ANALYZING THE IMPACTS OF BUILDING FORM ON THE ENVIRONMENT: A CASE STUDY IN ANKARA WITH A FOCUS ON SOLAR REFLECTION

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ABSTRACT

ANALYZING THE IMPACTS OF BUILDING FORM ON THE ENVIRONMENT: A CASE STUDY IN ANKARA WITH A FOCUS ON SOLAR REFLECTION

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In recent years, highly reflective materials have been widely used in building skins, not only for aesthetic reasons but also to reduce energy consumption and improve occupant satisfaction. Usage of highly reflective materials, combined with curvilinear building forms may cause undesired environmental impacts by creating uncontrolled solar reflections. This problem may lead to property and vegetation damage but more importantly, thermal and visual discomfort towards pedestrians, drivers and the occupants of nearby buildings.

This study investigates the solar reflection topic with an extensive literature review consisting of the definition of solar reflection and its effects on the environment, current measuring tools, mitigation techniques applied on post-construction period, precautions that should be taken during early stages of the design process and several infamous cases around the world. Furthermore, it discusses the similar patterns among the case studies with the help of an analysis of a building from Ankara selected based on specific criteria. To analyze the solar reflection problem of Ankara case, sun path diagrams for the exact location of the building at different dates and hours were generated. Using these sun path diagrams, paths of solar reflection and the approximate locations of solar focal points occurred due to the building's concave façade were determined around the vicinity of the building. This analysis is further supported by on-site observations and the results show similarity to the cases reviewed in the research, in regard to environmental impacts.

In conclusion, the study suggests a simple method for predicting the possible areas in the environment that may be affected by solar reflection and presents a guideline for designers on avoiding or mitigating this problem.

Keywords: Curvilinear Building Forms, Reflective Facades, Solar Reflectivity, Glare, Heat Gain

ÖZ

BİNA FORMUNUN ÇEVREYE OLAN ETKİLERİNİN ANALİZİ: ANKARA'DA SOLAR YANSIMA ODAKLI ÖRNEK BİNA İNCELEMESİ

Tümbaş, Havva Nur
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Son yıllarda, estetik nedenlerle birlikte, binanın enerji tüketimini azaltmak ve kullanıcıların memnuniyetini artırmak için bina cephelerinde oldukça yansıtıcı malzemeler kullanılmaktadır. Eğrisel yapı formları ile birlikte yüksek oranda yansıtıcı malzemelerin kullanılması, kontrolsüz güneş yansımaları yaratarak istenmeyen çevresel etkilere neden olabilir. Bu durum, çevredeki bitki örtüsünün ve yapılaşmanın zarar görmesine sebep olabilir, ama daha da önemlisi, alanı kullanan yayalara, sürücülere ve alandaki yapılarda oturan sakinlere ısıl ve görsel rahatsızlıklar verebilir.

Bu çalışma, güneş yansımasının tanımını ve çevreye etkilerini, mevcut ölçüm araçlarını, inşaat sonrası çözüm tekniklerini, tasarım sürecinde alınması gereken önlemleri ve dünyadan örnek binaları içeren kapsamlı bir kaynak taramasını içermektedir. Ayrıca, örnek binalar arasındaki karşılaştırmalar, Ankara'dan belirli ölçütlere göre seçilen bir binanın da yardımıyla genişletilmiştir. Ankara örneğindeki güneş yansıması problemini analiz etmek için farklı tarih ve saatler için oluşturulan güneş yörünge diyagramları kullanılmıştır. Bu diyagramlar kullanılarak güneş yansımasının izlediği yol ve binanın içbükey cephesi nedeniyle ortaya çıkan solar odak noktalarının çevredeki yaklaşık yerleri tanımlanmıştır ve sahada elde edilen görsel verilerle de desteklenmiştir.

Sonuç olarak, bu çalışma, tasarımcılara bina çevresinde güneş yansımasından etkilenebilecek olası alanları tahmin etmek için basit bir yöntem önermekte ve bu sorundan kaçınmak veya çevredeki etkilerini azaltmak için temel ilkeler sunmaktadır.

Anahtar Kelimeler: Eğrisel Bina Formları, Yansıtıcı Cepheler, Solar Yansıma, Parlama, Isı Kazanımı

Dedicated to my dear family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

ARC: Anti-reflective Coating

BREEAM: Building Research Establishment Environmental Assessment Method

CFD: Computational Fluid Dynamics

DGI: Daylight Glare Index

DGP: Daylight Glare Probability

HDRI: High Dynamic Range Imaging

LEED: Leadership in Energy and Environmental Design

Low-e: Low Emissivity

SHGC: Solar Heat Gain Coefficient

UK: United Kingdom

UN: United Nations

USA: United States of America

LIST OF SYMBOLS

SYMBOLS

E_V , the vertical illuminance at eye level

$L_{s,i}$, the luminance of i th glare source

$\omega_{s,i}$, the solid angle subtended by i th glare source

P_i , the Goth's position index by i th glare source

CHAPTER 1

INTRODUCTION

In this chapter, the argument of the study with the aim and objectives of the research are concisely explained. The procedure that took place and the disposition of each chapter is listed and briefed.

1.1. Argument

The human population began growing at an unprecedented rate since the industrial revolution with the help of medical advancements and agricultural productivity. This rapid growth of population and rural-urban migration has led to an inevitable outcome of denser cities. In order to accommodate larger number of people and meet people's expectations, high rise buildings have become the norm in modern cities. In this situation, energy demand for people in modern cities is continuously rising and raising a lot of problems in the sense of sustainability. Technological developments and growing sustainability concerns in the last decades enable the necessary yet insufficient improvements in the construction field.

These improvements managed to decrease energy consumption with highly reflective façade materials while achieving an increase in the quality of user comfort from the aspects of heating and cooling conditions, ventilation and lighting inside the building. Also, extensive usage of reflective materials have been increased not only for function but also for design purposes and to increase the commercial value of high-profile buildings. However, inadequate concern is raised about the obvious and pervasive effects of solar reflections caused by buildings on the outside world and the general public. Especially in the last decade, a growing number of solar reflectivity cases have emerged due to the increase of geometrically complex buildings and wide usage of reflective surfaces in their skin.

This study concerns the environmental impacts of building form that causes an undesirable amount of solar reflectivity. Curvilinear building forms combined with highly reflective building skins have the major risk of creating focused solar reflections in the buildings' vicinity as can be seen from several infamous cases all around the world. This phenomena cause property and vegetation damage in the surrounding outdoor environment, as well as thermal and visual discomfort to the people who use the area such as pedestrians, drivers or occupants of nearby buildings.

Estimation of solar glare reflected from free-form and highly reflective façades is a complex process that necessitates an extra budget from the developers. The tools that are currently used in order to determine the paths of reflected light and compute the intensity and duration of solar reflections require steep learning curves, enormous computational effort and long simulation run times. Therefore, a detailed solar analysis is often disregarded during the design process and developers choose to apply mitigation solutions to the problematic surfaces if a problem occurs after construction. Unless an industry-wide standard is adopted and incorporated in the building codes to assess the visual and thermal impacts of reflections, solar reflectivity may become one of the major problems in the construction industry.

