parts of the city and country (Figure 23). Just next to the site, there is a green park, called *“Lange Voorhout”* with old green trees and sitting areas belonging to the nearby cafés and bars, together with the beautiful scene of the buildings and museums, surrounding it, each one with different architectural languages and styles, giving an extraordinary character to the site (Figure 24).

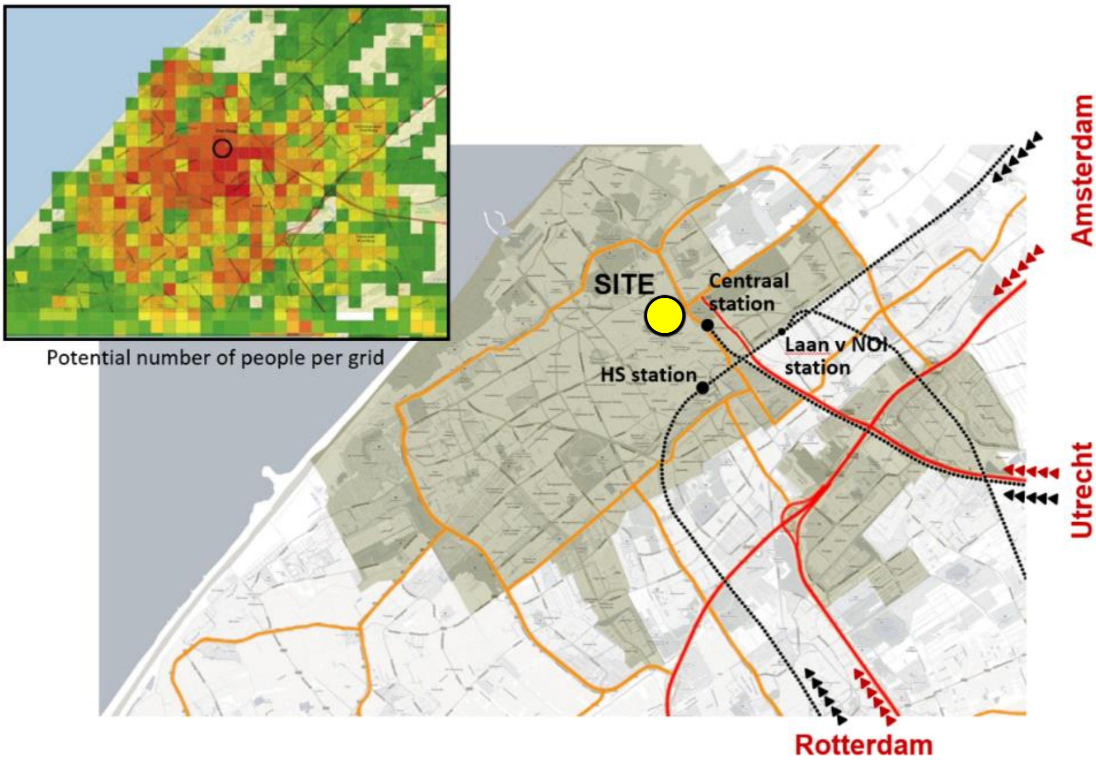

Figure 23. Site analysis regarding the accessibility and population density of the city.
Drawn by the author.

[17] For further information refer to https://www.denhaag.nl/en

Figure 24. Situation of the site within the city fabric. Drawn by the author.

4.2 Method implementation

4.2.1 Case study setup

The city of The Hague is situated in the northern hemisphere at *latitude 52.08° North* and *longitude 4.31° East*[18], with long days during summer and short days during winter. At this geographical coordination, the *altitude* of sun at the noonday of winter and summer solstices[19] are respectively *15°* and *61°*, which demonstrates the clear difference between the daytime hours of the two solstices. The city receives daylight for approximately 17 hours during the summer solstice, while it receives only around 8 hours during the winter solstice[20] (Figure 25). In this respect, the following figures illustrate that the buildings in this geographical situation are exposed to direct sunlight from all directions during the summer. This is a critical condition while considering daylight during the design process in this location.

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[18] http://www.latlong.net/

[19] http://sunposition.info/sunposition/spc/locations.php#1

[20] http://www.suncalc.org

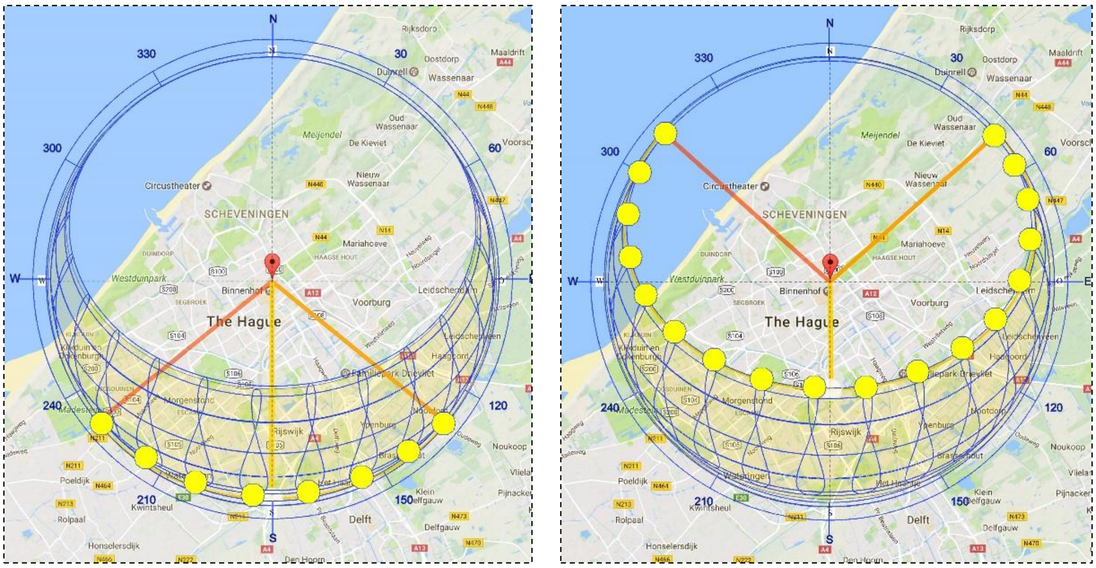


Figure 25. Daily sun path during summer and winter solstices.

4.2.2 Design of the museum

While designing the museum, the orientation of the building was mainly effected by the site and its context. The main goal was to design the museum to fit best into the city fabric and to provide more transparency to the site. For this purpose, the building was designed in the form of two separated cubical spaces. One of the spaces (the public space) provides visual and physical connection to the city fabric while the other one (the elevated exhibition space) is elevated alongside of the street to express the existence of the museum and attract the people that are passing by the site (Figure 26-Figure 27).

Figure 26. Proposed design concept of the museum by the author. Left block is the public space and right block is the elevated exhibition space.

Therefore the design can be defined in three main parts: Public space, Transition space and Exhibition space (Figure 27).

- ***Public space*** has the responsibility of interactions between the museum and the city with respect to its varying environmental and contextual conditions throughout the year. Due to the particular location of the site, during summer time when many activities take part outside the building – in Lange Voorhout – the museum can interact with such activities and extend its interior public space toward the exterior (Figure 27).

- ***Transition space*** acts as a connector within the city fabric through which pedestrians can access Lange Voorhout conveniently while being able to explore and interact with the activities of museum.

- ***Exhibition spaces*** (or semi-private space) have two parts that are connected to each other via two transparent vertical circulations (Figure 28):

    - ***Underground exhibition space*** is located completely under the ground level; therefore it receives no daylight except through the openings that are the vertical circulations. This part is intended to exhibit the permanent collection with intermediate and high sensitivity against light. Therefore the amount of light is required be controlled strictly in this exhibition space.

    - ***Elevated exhibition space,*** which is lifted over the ground, provides transparency to the site and allows passage and transition towards the site. This part is considered to exhibit temporary collections with low sensitivity against light. Therefore, more amount of light is allowed in this space compared to the Underground exhibition space. The elevated exhibition space was selected as the case study for evaluating and optimizing its interior daylighting performance that will be described in this chapter (Figure 29).

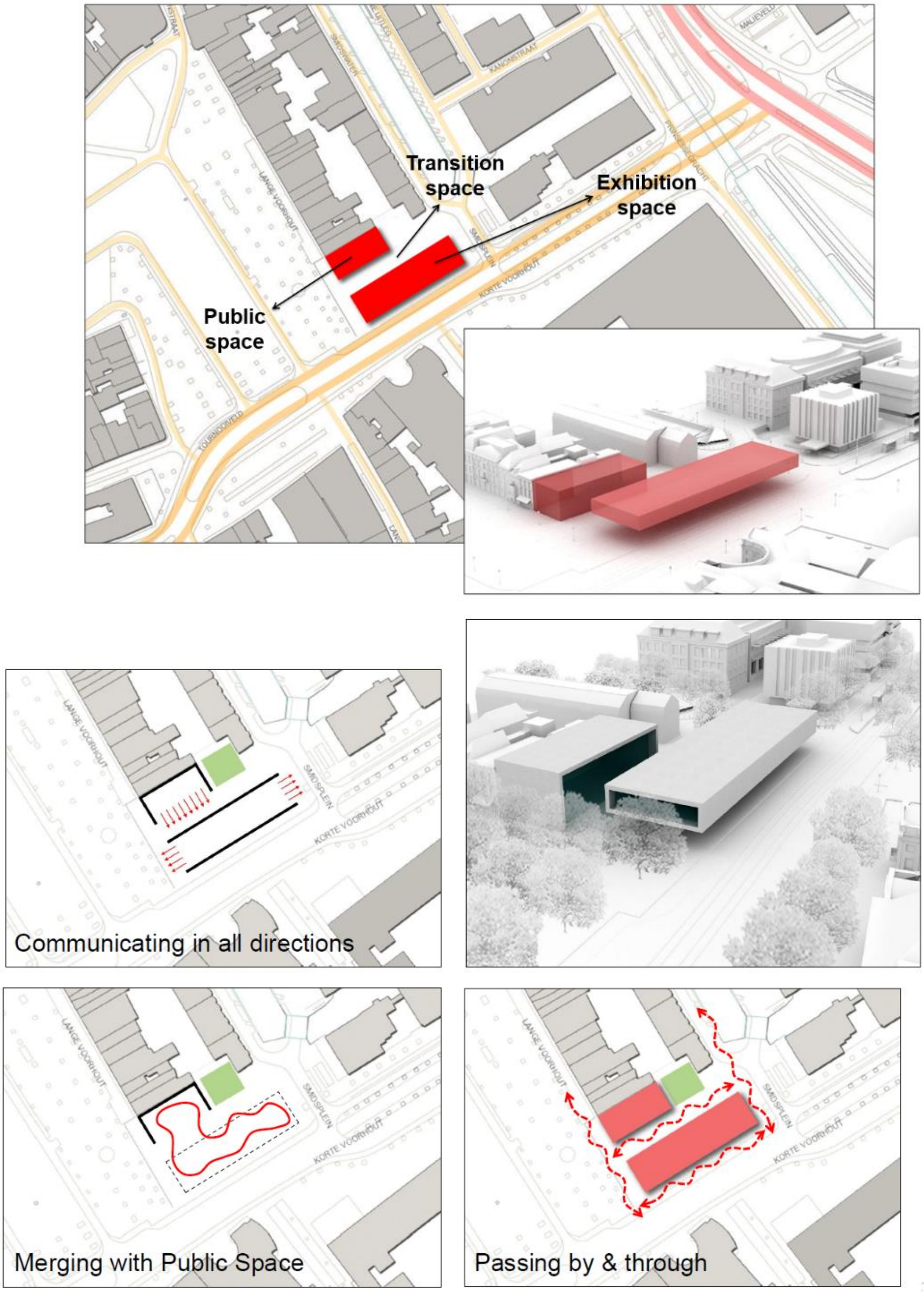


Figure 27. Design concept of the museum.