1.2. Aim and Objectives

User satisfaction for the building is a crucial part of the design process yet public satisfaction for the building is just as important, too. The aim of this study is to support the argument with a literature review on the subject of solar impacts and an analysis of case study buildings. Thus the objectives are:

- To examine the basic principles of heat and light reflectivity from glazed façades
- To evaluate the selected case studies as the examples of the problem
- To study the precautions that have to be considered both during design and construction phases

- To suggest ways of eliminating this problem from already constructed buildings

1.3. **Procedure**

The study contains a literature review in order to understand the effects of the problem on the general public and on the environment. In the light of the literature review, four buildings around the world that have drawn the most attention due to the severity of their problems were chosen for further examination. These buildings are Walt Disney Concert Hall in Los Angeles that was completed in 2003, 20 Fenchurch Street, also commonly known as Walkie Talkie, in London which was built in 2014, Vdara Hotel in Las Vegas completed in 2009 and the Museum Tower in Dallas built in 2012. Also, another case from Ankara was chosen in order to further explore the effects in a local area which is Yıldırım Kule built in 2017.

Sun path diagrams of Yıldırım Kule were generated for the selected dates and used in order to determine reflection paths and approximate locations of focal points throughout the year. Assessment of these results was done with the help of visual data obtained during site visits. Finally, all cases are compared with each other regarding their features that led to solar reflection problems, the environmental impacts, and various mitigation techniques tried and applied to their problematic surfaces.

1.4. **Disposition**

The thesis consists of six chapters.

In the first chapter, the introduction, motivation for the chosen subject, problem definition and aim and objectives of the study are explained.

In the second chapter, an extensive literature review that compasses the factors that affect solar reflectivity which are the integration of a building to its environment, building form covering both the mass shape and the skin are analyzed. After that, the environmental effects of solar reflectivity are identified and further explained. Finally, current approaches to assess solar reflection are listed and compared with each other and mitigation techniques applied post-construction are explained.

In the third chapter, four prominent cases around the world are studied according to the criteria of this research. The characteristics of the building that led to this problem and the solutions that were suggested, applied or rejected are examined.

In the fourth chapter, the material and methodology of the paper containing a case study in Ankara in order to compare to its worldwide precedents and its tangible effects to the public and to the environment are presented. The materials that helped to conduct a study is listed and the method that carried throughout the research is explained in detail.

In the fifth chapter, analysis and results that were concluded from the local case study are discussed extensively and compared with other case studies covered in the third chapter. As a productive approach, the precautions that have to be considered before the design phase are explained as well as the measures that could be taken after an issue is brought up by the public are discussed.

In the final chapter, the conclusion derived from the previous chapters are summarized and the results and comparisons between case studies are highlighted. Also, limitations of the study and recommendations for future studies are mentioned.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a literature review starting with the factors that may cause solar reflection which are the integration of the building to its environment and the building form. Afterwards, the results of solar reflectivity, exterior glare and heat gain are explained in detail and the environmental impacts of these results are identified and elaborated with examples. Finally, mitigation techniques divided into two main categories are explained and discussed regarding their effectiveness. And, current measuring tools used to assess solar reflectivity are listed with their abilities and shortcomings.

2.1. Integration of building to its environment

As Ishak, Hien, Jenatabadi, Ignatius, & Yaman (2018), states that lack of land and the growing number of population generates a demand for high rise buildings creating much more dense cities and sustainability problems as well. When it comes to sustainability in buildings, it is immediately linked with the building's features providing energy efficiency. Yet, it should also be associated with the integration to its environment as well. Especially, in the case of sustainability, the harmony between the surrounding and the building itself gains much more importance.

According to Feng & Xingkuan (2011), accurate location-specific knowledge of the sun path and climatic conditions of the building site should be the first factor to be considered while constructing a building. Especially, in the case of high rise buildings, it becomes more important due to their massive sizes.

In order to maximize the benefits of natural light while preventing the negative impacts, architects must achieve the optimal utilization of land. To achieve that a number of factors should be considered such as traffic, building density, neighboring building locations, existing landscape areas and open public areas. The relationship between the building and its surroundings should be well integrated by creating smooth transitions and adjusting the height and mass of the building according to the urban skyline and the sun.

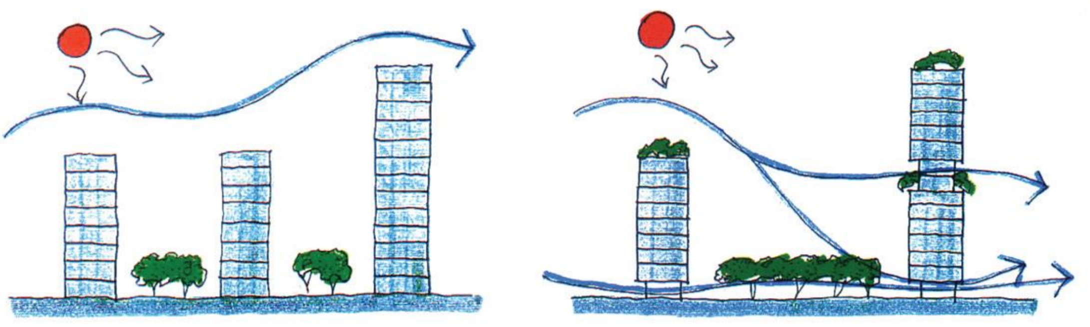


Figure 2. 1. Comparison of traditional and ideal land utilization. (Source: Feng and Xingkuan, 2011)

2.2. **Building Form**

Creating the form of the building is considered as one of the major decisions by architects in the design process. Form is determined by various factors such as site orientation of the building, floor-space optimization, structural necessities and regulations, natural lighting and natural ventilation possibilities, etc. (Brzezicki, 2012). Moreover, especially in high rise buildings, building form is the most important factor that adds value to its worth. Along with aesthetic concerns, while designing high rise buildings, sustainability concerns become major points as well due to their significant energy consumption. In the design process, along with the considerations of energy efficiency and user comfort, architects also must consider the environmental effects of this prominent buildings and adjust the mass shape and skin of the building according to these factors.

2.2.1. Building Mass

Brzezicki (2012) asserted that the mass shape of the building has a direct impact on solar reflectivity, along with sun's altitude. Flat, concave and convex surfaces of the mass directs the reflection differently according to the laws of geometric optics as seen in figure 2. While planar façades carry relatively lower risk of intense solar reflectance due its straightforward geometry, curved façades have the ability of scattering or focusing light beams into hotspots.

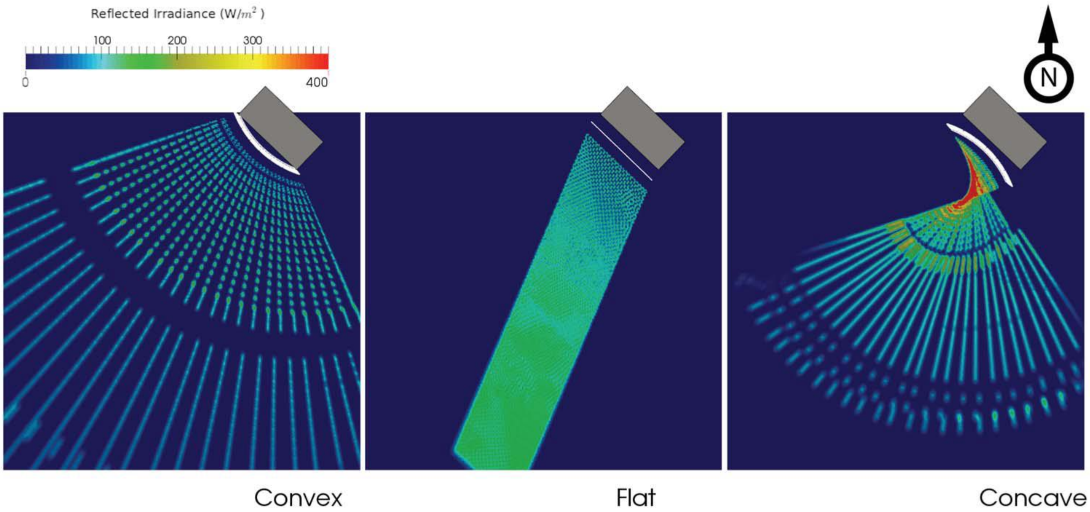


Figure 2. 2. Simulation graphics demonstrating the direction and intensities of light beams reflected from three different surfaces. (Source:Danks, Good and Sinclair, 2016)

Concave surfaces could act as a parabolic mirror depending on the direction of light beams. Reflected light beams merges in a focal point at some distance creating visual discomfort for observers and heat gain in the area (Danks, Good, & Sinclair, 2016a). The most intense thermal and visual impacts are caused by concave façades due to its ability of converging sunrays into very small areas even at a large distance from the building according to its curvature angle forming the mass shape. This type of glare formations is highly unpredictable and could be dangerous for drivers and pedestrians as well as surrounding buildings and vegetation. (Brzezicki, 2012)

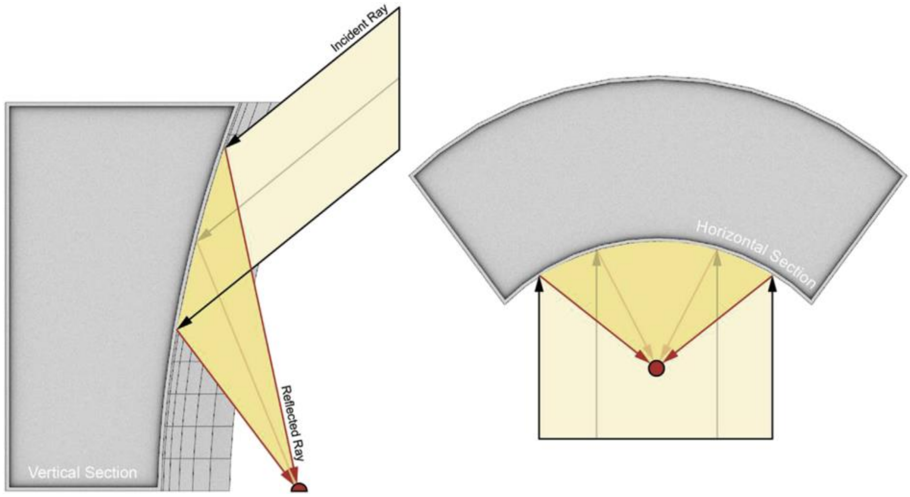


Figure 2. 3. Diagram of sun lights reflecting from a concave façade and converging on a single point. (Source: Danks, Good and Sinclair, 2016)

There is another parameter that affects the formation of focal points in the case of concave façades. With a smooth continuous concave surface, monolithic building masses reflect sunbeams in a way of generating an intense and large focal area. On the other hand, if the surface is faceted, the number of focal areas increase while their intensity is decreased which is helpful to prevent forming hotspots.(Danks, Good, & Sinclair, 2016b)

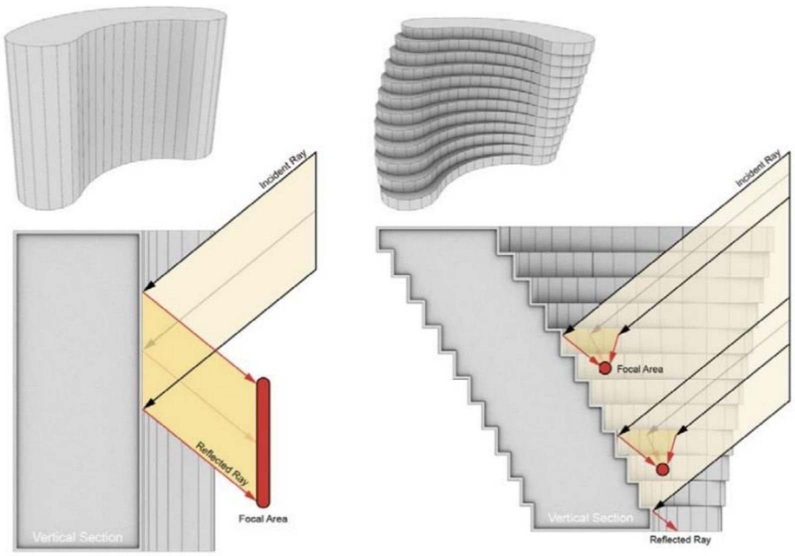


Figure 2. 4. Diagram of the effect of façade continuity on forming focal points. (Source: Danks, Good and Sinclair, 2016)

2.2.2. Building Skin

Rezaei, Shannigrahi and Ramakrishna (2017), mentions that building skin is the primary factor affecting comfort levels of the occupants by providing vision, natural lighting, natural ventilation, thermal insulation, acoustical insulation and so on. When it comes to building skin design, the increase of highly glazed façades is becoming a norm in modern architecture. Comparing to insulated walls, they cause much more problems such as excessive heat gain and uncontrolled natural light. To tackle with this issues, various strategies are developed. Internal shading devices such as blinds, curtains or window shutters, external shading devices such as louvres are most commonly used methods. However, shading devices are not always preferred due to design constrictions.

Façade performance of highly glazed buildings is mostly dependent on the ability of glass panes to absorb, transmit or reflect solar radiation. In cold climate region, high-transmittance glass is preferred in order to reduce energy consumption in heating and lighting. On the other hand, in temperate or hot climate regions, mostly highly reflective glass panes with low SHGC are used to prevent undesirable amount of solar heat gain into the interior. (Raji, Tenpierik, & Van Den Dobbelsteen, 2016)

In the last decades, architects prefer highly transparent façades in order to maximize the view while complimenting the form of the building. This feature while increasing the performance of natural lighting, also increases the demand for heating and cooling energy. The most effective way of avoiding these problems is to block the direct solar radiation from reaching to façade which could be achieved by using exterior shading devices as mentioned by Cho, Yoo, & Kim (2014). The alternatives for shading types (horizontal, vertical, panel), orientation, depth and spacing of shading units should be decided according to variations like building’s location, orientation and sun path diagrams etc.