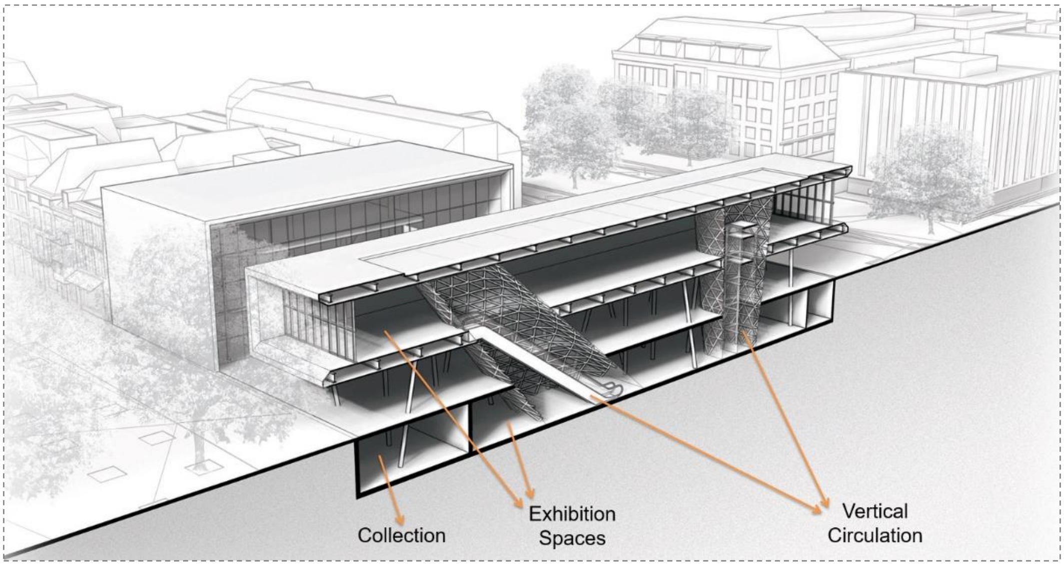
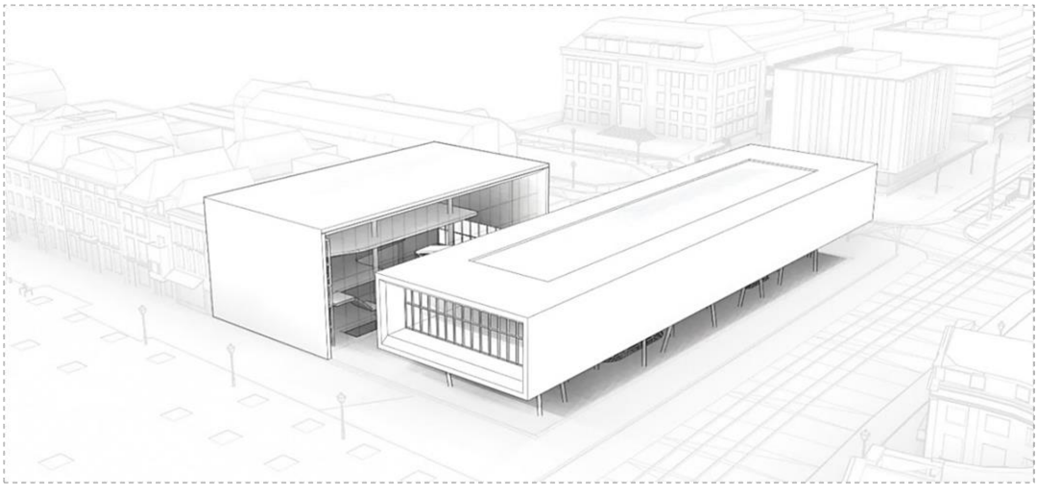


Figure 28. Longitudinal section, demonstrating the vertical circulations within the museum.



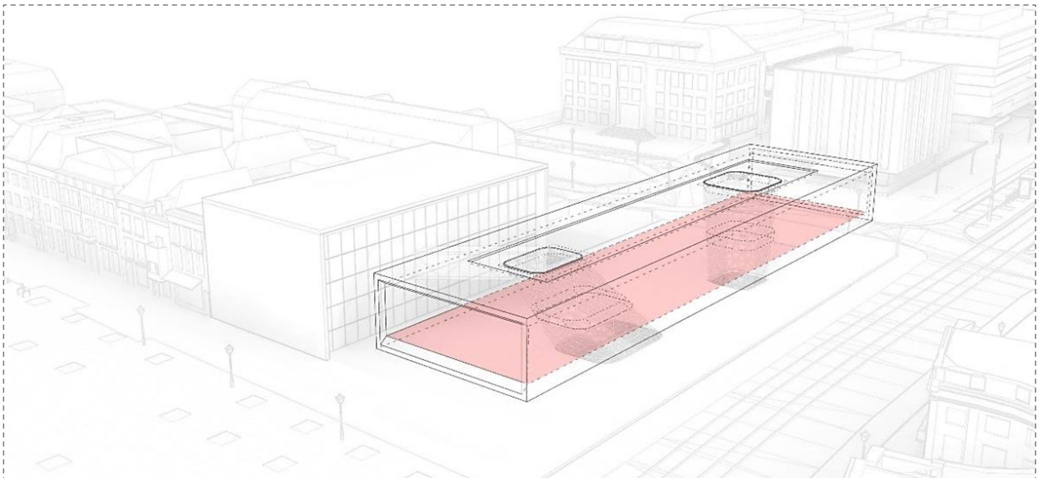


Figure 29. The elevated exhibition space.

4.2.3 Modeling the museum

As the first step, the museum and its surrounding context were modeled with required level of details in AutoCAD and Rhino.

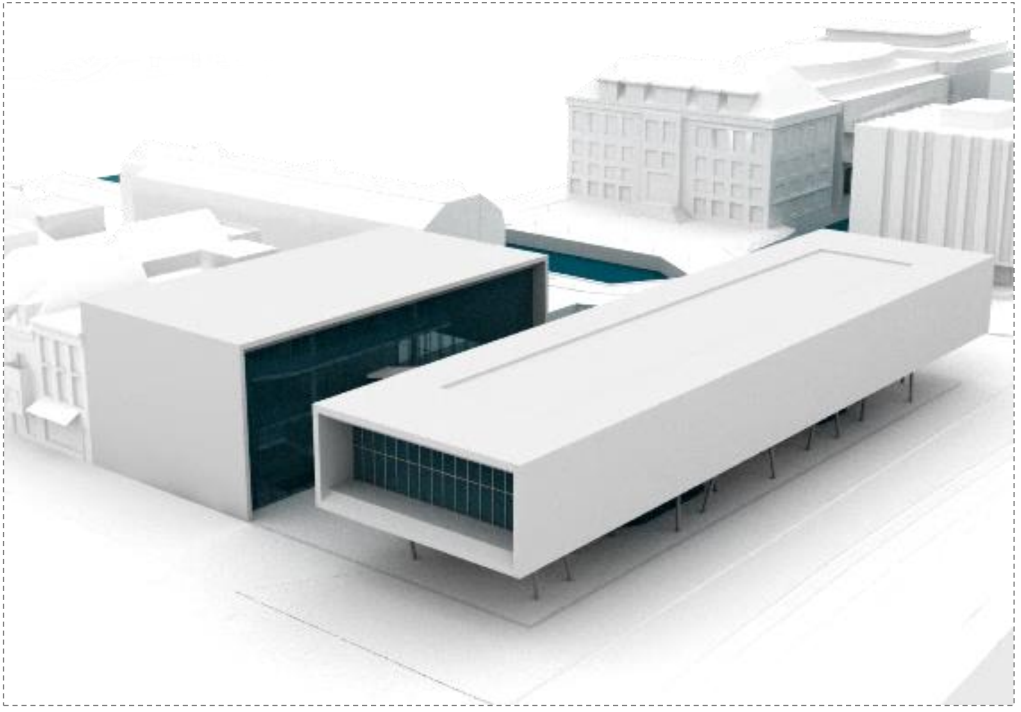


Figure 30. 3D model of the museum that is developed in Rhino.

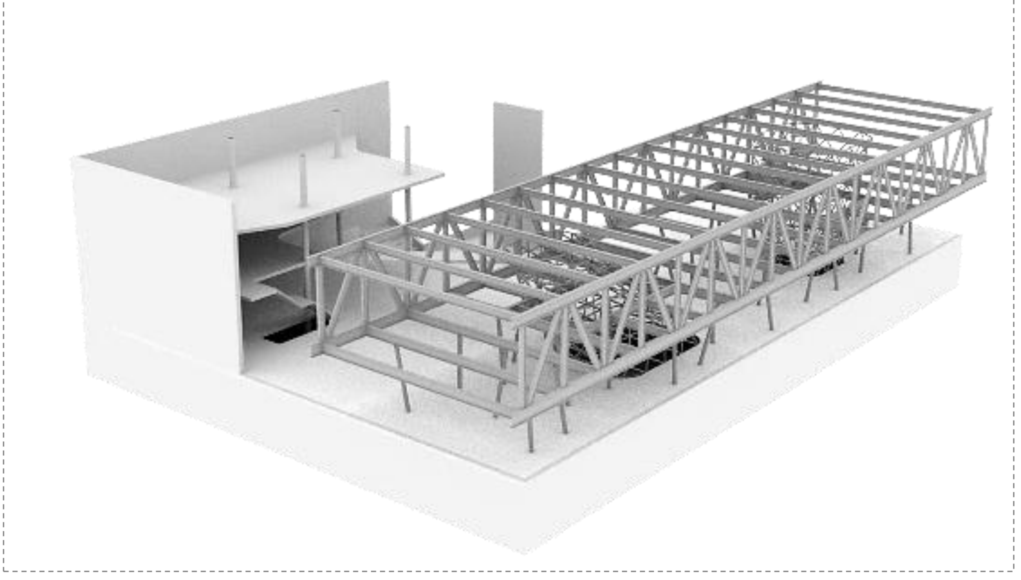


Figure 31. 3D model of the structural system of the museum that is developed in Rhino.

4.2.4 The shading system and their parameterization

In this phase, a *horizontal louvered paneling (HLP)* system was parameterized and customized to the exhibition space. The shading system was installed to the elevated exhibition space only. The *HLP* system was considered, due to its widespread practical use and its geometric simplicity in modeling and simulation. However, the proposed *ODAM* method can be applied on shading systems with arbitrary complexity.

As discussed before, the city of The Hague receives sunlight from all directions during some part of the year. However, it receives direct sunlight mainly from the *North-West* (NW) and *South-East* (SE) façades. Because of the orientation of the exhibition space, the SE façade receives direct sunlight throughout the year while NW façade receives direct sunlight almost during half of the year (Figure 32). In this respect, the horizontal louvered shading system was adjusted to the exhibition space in a manner that each of the two facades can operate individually while preserving the uniformity of design. For this purpose, the variable parameter of "***β***" (rotation angle of panels) may change differently on both facades during the simulation process while the other parameters remain the same dependently.