According to Al-Tamimi & Fadzil (2011), regarding façade design, additional solutions could be used to improve indoor thermal environment such as using reflective glazing system, appropriate material selection for building envelope and decreasing wall to window ratio etc. However, in cases that these methods become inadequate, using shading devices for high rise buildings could be beneficial to avoid overheated indoor environment and decrease cooling energy loads.

On the other hand, as Varodompun & Asavapitayanont (2012) stated, commonly used solutions such as shading devices may conflict with the design concept and become inapplicable in some cases.

As Danks, Good and Sinclair (2016) explain that high performance glazing which equipped with multiple panes, low-conductivity gas fills, advanced thermal breaks and low-emissivity coating (low-e) has been used in order to minimize the cooling energy demand of highly glazed buildings. These features provide visible light to enter through the glass without obstruction while thermal radiation is mostly reflected as could be seen in figure 2.5. The authors also mention that along with these improvements, even some rather simple measures affect reflectivity ranges such as using darker glazing units or adding frittings.

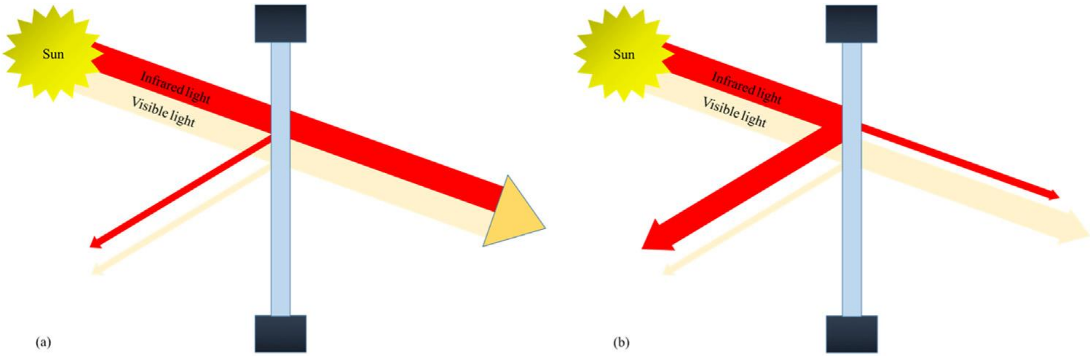


Figure 2. 5. The distribution of visible light and infrared light on a) conventional glass and b) highly reflective glass with low-e coating. (Source: Rezaei, Santiranjan and Ramakrishna, 2017)

Also, as elaborated by Chow, Li, & Lin (2010) advancements in the fenestration technology provide a substantial decrease in cooling demands in buildings. Material improvements such as tinted glazing, reflective glazing, low-emissivity glazing, photovoltaic glazing, and innovative design approaches such as double glazed windows with air sealed cavity, gas-filled cavity, evacuated windows, air-flowed windows, and water-flowed windows are mostly preferred in order to meet the demands of low energy consumption. Among these solutions, reflective glazing is one of the most commonly selected glazing type by the architects due to its ability to control indoor glare and appealing outside appearance. The reflective coatings consist of thin metallic or metal oxide layers with various color choices such as bronze, silver or gold. Some coatings must be sealed in the cavity of the system but more durable ones could be placed on the exposed surfaces of the glass panes. Thickness, reflectivity rate and the placement of reflective coating in the glazing system affect the SHGC.

Shih & Huang, (2001) states that reflective glass with a reflectivity rate of 20-40 % is used mostly in high rise buildings in order to meet the criteria of lowering cooling energy load. Due to its massive surfaces, they could obtain enormous amounts of thermal gain. To solve this problem, architects find the solution to use highly reflective glasses to accommodate the users in comfortable temperatures while giving them maximum view through their almost all reflective façades. However while achieving optimum indoor comfort, this causes significant problems such as exterior glare and heat gain by its surroundings.

2.3. **Solar reflectivity**

To understand the basic principles of solar reflectivity, one should be familiar with the optic laws on reflection which occurs on different types of surfaces such as flat or curved and opaque or transparent. In the case of transparent surfaces, some of the light transmitted through the medium and the rest is reflected as seen in Figure 2. (Montes-Amoros, 2015)

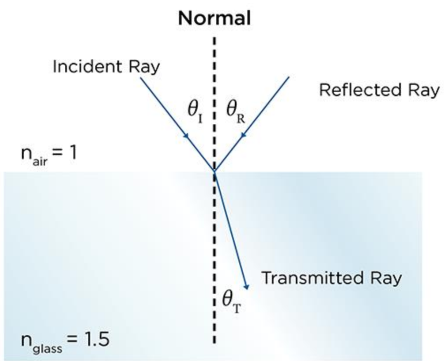


Figure 2. 6. Diagram of reflection law on glass. (Source: http://www.koppglass.com/blog/optical-properties-of-glass-how-light-and-glass-interact/)

As stated by Danks, Good and Sinclair (2016), when light travels through a medium and meets another one, it shows different behaviors. The surface of the medium determines the distribution of the light. When the light reflects in a single direction, it is described as a specular reflection and when it is scattered into the former medium, it is described as diffused reflection which can be seen in the Figure 2.7.

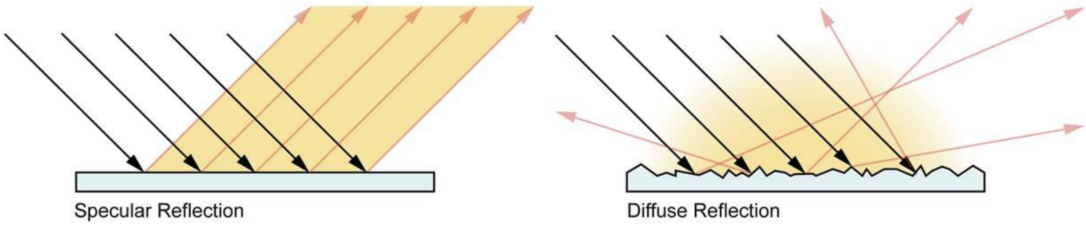


Figure 2. 7. A diagram of how light reflects through different surfaces (Source: Danks, Good and Sinclair, 2016)

Whereas rough and matte surfaces diffuse the light into different directions thus preventing light beams to merge into one specific point, smooth and shiny surfaces reflect the light in a singular direction with the same angle as they hit the surface which causes light to converge in the same area and retain large portion of their energy. This reflection type is the main concern of this research because it causes unwanted environmental impacts such as glare and thermal load to its surroundings.(Danks et al., 2016b)

2.3.1. Thermal Load

Majority of the world's population live in cities rather than rural areas and this number is believed to be as high as 67% by 2030. (United Nations, 2012). To accommodate the dwellers, high density cities have emerged without considering possible ramifications such as temperature rise. Spatial configurations of urban areas could increase local temperature comparing to the surrounding areas. This temperature rise which could generate environmental and public health problems is the result of a phenomena called heat island effect. The reasons for urban heat island effect could be varied such as lack of vegetation and green areas, extreme use of asphalt and concrete that comes with dense housing. Schiler & Valmont (2006) suggests that many architects do not consider the effect of solar reflections occurring on their buildings' façade when they are trying to decrease thermal gain in their buildings and with that, heat island effect consequentially.

The statement of any modern and dense city, high rise buildings with fully glazed façade systems, contribute to this issue through solar reflectivity properties of their skin. Even though, glare caused by solar reflections from highly glazed façades is relatively less discussed and researched topic, there are even less publications about thermal load caused by solar reflections. Danks, Good and Sinclair (2016) asserted that not only the intensity of solar reflection affects the temperature of reflected surface but also the material properties of the reflected surface as well.

2.3.2. Glare

Although glare is a subjective term, it could be defined as presence of highly illuminated areas within the visual field of observers that affects visual performance and cause nuisance (Gelan, 2012). Glare occurs when the observer's eye have adjusted to illuminance level of the surroundings, another light source that is disturbing emerge within the visual field of the observer (Suk, Schiler, & Kensek, 2013). The authors categorized the process of glare into two factors:

1. Absolute glare factor: Exceedingly high illuminance sources such as sun causing extreme discomfort or damage to the receiver's eye sight is considered as absolute glare factor. In the presence of this type of a light source, contrast between the surrounding and the light source is not effective.
2. Relative glare factor: Glare source which is adaptable to the human eye is called relative glare factor. Unlike the absolute glare factor, it could be measured by analyzing the contrast between light source and background in the visual field.

Based on the results of these glare factors, glare disturbances have generally been divided into two types which are disability glare and discomfort glare.

a)Disability glare

This defines an extreme case of glare which gives an absolute blindness in a period of time or even eye damage. Danks, Good and Sinclair, 2016 states that disability glare occurs if the light source is bright enough to impair visual performance and decrease the ability of recognizing other objects caused by contrast loss.

b)Discomfort glare

Discomfort glare could be described as nuisance or pain caused by uneven distributions of illuminance levels within the visual field (Hirning, Isoardi, & Cowling, 2014). Both discomfort and disability glare could be identified and measured using various metrics, thus, consensus in the literature is lacking. However, it is a lot harder to conclusively assess discomfort glare due to subjective responses of the observers. (Fotios, 2015) Moreover, it has been stated that the degree of discomfort glare levels decreases over time even though the light source has not been removed. (Gelan, 2012)

Figure 2. 8. a) Disability and b) discomfort glare examples. (Sources: a) https://robus.com/news/news-article/glaringly-obvious-ugr-and-en-12464-1-for-offices b) https://leotek.com/discomfort-glare/)

As stated in (Ruesch, Bohren, Battaglia, & Brunold, 2016), visual comfort of the observer is based on different parameters such as total amount of light, the distribution of light in the visual field and the adaptation state of the observer’s eye. To quantify the visual discomfort, indices such as Daylight Glare Probability (DGP) or Discomfort Glare Index (DGI) are the most common ones.

Daylight Glare Probability is calculated with the following equation (Pierson, Wienold and Bodart, 2017):

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2})$$

Where E_V is the vertical illuminance at eye level (lux) and it is the intensity of the luminous flux emitted per unit area of the source;

$L_{s,i}$ is the luminance of the i th glare source (cd/m2) and it is the luminous flux reaching the eyes and setting the adaptation of the eyes;

$\omega_{s,i}$ is the solid angle subtended by the i th glare source (sr) and it expresses the size of the glare source as seen by the observer;

P_i is the Goth's position index of the i th source in the visual field and it is a correction factor considering the different perceptions of glare sources for horizontal and vertical displacements from the line of vision of the observer.

Although, several glare analysis methods are available, none of them meet the criteria of delivering accurate results due to a lack of consistency among results obtained by HDRI captured images or computational calculations. (Suk, Schiller and Kensek, 2013). Moreover, as asserted by Pierson, Wienold, & Bodart (2017), the list of factors that affects visual discomfort is not constant due to high variability between observers. Possible factors that could affect determining discomfort glare are compiled and classified according to their relations to the light, context or observer. Lighting related factors are not subjective and were defined decades ago in a consensus, such as luminance of the glare source, adaptation level, contrast effect, saturation effect and size and position of the glare source from the observer. On the other hand, context and observer related factors are subjective, such as room temperature, time of the day, season, gender, age, culture, vision correction, iris pigmentation, physical state and even emotional state.

Figure 2. 9. Visible indications of solar reflection on its surroundings. (Source: Suk, Schiler & Kensek, 2017)

2.4. **Negative impacts of solar reflectivity**

The light beams bouncing off of from reflective façades have many effects on the surroundings and the observers. These effects could cause various outcomes ranging from fatal to negligible. As Shih and Huang (2001) state, solar reflectivity effects can be analyzed in three different categories such as fast speed, moderate speed and slow speed, based on the relative movement of the observer. In the case of fast speed, the drivers who are exposed to reflection glare have the possibility of fatal danger for themselves or others. Moderate speed explains the effects related to pedestrians. Finally, the most consistent effect of reflection glare which occurs in slow speed that exists between glare source and the neighboring buildings and vegetation that are located permanently in the area of the reflection location. Further analysis of the effects show that they are divided into two categories according to the possibility of momentary or constant impacts.

2.4.1. Nuisance to drivers and pedestrians

Suk, Schiler, & Kensek (2017) state that glare raises a concern among drivers and pedestrians, as it could limit their visual field and cause traffic accidents. According to a number of reported accidents, drivers that were blasted from reflecting lights experience temporary visual impairment which led to loss of life and property.

Even though in some situations, the glare source does not directly affect driver's vision, it may cause some behavioral adaptations to avoid the glare, such as looking away from the glare source or fixating on a specific area in the field of vision. These adaptations may lead to a decrease in performance of object detention which is vital during operating a vehicle. (Theeuwes, Alferdinck, & Perel, 2002)

Montes-Amorros, (2015) notes that according to a research conducted by UK Automobile Association, nearly 3000 accidents occur in a year, and one in three people is affected by sun glare while driving through a tall buildings zone. Especially, at sunset or sunrise, when sunrays are coming to the earth at lower angles, direct sunlight and/or reflections from the environment can be critical; drivers are most likely to be affected because light beams will be directly at their eye-level as shown in Figure 2.9.

Figure 2. 10. Glare at sunset affecting the vision of pedestrians and drivers. (Source: https://www.aa.co.nz/membership/aa-directions/driver/sunstrike-beat-the-glare/)

2.4.2. Nuisance to neighbor buildings and vegetation

The reflectance off the building's façade could cause serious issues if it reaches to an occupied space. Solar reflectivity can cause temperature rise in a surrounding area causing discomfort and even property damage. The users of neighboring buildings might have to close their blinds or shades in order to minimize the discomfort even though this action limits their opportunity of receiving natural light or view in the daytime. Also it is mentioned that in some cases of significant temperature rise, inhabitants are forced to keep their air conditions on to avoid this problem requiring much more energy. (Montes-Amorros, 2015). As Shih and Huang (2001) state additional thermal load that comes from solar reflectance from neighbor buildings has the power of altering the indoor climate and comfort of occupants by raising temperature and humidity levels.