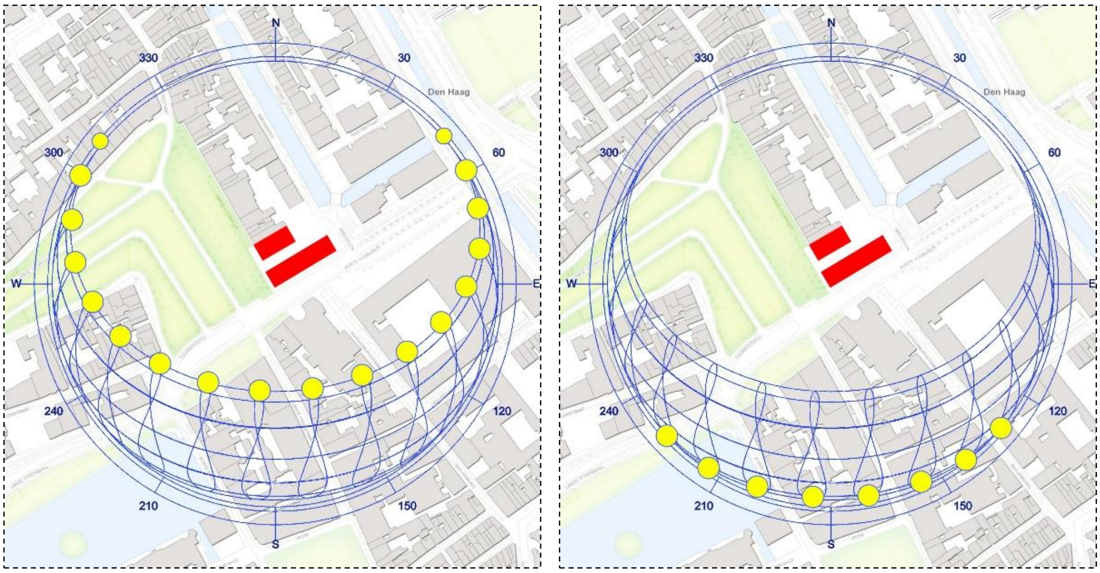


Figure 32. Orientation of the museum and its exposure to sunlight during summer and winter solstices.

Because of the insignificant impacts of the *South-West* and *North-East* facades on daylighting performance of the exhibition space, the shading system was used on these facades only for maintaining the uniformity of the design as an architectural decision. Therefore, their form was considered to be dependent on the South-East façade.

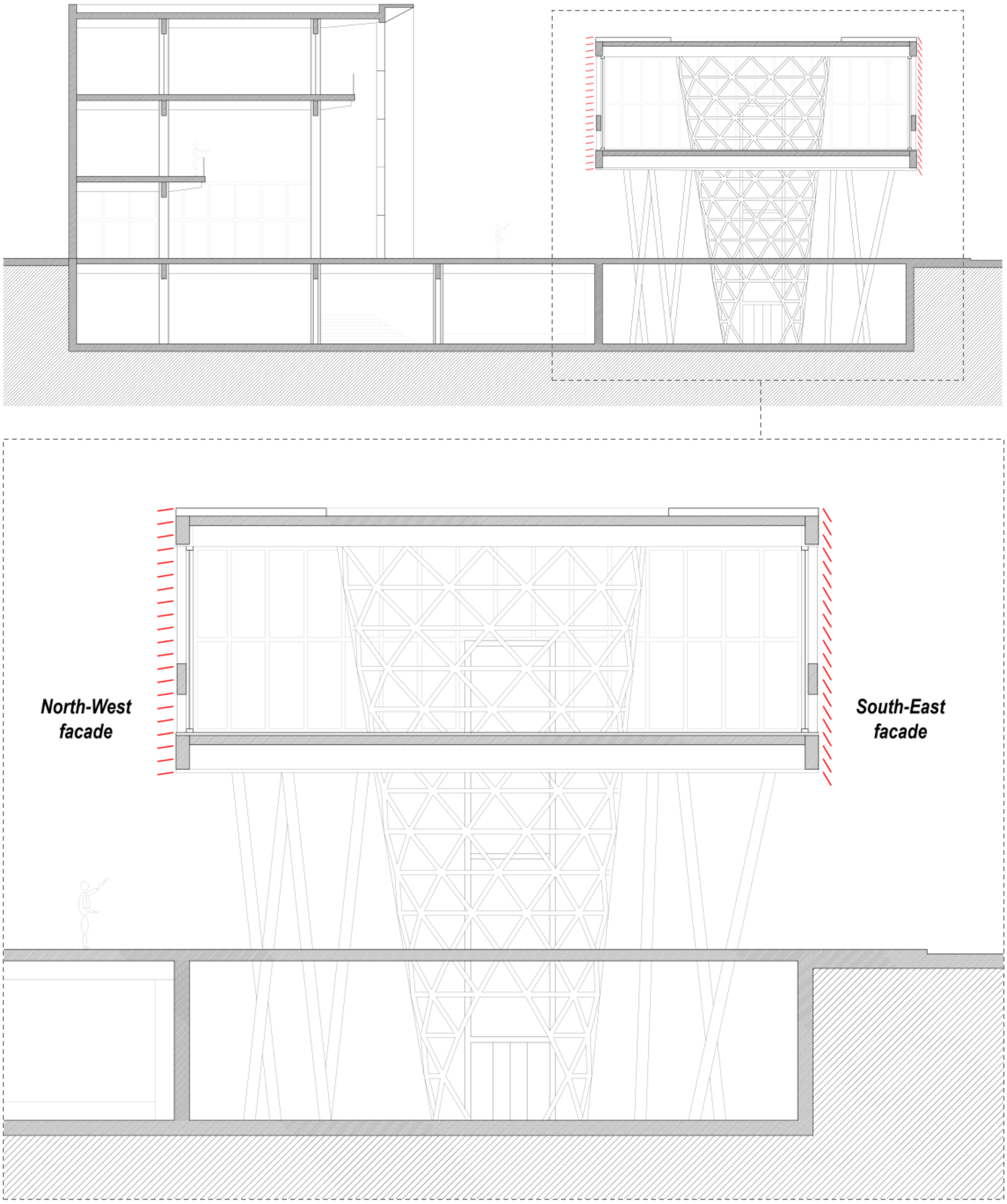


Figure 33. Cross section of the museum and the exhibition space, illustrating the individual performance of horizontal louvered shading panels on South-East and North-West façades.

In this regard, parameters of the horizontal louvered panels were defined as:

- **Fixed parameters:**
  - ***h*** (height of the opening): 700 cm
  - ***n*** (number of panels): 20
  - ***s*** (spacing between panels): 35 cm
  - ***w*** (width of panels): 40 cm
  - ***α*** (altitude of sun): 0°
- **Variable parameters (parametrically defined)**
  - ***β*** (rotation angle of panels)*:* (0° - 120°)

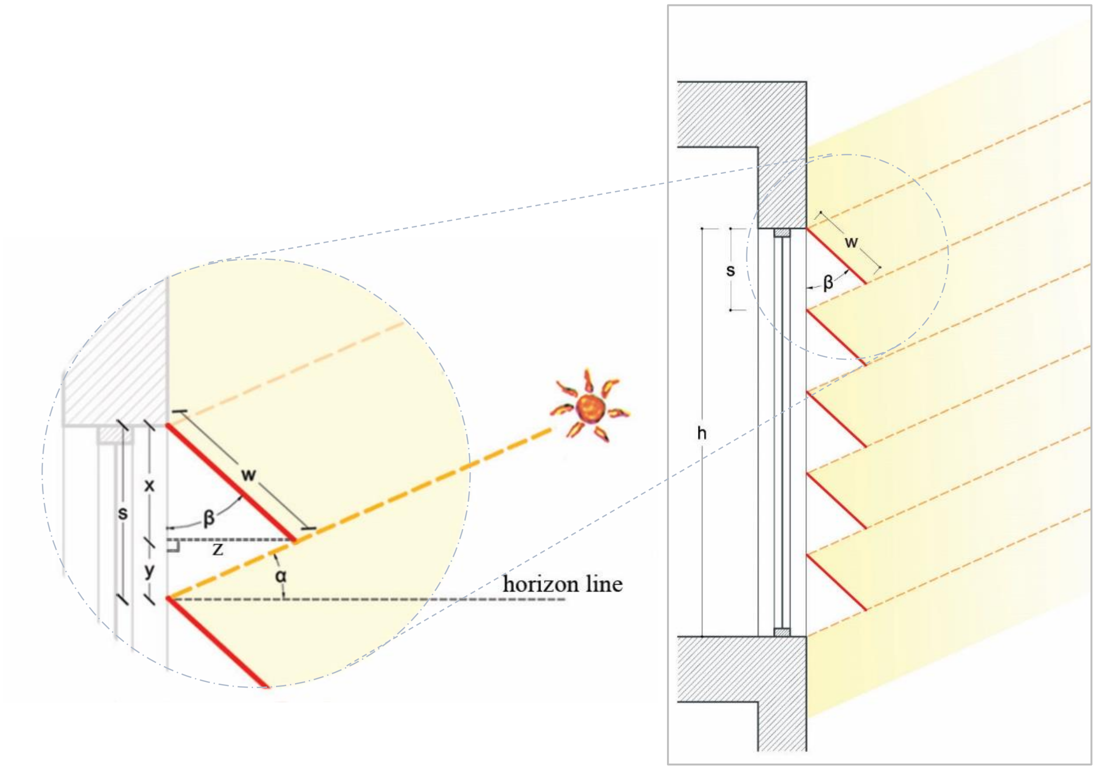


Figure 34. Design parameters of the horizontal louvered shading system.

4.2.4.1 Design parameters

As previously explained, museums require direct penetration of sunlight to be strictly eliminated. For this purpose, in order to protect the museum from direct sunlight throughout the year *"α"* was defined as *"$0°$"*, as the worst-case scenario, expressing the altitude of sun during the sunrise and sunset when it reaches the horizon line.

The number of panels (**n**) was defined as *"**20**"* during the daylighting simulation process which was decided based on architectural choices[21]. Therefore, by dividing the height of the envelope (**h**), which is ***700 cm***, to the number of the panels (**n**) the spacing between the panels (**s**) arises as ***35 cm*** (700/20=35).

As aforementioned, the width of the panels (**w**) must be greater than *"**s**"* to satisfy indirect lighting within a permitted rotation angle of *"β_{max}"* that panels can take. In this regard, "w" was defined as 40 cm based on the material selection criteria. The *"β_{max}"* can be derived from the following formula that was explained in the previous chapter:

$$\beta_{max} = \alpha - \cos^{-1}\left(\frac{s\ cos(\alpha)}{w}\right) \qquad \text{(Eq. 20)}$$

$$\beta_{max} = 0 - \cos^{-1}\left(\frac{35\ cos(0)}{40}\right)$$

$$\beta_{max} = 28.95°$$

Therefore, the maximum angle that the panels can take to satisfy indirect lighting throughout the year is 28.95° which is rounded down to 28° to guarantee the blockage of direct sunlight.

[21] The value for "n" was decided to be constant mainly to simplify the simulation process. It can be considered as a variable parameter for further researches.

4.2.5 Analyzing daylight simulation

As previously discussed in the first chapter, compared to static systems, dynamic systems have many advantages in tackling with changing daylight conditions. However, the main reasons that make dynamic systems less reliable than static ones are that:

- their high level of complexity due to their mechanical and/or electrical components.
- their constant need of maintenance to prevent malfunctioning, which can be costly and time-consuming

These problems occur in a higher rate when these dynamic systems have to adjust themselves and respond instantly to their environmental conditions. Therefore, to solve this problem, this research proposes monthly based adjustment of the parametric shading system to decrease the mechanical an electrical components which also leads to less maintenance and therefore saving energy, money and time. However, *ODAM* can be adapted to any schedule type such as hourly, daily, weekly, monthly, seasonal or yearly. Thus, the optimum daylighting performance of the space can be achieved by finding the best rotation angle of the panels ***(β)*** for each month. In this manner, by knowing the true value of *"**β**"* for each month, the shading system can be adjusted easily even through basic manual operations and without using any electrical components. The simulation model that was developed for this purpose is explained as follows:

4.2.5.1 Development of the simulation model

As previously mentioned, for developing of the simulation model several steps are followed.