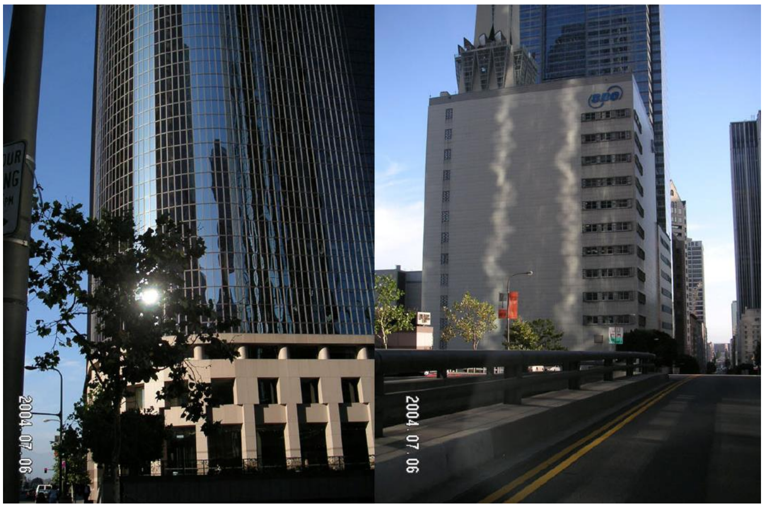


Figure 2. 11. The glare of Deutsche Bank and its reflection onto its neighbor building. (Source: Schiler and Valmont, 2006)

Montes-Amorros (2015) states that vegetation which is planted in the reflection volume may start to decay due to consistent temperature rise and sunlight exposure at focal points caused by solar reflection as can be seen in the figure.

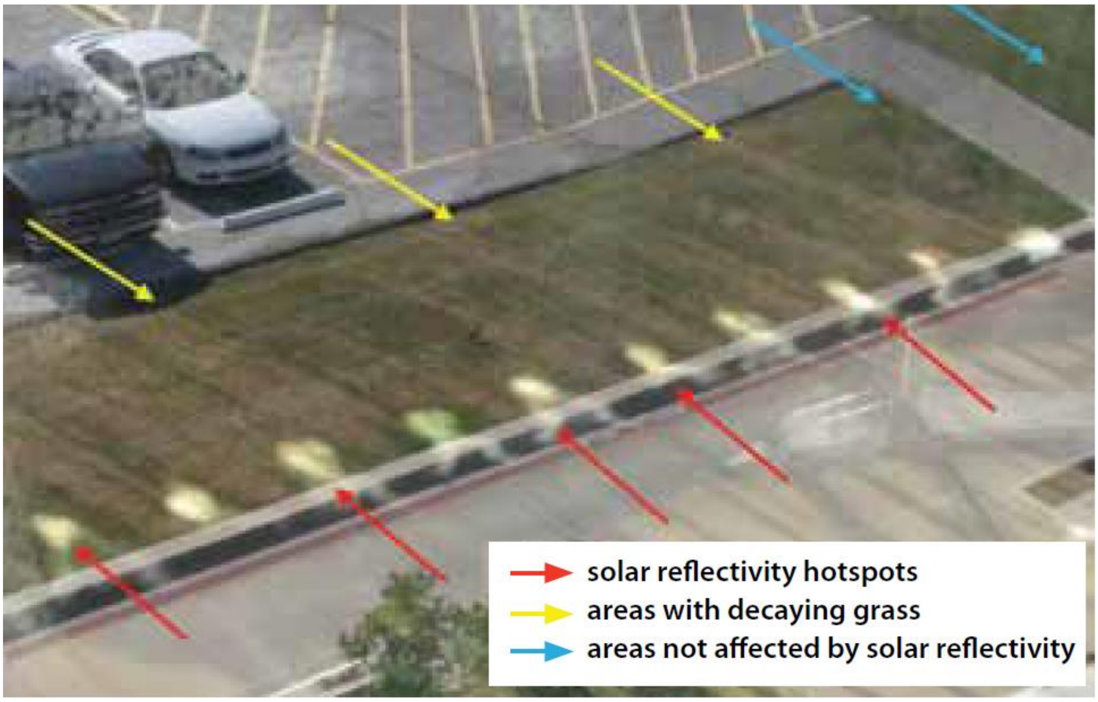


Figure 2. 12. Vegetation decay due to hotspots created by solar reflection. (Source: Montes-Amorros, 2015)

However, according to Danks, Good and Sinclair (2016), it is not easy to assess the reasons from plant decay unless it is occurred in single focal points as the figure below. Because, various factors could be asserted as the reason of vegetation decay such as excessive or insufficient pruning, pedestrian traffic, insect infestation and over or under watering. Moreover, decay shows range among different species which limits evaluating the impact of solar reflections.

2.5. Mitigation Techniques

As mentioned in the previous part, there are tools to detect solar reflection in the design phase. However, in some cases, these methods might be insufficient and the impacts of solar reflection may be gone unnoticed until the construction period is completed. In this situation, modifying the form or the orientation of the building is not an option. Therefore, some mitigation approaches should be adopted. There is number of mitigation techniques that could be divided into two categories; altering reflective surfaces and blocking solar reflections.

2.5.1. Altering Reflective Surfaces

Reflective surface modification varies according to the material used on the façade. If the problematic surface is large and consisted of glazing systems, various types of coatings in the form of film or spray could be used. If the surface is small and consisted of metal panels, roughening the surfaces with sanding techniques or completely covering the surfaces with fabrics or paint might be a solution. Roughening or covering the surface could be used only in opaque building materials since it is used on the outermost surface of the façade and completely alter the occupant view. (Danks et al., 2016b)

Glass coatings have been widely studied and used since the second half of the 20th century for various reasons. In 2000, 70% of the glazing systems produced worldwide possess some sort of coating such as antireflective, low-e, solar control or even not functional ones for design purposes. They alter the surface properties of glass in order to optimize the visual and thermal transmittance levels. (Cannavale et al., 2010)

Despite being highly transparent, most glass surfaces have an approximately 4% reflectance rate. In the cases where glazing with low reflectance rates are needed, ARCs are effectively used, as stated in many recent studies. By optimizing the composition and thickness of ARCs, reaching a desired solar reflectance and transmittance level can be achieved. (Grosjean, Soum-Glaude, Neveu, & Thomas, 2018)

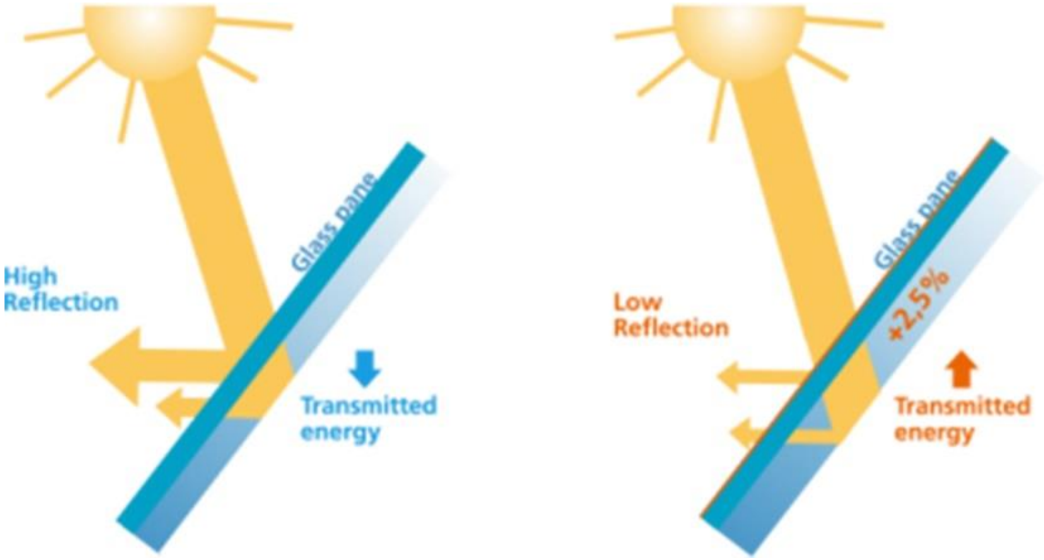


Figure 2. 13. The comparison of an uncoated standard glass pane and a glass pane with anti-reflective coating. (Source: https://www.fsolar.de/en/ultra-durable-ar)

However, the performance of ARCs is based on the wavelength of light and the angle of incident rays, meaning most coatings are designed for either thermal or visual reflectance reduction. Therefore, it must be considered that by reducing solar reflection via ARCs, solar energy absorbed by and transmitted through the façade also increases. Since this is a mitigation solution applied post-construction, these additional heat gains were not included in the design process of HVAC systems and could lead to occupant discomfort. Another important factor to consider while choosing this method is that applying ARCs requires manual labor, regular maintenance, and replacements over the years, implying significant costs. (Danks et al., 2016b)

2.5.2. Blocking solar reflection

Obstructing the reflection path could be easier and more cost-effective compared to modifying the problematic surfaces. Another advantage of this method is that this could be done on the façade itself or along the path of reflection before reaching the surface. The shading devices could be in many forms and sizes in requirement of blocking the sun rays before hitting the surface or shortly after being reflected. While implementing shading devices, added structural load, façade wind loading, ice, and snow build-up and aero-acoustical effects should be considered in order to avoid causing more problems.

Although it is preferred to block sun rays as close as possible to the façade, in some cases, it is preferable to use obstructions in the pedestrian realm such as canopies, umbrellas, vegetation or even billboards. However, this approach comes with its difficulties as well. Due to the focal point movements throughout the year, it could become unfeasible to cover all the problematic areas and it could lead to significant heat gains in the obstruction elements, even enough to pose danger to people and vegetation around it. (Danks et al., 2016b)

2.6. Existing Tools to Measure Solar Reflectivity

As mentioned above, there are major risks caused by solar reflection. However, there is little concern given by architects or governing bodies during both in early design phase or approval phase. The reason for that may be linked to the lack of tools to measure solar reflectivity precisely or existing methodologies being quite time consuming and expensive. It may also be related to the fact that solar reflection caused by complex forms and highly reflective materials is a new phenomenon. (Danks & Good, 2016).

There are basically three different options being used to determine the impacts of solar reflection; geometric approaches, rendering approaches and computational fluid dynamics approaches. Geometric approach is the simplest and most laborious technique that has been used. It is basically relied on the geometrical relation between the sun, the reflective surface and a viewer. This approach is a trial-error system that estimates the problematic areas by creating diagrams point by point. A more complicated approach used for analyzing solar reflection is based on rendering. The most common software used is Radiance, either on its own or a part of a package such as DIVA-for-Rhino or OpenStudio. Despite being highly effective in estimating light reflectance using indoor glare metrics, it has several drawbacks when it is computing exterior reflectance. These disadvantages could be listed as; steep learning curve on using the software, requirement of detailed data for materials' physical features and operating quite slowly due to its complex calculations. And the latest tools that have been used in determining solar reflectance are CFD packages such as Star-CCM or Fluent. Despite being a highly advanced tool, there are also have drawbacks to this method, too. These software packages are able to include solar radiation and reflectance of materials to predict the temperature of surfaces. However, surface temperature is dependent on various and unpredictable factors such as local wind speeds and ambient temperature of the area. These transient factors make it impossible to give a precise result and directing the designers into a false path in the early design phase. Furthermore, CFD tools require an enormous computational effort and money, especially for complex building forms. (Danks & Good, 2016)

In conclusion, as it is stated by Freitas, et al. (2015) that these tools are becoming more enhanced with the help of developments in information technology, as they require great computational power. Each new method has the ability to overcome previous limitations. However, the current methods for assessing the environmental impacts of solar reflection are incapable of delivering precise results regarding the intensity and the location of solar reflectance convergences, considering complex geometries of the building and its surroundings and taking into account of visual or thermal requirements of locations where solar reflectance is expected to fall. Therefore, inevitable cases around the globe have emerged and caused major discomfort to the environment as discussed in the section below.

CHAPTER 3

CASE STUDIES

Infamous case studies around the world are gathered and analyzed from the viewpoint of solar reflectivity and its consequences. The four selected cases were chosen due to their architectural significance and magnitude of their problems. They have been considered as architectural sins due to their flawed design and referred to as ‘death rays’ by the media. The first one may be considered as the most substantial case due to several reasons such as posing one of the earliest problems of solar reflection phenomena, being considered among the most notable buildings of an architectural movement and designed by Frank Gehry, arguably one of the most renowned architects of modern architecture. The second and third buildings have enormous negative effects on the environment, especially on the people who used the vicinity of the building while sharing a thought-provoking feature of being designed by the same architect. Therefore, the buildings and the architect himself are highly covered by the media, exposing the inadequacies of building codes and the attitudes of designers and developers towards this topic. And the final case is also highly publicized for not only its harmful impacts on the environment but also on the neighboring building which is a sculpture gallery containing a world-class collection of artworks by modern and contemporary masters and designed by another great modernist architect, Renzo Piano. These cases have been discussed in greater detail in the following sections, explaining the problem and mitigation solutions that were suggested, tried and applied.

3.1. **Walt Disney Concert Hall**

Building Information

Location: LA, California, USA
Architect: Frank Gehry
Construction date: 1999-2003
Building Function: Concert Hall
Building Mass: Concave/Convex
Building Skin: Stainless steel/
Polished steel

Figure 3. 1. Southwest view of Walt Disney Concert Hall with the building information. (Source: http://blogging.la/2010/08/15/la%E2%80%99s-greatest-landmarks-walt-disney-concert-hall/)

Designed by one of the most renowned architects of present day, Frank Gehry, the building was completed in 2003. Schiler and Valmont (2005) note that Walt Disney Concert Hall is a landmark which is partly building and partly free form sculpture. The complex includes an office wing that is clad in limestone, two amphitheaters and and two buildings clad in stainless steel, which is mostly a free standing curtain or a skin. Most of the stainless steel surfaces are curve composed of both convex and concave waving surfaces as can be seen in Figure 3.1.