- **Building components:** In this step, all the components of the exhibition space that might have an impact on daylighting performance are considered for the simulation. For this purpose, all components of the exhibition space such as visible structural elements, floor, ceiling, walls, glazing surfaces and the shading devices (parametrically defined) are added to the daylighting model. The material properties of these elements are as follows:

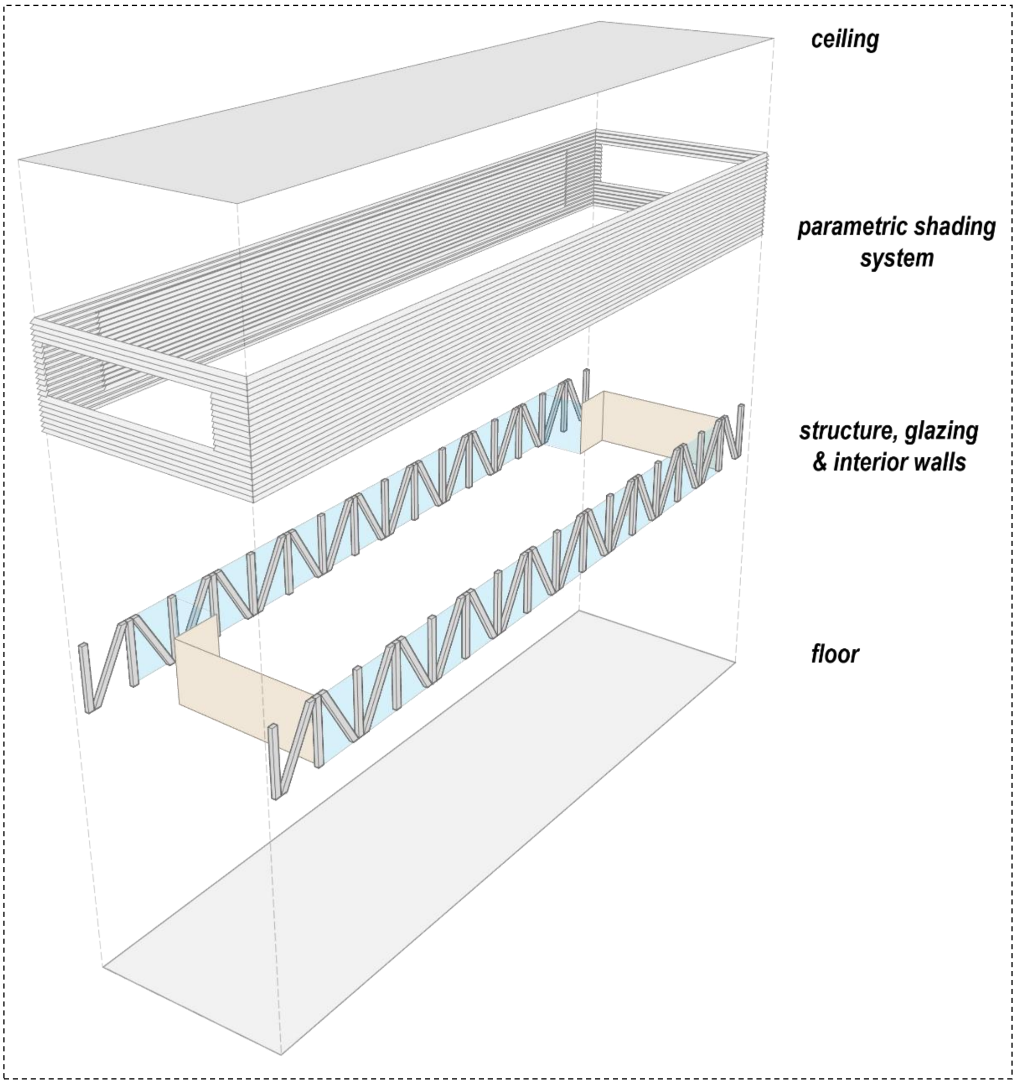


Figure 35. Different layers of building components that were modeled.

- ***Glazing surfaces*:** transmittance value of 0.45 and refractive index of 1.52 were assigned to these components.
- ***Structural elements*:** these components were given the properties metal with reflectance value of 0.4, specularity value of 0.9 and roughness of 0.05.

- ***Interior walls*:** situated on the both sides of the exhibition space, these components were given translucent properties, so that a certain level of daylight is allowed to pass through them. Their transmission value was set to 0.10, specular reflection value of 0.04 and diffused reflectance of 0.05.
- ***Envelope:*** the horizontal louvered shading systems were assigned an opaque parasol material with reflectance value of 0.4, specularity value of 0.9 and roughness of 0.01.

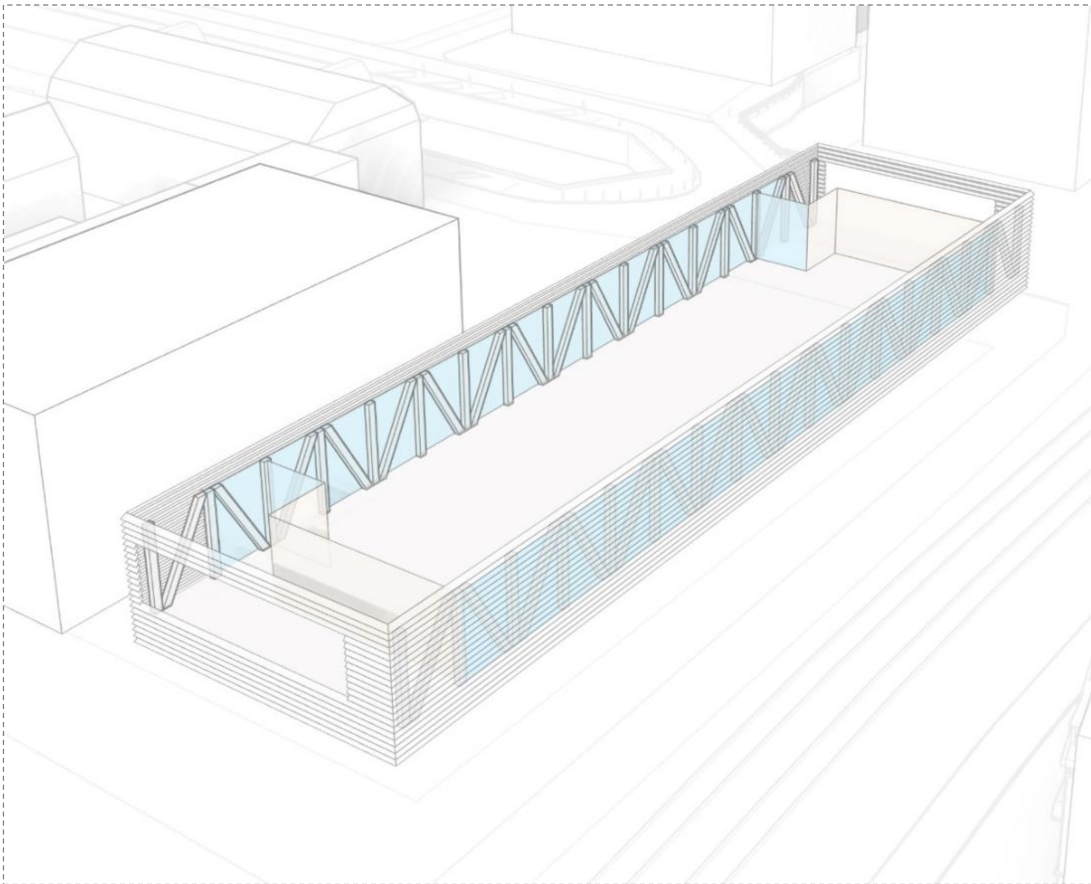


Figure 36. 3D model of the exhibition space with required level of details.

- **Contextual shading elements:** In this step, all contextual elements such as buildings, trees and any other objects that may impact the interior daylighting of the exhibition space by blocking or redirecting sunlight, was added to the simulation model in required level of details (Figure 37).

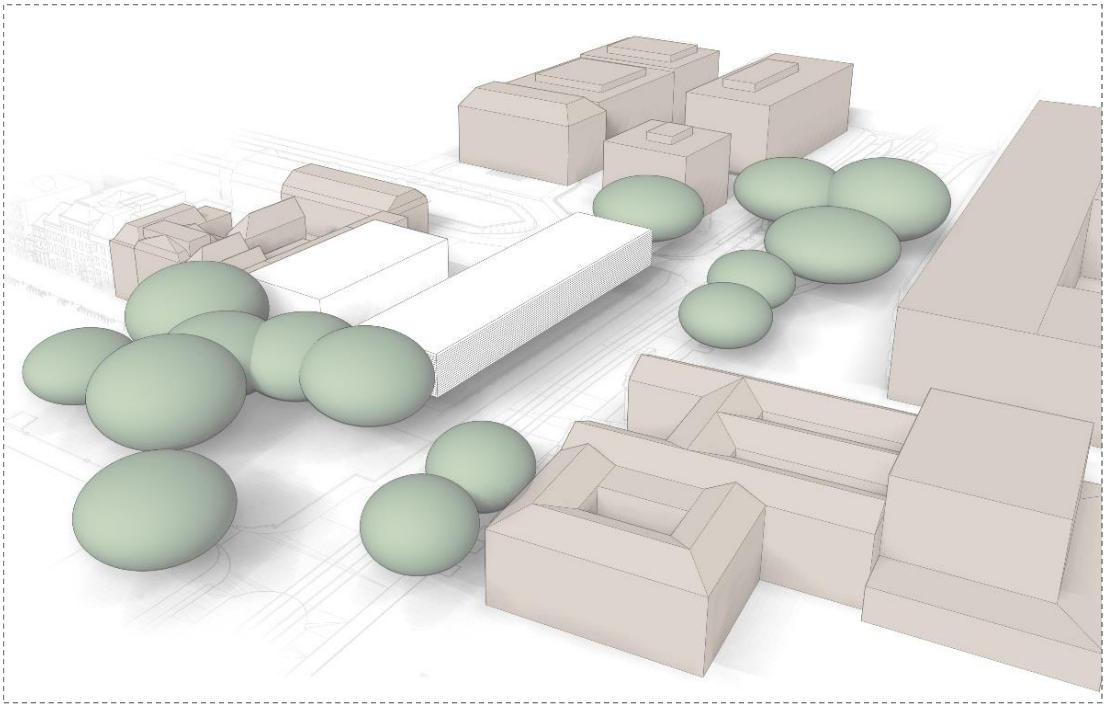


Figure 37. Contextual elements were modeled with required level of details.

Unlike static site elements such as buildings, deciduous plants have dynamic behavior in blocking or redirecting sunlight as a result of losing their leaves during the winter or dry season. Therefore, while adding the contextual elements, a transparency schedule was assigned to the modeled trees. In this regard, a transparency value of 0.9 (out of 1) was assigned to the trees without leaves for 2.5 months during the winter, a transparency value of 0.1 was given to trees with leaves for 5.5 months of the year, and for the remaining months of the year a transparency value of 0.5 was assigned to the trees when they are losing or getting leaves.

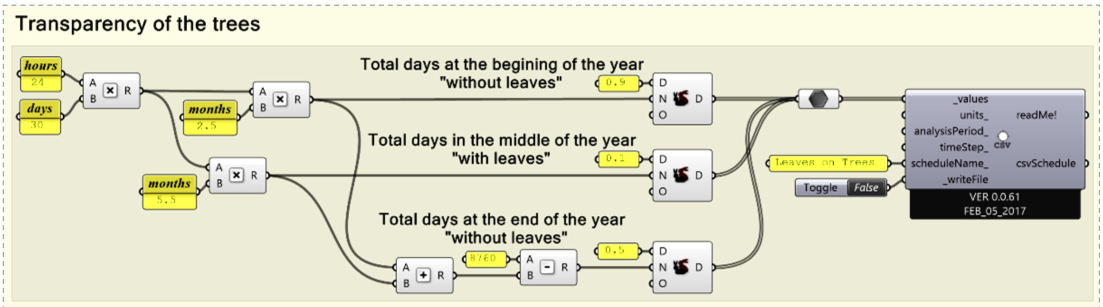


Figure 38. Transparency schedule of the trees in Grasshopper.

- **Sky type and weather data:** As previously mentioned, selection of sky type depends on the analysis approach. Since, the aim of this research is to find the monthly based daylighting performance of the exhibition space. Therefore the *Average Climate Based* (ACB) sky was selected. This type of Sky generates an average climate based data for a single hour during a month. For this aim, the weather data of Amsterdam was used which is similar to climatic data of The Hague (Figure 39).

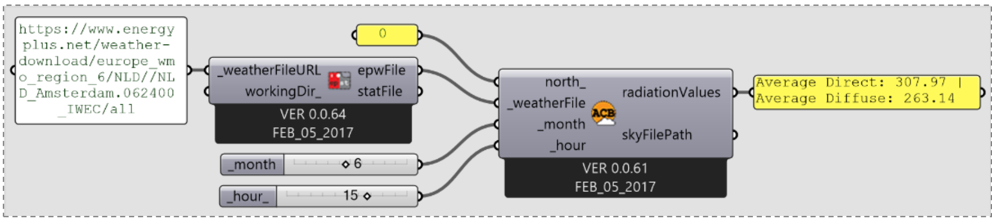


Figure 39. Average climate based sky component in Honeybee.

- **Working plane**: The working plane of the exhibition space, on which daylighting calculations will be carried out, was set at the height of 100 cm over the floor. This is considered as the average height of the exhibited artifacts. The dimensions of the working plane of the exhibition space is 1600 cm by 6600 cm. The size of the grid cells on the working plane was set to 50 cm. This results in a total number of 4224 analysis cells.
- **Ray-tracing parameters:** The ray-tracing parameters for the simulation were defined as:

Table 3. Defined ray-tracing paramters for daylight simulation

Ray-tracing parameters	ambient bounces (ab)	ambient divisions (ad)	ambient samples (as)	ambient accuracy (aa)	ambient resolution (ar)
Values	2	512	128	0.25	16

After accomplishing all the aforementioned steps, the simulation model is ready to run daylighting performance analysis.

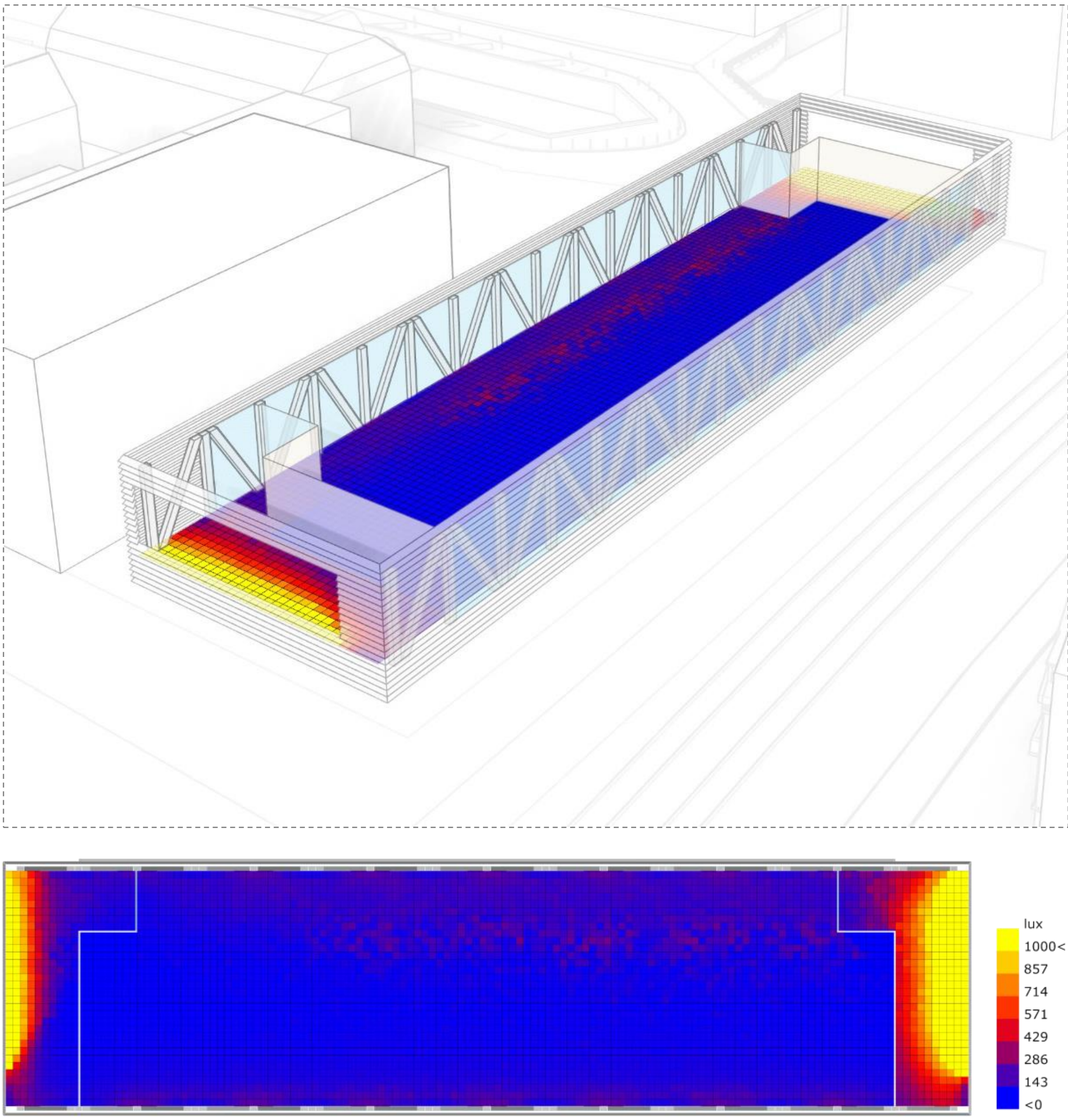


Figure 40: Plan and perspective views of the exhibition illustrating the average level of illumination on the working plane during December at 2 pm. ***β*** for South-East and North-West façades were accordingly set as 8° and 66°. Prepared in Honeybee.

4.2.6 Implementing Optimum Daylight Availability Method (ODAM)

As explained previously, for each shading instance (that is defined by a different rotation angle as ***β***), a different daylighting simulation is performed. Afterwards, the data from daylighting simulations of parametric building instances are collected, evaluated and utilized through the application of "*ODAM*" to find the best value for "β" and consequently, finding the most optimum daylighting illumination for the exhibition space.

In this research, monthly based daylighting performance of the exhibition space is assessed. For this aim, daylighting simulations were implemented for the two months of June and December that are representative of summer and winter solstices. The same approach can be applied to other months of the year, if required.

4.2.6.1 Generating solutions

As aforementioned, in order to control interior daylighting of the exhibition space more effectively and preserve it from direct sunlight more strictly throughout the year, *NW* and *SE* facades were designed to respond individually toward direct sunlight. Therefore, for each combination of "β_{NW}" and "β_{SE}" a daylighting simulation was required to be performed.

4.2.6.1.1 Assigning the fuzzy Gaussian membership value

After each daylighting simulation, membership values are assigned to the desired range of lux values through the implementation of the Gaussian functions (Figure 41). In this regard, the set-points of "L_1", "L_2", "L_3" and "L_4" were appointed accordingly as "0", "100", "200" and "250". These set-points were defined based on the sensitivity of the artifacts against light and providing visual comfort within the exhibition space.

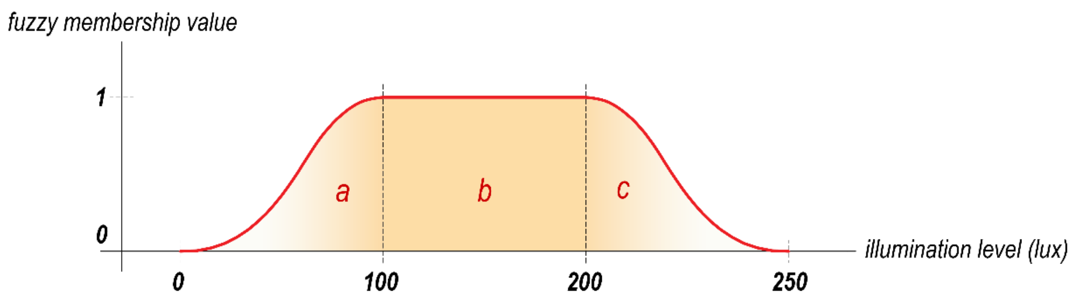


Figure 41. Graph of fuzzy Gaussian membership values between 0 and 250 lux.
Drawn by the author.

If “I” defines the level of daylight illumination (lux value) that is received by a grid cell, then the three parts of the function can be derived as:

- ***Range “b”:*** $\boldsymbol{G(I) = 1}$ if; **100 < *I* < 200**
- ***Range “a” and “c”:*** $\boldsymbol{G(d) = e^{\frac{-(I-\mu)^2}{2\sigma^2}}}$
  - For range *“**a**”*: $\boldsymbol{\mu = 100}$, $\boldsymbol{\sigma = \frac{100-0}{3} = 33.33}$
  - For range *“**c**”*: $\boldsymbol{\mu = 200}$, $\boldsymbol{\sigma = \frac{250-200}{3} = 16.67}$

For example, if after a simulation, 4 different cells that are randomly selected on the working plane receive lux values of “60”, “175”, “230” and “400”, the corresponding membership values for these cells can be calculated as follows:

- Since the cell with the value of **60** lux is situated in the range “**a**”, therefore its membership value can be derived as:

$$\boldsymbol{G(60)} = e^{\frac{-(60-100)^2}{2(33.33)^2}} = \boldsymbol{0.49}$$

- Since the cell with the value of **175** lux is situated in the range “**b**”, therefore its membership value is “**1**” :

$\mathbf{G(175) = 1}$ since; 100 < **175** < 200

- Since the cell with the value of **230** lux is situated in the range “**c**”, therefore its membership value can be derived as:

$$\boldsymbol{G(230)} = e^{\frac{-(230-200)^2}{2(66.67)^2}} = \boldsymbol{0.2}$$

- Since the cell with the value of **400** lux is situated out of the ranges of “**a**”, “**b**” and “**c**” therefore its membership value is “**0**”.

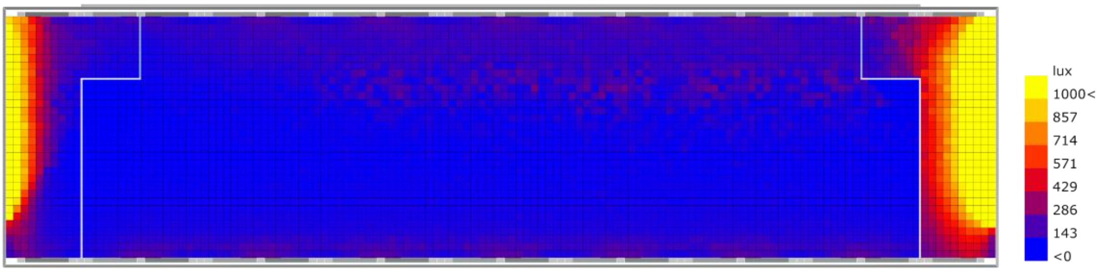


Figure 42. Plan view of the exhibition space illustrating the average level of illuminanation on the working plane during December at 2 pm. ***β*** for South-East and North-West façades were accordingly set as 8° and 66°. Prepared in Honeybee.

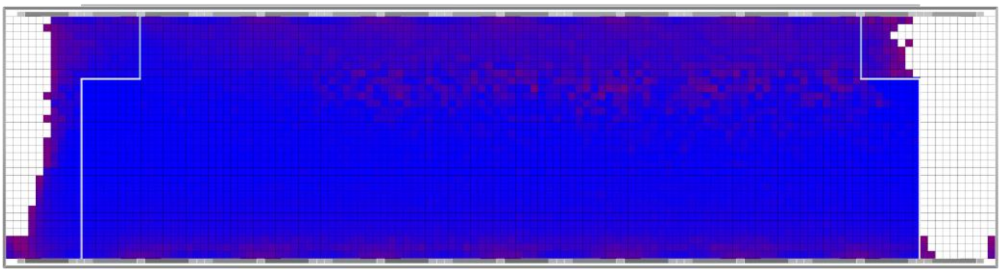


Figure 43. Desired daylight availability analysis within the exhibition space between the ranges of 0 to 250 lux. Prepared in Honeybee.

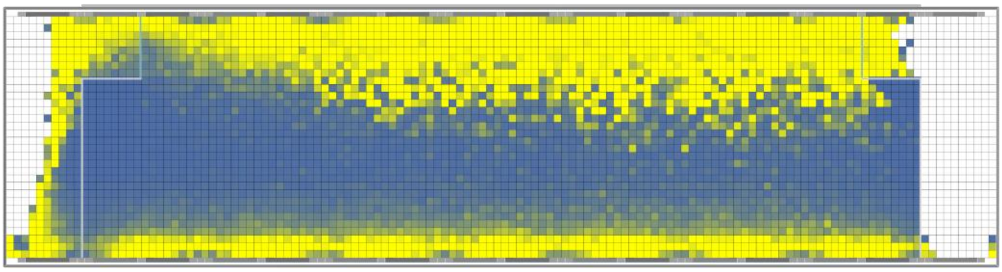


Figure 44. Fuzzy Gaussian membership values between 0 and 250. Generated by the author in Grasshopper.

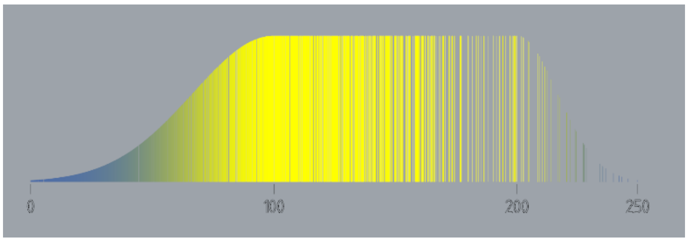


Figure 45. Graph of the Fuzzy Gaussian membership values, illustrating the desired range between 0 and 250, generated by the author in Grasshopper.

4.2.6.1.2 Hourly Desired Daylight Availability (HDDA)

After calculating the membership values for all cells, their average value that is representative of the whole exhibition space is calculated. The resultant value illustrates the *Hourly Desired Daylight Availability (HDDA)* of the exhibition space for a shading instance. As explained in the previous chapter, the formula of HDDA can be written as:

$$\boldsymbol{f(h) = \frac{\sum_{i=1}^{n} G(I_i)}{n} \times 100} \qquad \text{(Eq. 19)}$$

- ***h:*** a specific hour of a day (i.e. 15:00 pm on 30 June).
- ***f(h):*** the percentage of *DDA* for a shading instance of *"**h**"*.
- ***I:*** the level of daylight illumination (lux) that is received by a grid cell.
- ***G(I):*** the Gaussian membership value of ***I***.
- ***n:*** the total number of grid cells in the analysis space

For example, the hourly based DDA value of the exhibition space during December, 4:00 pm, with ***β***-value of **8°** for South-East façade and **66°** for North-West façade (Figure 40) can be calculated as follows:

$$f(4_{pm}) = \frac{\sum_{i=1}^{4224} G(I_i)}{4224} \times 100$$

$$f(4_{pm}) = \frac{1648}{4224} \times 100 = \mathbf{46.82\%}$$

4.2.6.1.3 Monthly Desired Daylight Availability (MDDA)

In this research the occupancy time of the exhibition space is defined between 8:00 am to 5:00 pm. In this manner, the shading system can take the desired ***β***-values to receive daylighting illumination for the exhibition space during the occupancy hours, while it can be completely closed to protect the artifacts by decreasing the exposure time of illumination when the exhibition space is unoccupied.

Since ACB sky generates the average climate based data for a single hour during a month, by repeating the above mentioned process under this sky condition during the visiting time of the exhibition space, a monthly based *Desired Daylight Availability (DDA)* can be calculated for each shading instance (each combination of *"$\boldsymbol{\beta_{NW}}$"* and *"$\boldsymbol{\beta_{SE}}$"*). Therefore the formula can be rewritten as:

$$\boldsymbol{f(m)} = \frac{\sum_{j=h_s}^{h_e} \sum_{i=1}^{n} G(I_{j,i})}{(h_e - h_s + 1)n} \times \mathbf{100} \qquad \text{(Eq. 21)}$$

- ***m:*** a specific month of the year.
- ***f(m):*** the percentage of monthly based *DDA* for a shading instance of "m".
- ***h_s:*** the starting hour of the day.
- ***h_e:*** the ending hour of the day.
- ***I:*** the level of daylight illumination (lux) that is received by a grid cell.
- ***G(I):*** the Gaussian membership value of ***I***.
- ***n:*** the total number of grid cells in the analysis space.

Therefore by using the abovementioned formula monthly based Desired Daylight Availability can be achieved for each parametric shading instance. For example, the monthly based DDA of the exhibition space for December (from 9:00 am to 16:00 pm) with ***β***-value of **8°** for South-East façade and **66°** for North-West façade can be calculated as follows:

$$\boldsymbol{f(m_{Dec})} = \frac{\sum_{j=9}^{16} \sum_{i=1}^{4224} G(I_{j,i})}{(16-9+1)4224} \times 100$$

$$\boldsymbol{f(m_{Dec})} = \mathbf{32.2}\ \%$$

This resultant value indicates that if the ***β***-values for South-East and North-West façades are accordingly adjusted as **8°** and **66°** during December, therefore **32.2%** of the exhibition space receives required range of daylighting illumination throughout the month. Therefore, the rest of the space (67.8% of the space) is required to be illuminated by artificial lighting during December.

4.2.6.1.4 Optimum Daylight Availability (ODA)

In order to find the optimum daylighting performance of the exhibition space during a month, monthly based DDA is required to be calculated for all parametric shading instances. In this manner, the highest value illustrates the optimum $\boldsymbol{\beta}$-value for the parametric shading system, which corresponds to the Optimum Daylight Availability (ODA) of the exhibition space.

4.2.6.2 Design space exploration

As formerly explained, this process requires a number of simulations which depends on:

- the number of hours
- the number of variable parameters ($\boldsymbol{\beta_{NW}}$ and $\boldsymbol{\beta_{SE}}$)

The occupancy hour of the exhibition space (visiting hours) was considered as:

- June: 9:00 - 17:00 (9 hours)
- December: 9:00 - 16:00 (8 hours)

In this research there are two variable parameters: *"$\boldsymbol{\beta_{NW}}$"* and *"$\boldsymbol{\beta_{SE}}$"*. As discussed previously, in order to block direct sunlight the maximum value that these parameters can take is **28°**. Since the exhibition space receives direct sunlight only from South-East façade during the visiting time throughout the year, $\boldsymbol{\beta}$-values for both months of June and December can be defined as:

$$\mathbf{1° < \boldsymbol{\beta_{NW}} < 120°\ ,\qquad 1° < \boldsymbol{\beta_{SE}} < 28°}$$

Considering the occupancy hours together with all combinations of *"$\boldsymbol{\beta_{NW}}$"* and *"$\boldsymbol{\beta_{SE}}$"* (for each angle), the actual number of simulations that are required to find the optimum daylight availability of the exhibition space is:

- for June: 120 × 28 × 9 = **30240**
- for December: 120 × 28 × 8 = **26880**

The average time for each simulation is 20 seconds, therefore the total time of simulations for each month counts for:

- for June: 53760 × 20 = 604800 sec = **168** hours
- for December: 26880 × 20 = 537600 sec = **150** hours

This approach of design space exploration is known as *exhaustive enumeration* or *brute-force* search in which all possible candidates are checked to find the best solution. However, due to the vastness of the parametric space and high computational cost of daylighting simulations, the *brute-force* method remains inefficient and unrealistic for design. Therefore, there is a need for smarter search methods to explore the design space.

In order to decrease the actual number of simulations and the computational effort, a search method similar to *Uniform Search* is used. Uniform search is a one dimensional search method in which the functional evaluations are made at the points that are previously determined. Therefore, the interval of uncertainty is divided into smaller sub-intervals. In general, to reduce the computational effort, the search is initiated by selecting large step size and then switching to finer step size (Bazaraa et al., 2006).

Similarly, in this study the Uniform Search approach was used to find the best solutions among all possible candidates however, in two dimensions ($\boldsymbol{\beta_{NW}}$ and $\boldsymbol{\beta_{SE}}$). In this realm, using this search approach on the parametric space, assists to find the best solutions by increasing the resolution of the search space gradually towards the optima. In this search approach, after finding the parameter(s) with the best solution in each iteration, a new parametric step size is required to be defined for the selected interval and its neighboring ones. This process will be continued until a satisfactory resolution being achieved (Figure 46).

By using this search method, the generated solutions for each month (in this case, June and December) are sampled in Excel spreadsheets. This sampled data is evaluated through the process of visualization and comparison, and consequently the best solution is selected by the user from all possible candidates.

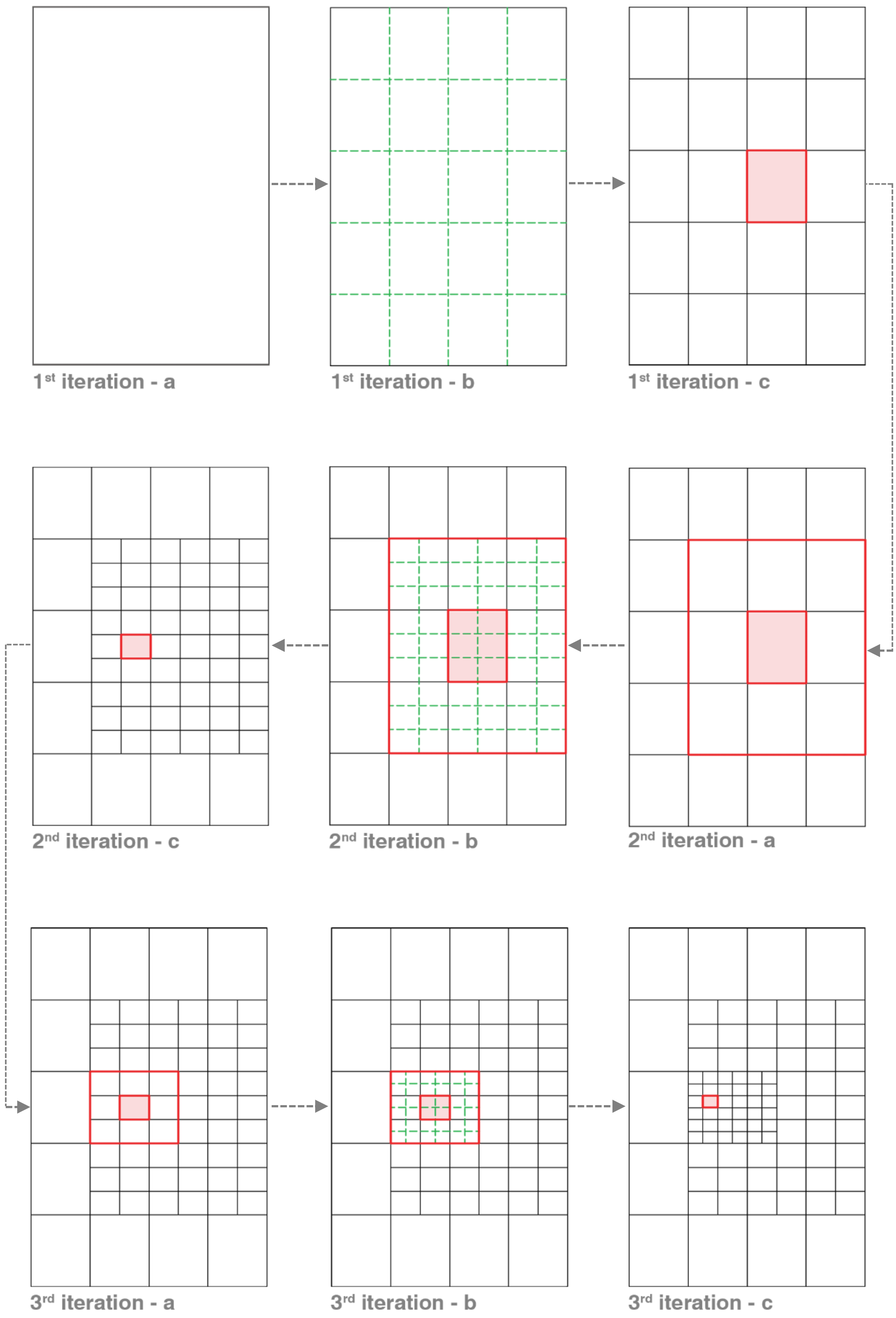


Figure 46. The process of the search method (for 3 iterations).

4.3 Results

Based on the explained procedure, the results of the Optimum Daylight Availability Method (ODAM) for the two months of June and December were calculated. In this regard, the optimum daylight availability came out to be as **43.6%** and **51.31%** accordingly for June and December (Figure 48 - Figure 50), which means that during these two months **43.6%** and **51.31%** of the exhibition space receives daylight at the best situation of the shading system. Therefore, the rest of the exhibition space (56.4% during June and 48.69% during December) requires to be illuminated by artificial lighting during these two months.

The Optimum daylight availability of the exhibition space during June can be achieved through the adjustment of the shading system at **6°** for $\boldsymbol{\beta_{SE}}$ and **63°** for $\boldsymbol{\beta_{NW}}$, while for December it can be achieved through the adjustment of the shading system at **2°** for $\boldsymbol{\beta_{SE}}$ and **97°** for $\boldsymbol{\beta_{NW}}$ (Figure 47 -Figure 49).

The resulting $\boldsymbol{\beta}$-Values for the both months of June and December illustrate that the horizontal louvered shading systems on South-East façade attempt to get closed as much as possible to control the incident direct sunlight from the south direction, while they attempt to get opened as much as possible to let the indirect daylight of the North direction enter the exhibition space to fulfill the optimum daylight availability within the desired range of 0 to 250 lux.

For the design exploration, 3 iterations were performed to achieve the satisfactory resolution of the parametric space and consequently finding the optimum solution (Figure 48 Figure 50). However, the last iteration of the design exploration illustrates that the values of the candidate solutions are very close to each other. This implies that, the small changes in the angle of the panels ($\boldsymbol{\beta}$) does not affect the interior daylighting of the exhibition space vastly. The design explorations of the two months of June and December for the exhibition space are illustrated as follows:

4.3.1 Optimum Daylight Availability for June

- For the **1st** iteration of the search the grid points for:
  - β_{SE} were defined with step size of **4**: {4°, 8°,…, 28°} = 7 steps
  - β_{NW} were defined with step size of **6:** {6°, 12°,…, 120°} = 20 steps
- For the **2nd** iteration of the search the grid points for:
  - β_{SE} were defined with step size of **2**: {2°, 4°, 6° , 8°} =4 steps
  - β_{NW} were defined with step size of **2:** {56°, 58°,…, 72°} = 9 steps
- For the **3rd** iteration of the search the grid points for:
  - β_{SE} were defined with step size of **1**: {3°, 4°,…, 8°} = 6 steps
  - β_{NW} were defined with step size of **1:** {63°, 64°,…, 68°} = 6 steps

At the end of the last iteration the optimum ***β***-values came out to be **6°** for the South-East façade and **63°** for the North-West façade (Figure 47).

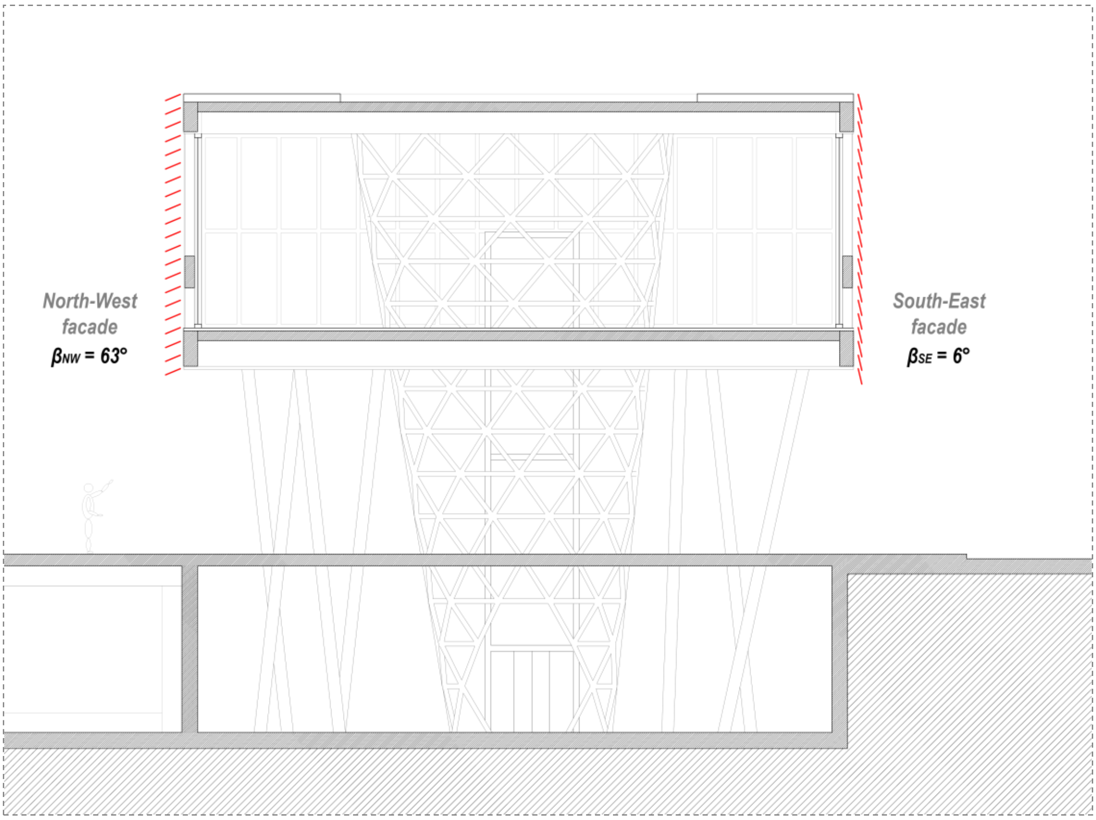


Figure 47. Optimum rotation angle of the panels to achieve the optimum daylight availability of the exhibition space during June.

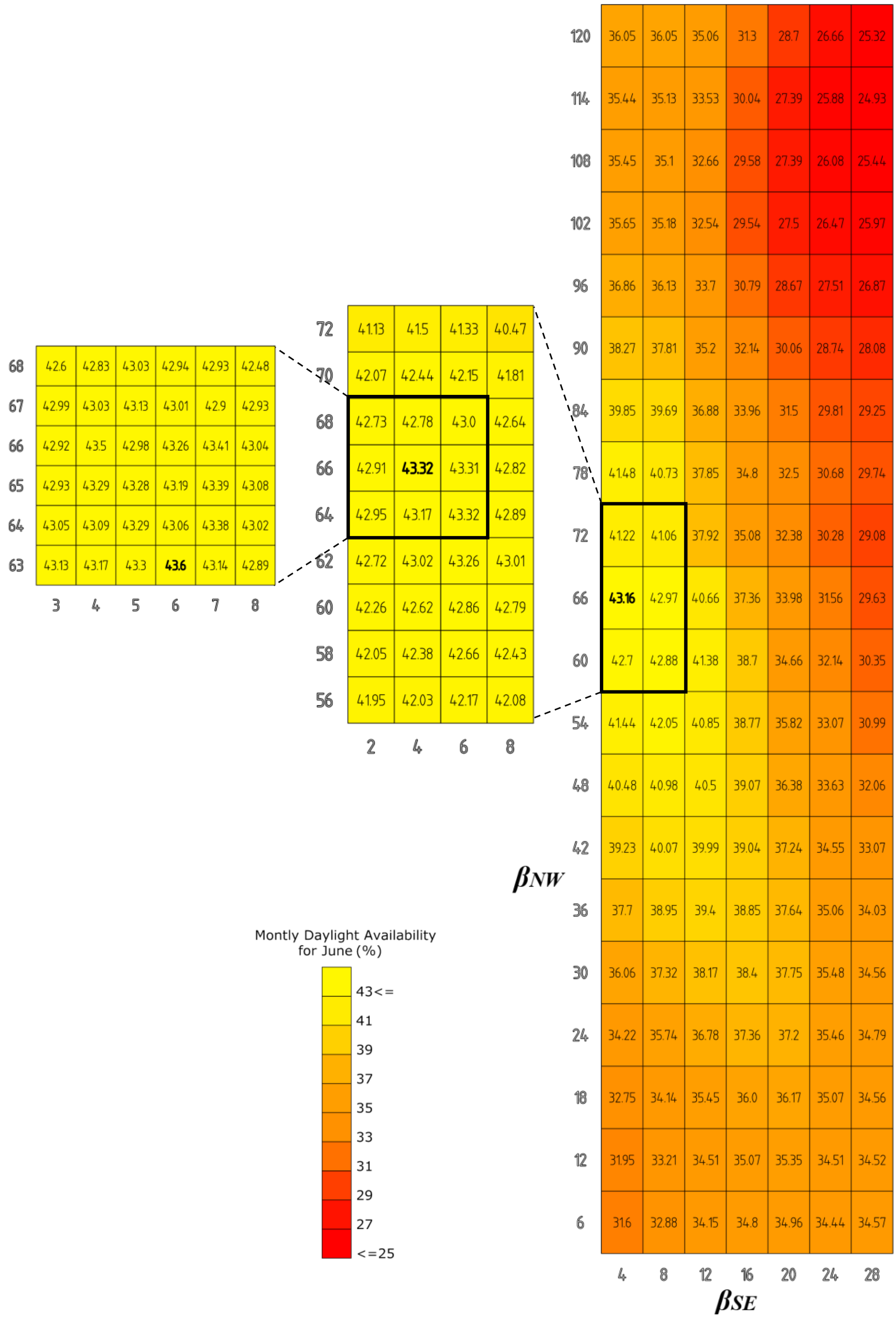


Figure 48. Finding the Optimum Daylight Availability of the exhibition space during June through the parametric design exploration. Developed by the author in Grasshopper.

4.3.2 Optimum Daylight Availability for December

- For the 1st iteration of the search the grid points for:
  - β_{SE} were defined with step size of **4**: {4°, 8°,…, 28°} = 7 steps
  - β_{NW} were defined with step size of **6:** {6°, 12°,…, 120°} = 20 steps
- For the 2nd iteration of the search the grid points for:
  - β_{SE} were defined with step size of **2**: {2°, 4°, 6° , 8°} = 4 steps
  - β_{NW} were defined with step size of **2:** {86°, 88°,…, 102°} = 9 steps
- For the 3rd iteration of the search the grid points for:
  - β_{SE} were defined with step size of **1**: {1°, 2°, 3°, 4°} = 4 steps
  - β_{NW} were defined with step size of **1:** {95°, 96°,…, 100°} = 6 steps

At the end of the last iteration the optimum ***β***-values came out to be **2°** for the South-East façade and **97°** for the North-West façade (Figure 49).

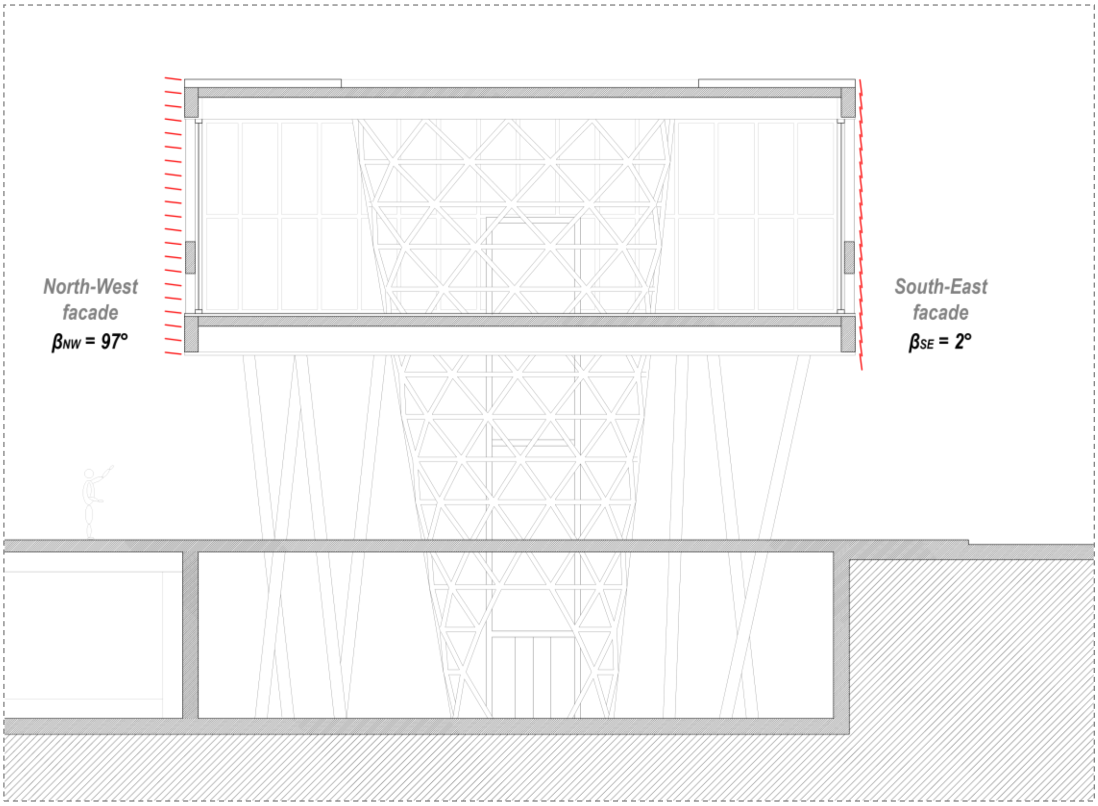


Figure 49. Optimum rotation angle of the panels to achieve the optimum daylight availability of the exhibition space during December.

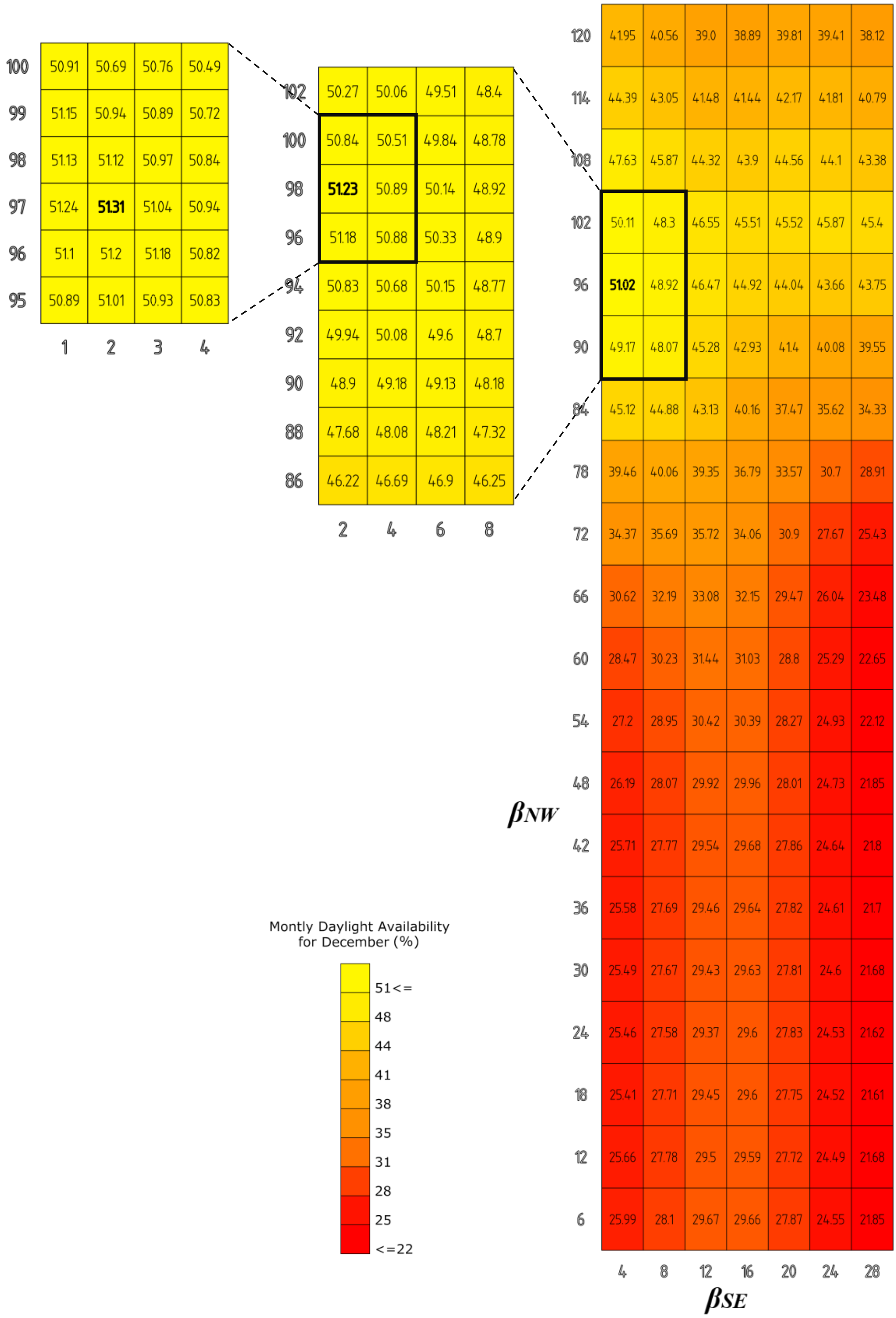


Figure 50. Finding Optimum Daylight Availability of the exhibition space during December through the parametric design exploration. Developed by the author in Grasshopper.

CHAPTER 5

CONCLUSION

"A room is not a room without natural light"

~Louis Kahn, 1961

5.1 Conclusion and future works

It is an essential issue for museums to provide a strictly controlled interior lighting to protect the artifacts from damage while providing visual comfort for its occupants. Museums require a constant level of illumination, since shortage of light runs the risk of loss of vision while excess amounts of it can be destructive for the artifacts. In addition, direct penetration of sunlight needs to be strictly eliminated throughout the year. However, the dynamic behavior of sunlight throughout the day, month and season, results in a complex and unique design situation which makes it difficult to accomplish such tasks.

Based on the findings of this research, there is a need for computational methods to support the design and evaluation of daylighting performance of interior spaces which have strict daylighting requirements such as museums. Also there is a need for the development of daylighting metrics and tools as well as smart strategies to respond to the needs of such spaces that are particularly less tolerant to daylight.

In this regard, this thesis proposed a novel computational approach, Optimum Daylight Availability Method (ODAM), for the design exploration and optimization of interior daylighting performance in museum buildings. ODAM aims to assist architects in controlling and adjusting the daylighting illumination level more effectively while ensuring indirect daylighting within the museums by supporting the design and control of dynamic shading devices.

ODAM indicates the optimum percentage of the space that is illuminated within a user-defined threshold during a specific period of time (hourly, daily, weekly, monthly, seasonal or yearly). In this research, ODAM was tested and validated on the exhibition space of a museum in The Hague that was designed by the author during his Graduation Project as part of his master's study at Technische Universitat Delft. ODAM was tested for the two months, June and December, which are representative of summer and winter solstices. The results of ODAM indicated that the optimum daylight availability of the exhibition space during June and December are accordingly **43.6%** and **51.31%**. This means that during these two months **43.6%** and **51.31%** of the exhibition space receives daylight at the best situation of the shading system and therefore, the rest of the space requires to be illuminated by artificial lighting. These optimum daylight availability conditions of the exhibition space can be achieved through the adjustment of the shading system at **6°** for $\boldsymbol{\beta_{SE}}$ and **63°** for $\boldsymbol{\beta_{NW}}$ during June, and at **2°** for $\boldsymbol{\beta_{SE}}$ and **97°** for $\boldsymbol{\beta_{NW}}$ during December.

ODAM is a climate based metric that can calculate accurate results of interior daylighting illumination levels compared to metrics such as Daylight Factor (DF), which ignores some basic daylighting parameters such as orientation, latitude, climate, and direct sunlight in their calculations. Moreover, just opposed to metrics such as Useful Daylight Illuminance (UDI) that use crisp thresholds for evaluating daylighting performance assessment of spaces, ODAM benefits from Fuzzy logic, which provides the soft computation of the thresholds. This method also has the potential to be integrated with different search algorithm methods based on the requirements of the design to decrease the computational effort during the parametric design exploration.

In addition, a distinctive characteristic of ODAM is that it can be used as a guide to a wider range of building types in which providing controlled daylighting is crucial. For instance, libraries, laboratories, classrooms and hospitals are potential building typologies that can benefit from the ODAM approach.

The other potential of ODAM is its instant and convenient adaptability in case of alterations or modifications that can affect daylighting performance of a space such as changes in:

- the functionality of the spaces
- the envelope or shading systems
- the geographical location of the building
- the contextual properties of the building (buildings, trees, obstacles, …)
- …

Beside all the advantages and potentials of ODAM, this method still has several limitations that call for further studies and future works. In this research, in order to decrease the computational effort only parameters related to the geometrical properties of the shading system were considered during the analysis, however, some other parameters such as the transparency of the shading system, glazing properties (for example, UV filters) and etc. can affect the interior daylighting of a space as well which can be investigated in future studies. The other limitation was the implementation of ODAM on a geometrically simple space. Implementing this method on geometrically complex spaces can increase the computational effort and time significantly. This is because of the computational cost of climate-based daylighting simulation. In addition to this, two variable parameters that define the shading device angle were selected during this research. ODAM can deal with an arbitrary number of variables that control the angle information. However, with increased dimensionality of the parametric space, there arises problems regarding the visualization of the relationship between parametric combinations of design alternatives and their objective values. This might pose problems in the users' understanding and exploration of the design space. However, such problems are out of the scope of this thesis.

Moreover, in this research, as a common approach in evaluating daylighting performance, a single horizontal working plane was defined which illustrates the level of illumination within the exhibition space at the height of 100 cm over the floor level. Since this approach illustrates the results in 2-dimensions at a specific height level, therefore, for future studies, a series of working plane can be set on different heights where their interpolation can be used to provide a 3-dimensional sensory and increase the accuracy of the analysis.

Finally, optimizing daylighting performance of a space with more complex geometries, multiple objectives and more than two variable parameters address the need for other smart computational approaches such as generative algorithms that will be aimed in further studies. This research can also motivate future studies that build upon the findings of the implementation of ODAM, towards the development of smart computational based tools and metrics for exploring and optimizing energy and daylighting performance of spaces that require strict environmental conditions.

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