The Problem

The iconic building had gained worldwide admiration and fame, however, soon after its completion date, difficulties in its vicinity started to emerge. While Frank Gehry was designing Walt Disney Concert Hall, he did not foresee the ramifications of this curved undulating façade which is completely composed of convex and concave surfaces.

As stated by Schiler (2009), in the original design, the façade was to be built with white limestone, but later it was replaced with stainless steel, which has similar or lower reflectance rate than limestones. Therefore, the environmental impact report was passed and the construction period was started without further consideration of possible impacts on the surroundings. However, the stainless steel has a higher specularity rate that was not taken into account. This mistake led to quite harmful results due to not only the overall higher reflectance façade but also concentration of light beams into singular points creating thermal hotspots in the neighborhood due to its curved form.

Figure 3. 2. Close up photograph of curved surfaces of Walt Disney Concert Hall. (Source: https://www.thoughtco.com/gehry-responds-to-concert-hall-heat-178089)

The Solution

Due to the extent of its harm to the surroundings and inhabitants of neighboring buildings, some measures to prevent this problem had to be taken. To analyze the glare and where on the surfaces it concentrates, the histograms of several photographs were analyzed to measure the ratio of peak illuminance to the background luminance. Consistent results that showed luminance levels exceeding 12,000 cd/m2 were problematic and indicated glare, as shown in the figures below in a color coded scheme. (Schiler & Valmont, 2005)

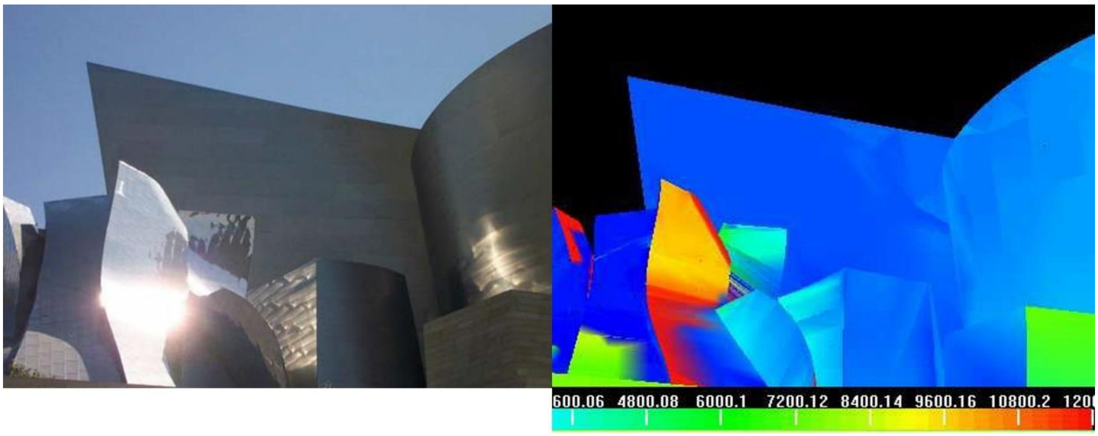


Figure 3. 3. Photograph and isoluminance plot of Walt Disney Concert Hall. (Source: Danks and Valmont, 2016)

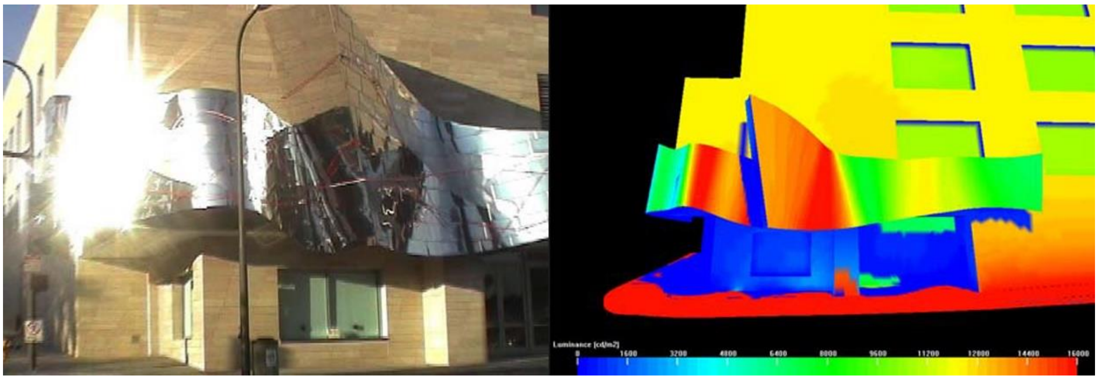


Figure 3. 4. Photograph and isoluminance plot of Walt Disney Concert Hall. (Source: Danks and Valmont, 2016)

Several solutions to decrease specularity and eliminate solar reflection were suggested and tested, however only two of them were found to be reasonable because of their high effectiveness and low interference with the original architectural design. As listed by Schiler and Valmont (2005), the major solutions suggested were:

1. Use of Vegetation: The first solution that was rejected was to surround the problematic surfaces with vegetation. However, there was some indication that the reflection was also killing plants and some of the problematic areas were much higher than the normal tree heights.
2. Using Paint: The second solution that was also rejected was to use paint with low reflectivity values. But, it was not accepted by Frank Gehry as it was contradicting the major design concept.

3. Using Surface films: To lower the specularity rate of stainless steel, using surface films were suggested. Six different surface films were tested and three of them were found acceptable. Yet again, this solution was not applied.
4. Using Fabric: The first applied solution was fabric coating, which was a reasonable solution to diminish the reflectivity, but not in terms of durability. Chong (2004) states that the temporary solution of fabric covering to the most disturbing areas cost 6,000 dollars before the sandblasting solution was applied. Also, this solution provided verification of the problematic areas since further analysis had to be conducted before its application.

Figure 3. 5. Application of fabric covering to the problematic surfaces. (Source: Schiler and Valmont, 2005)

5. Using Sandblasting: The best one solution offered was a combination of vibrational sanding and orbital sanding in order to achieve not only an aesthetic visual effect but also a long-lasting solution. Several treatments were applied on sample areas and measured with a gloss meter. Two of them showed the greatest benefits, which were achieved by using a 220 grit vibrator sanding at shallow angles, 110 grit vibrator sanding at steeper angles. Therefore; vibrator sanding was used as a base treatment, after that orbital sanding was applied due to aesthetic reasons. Also, it was not necessary to treat the entire panels,

thanks to their curved forms, so only a portion of the panels were sanded creating stair-step patterns in some areas. Glastier (2004) states that the surface area of sandblasted panels were 370 m2 of total 19,000 m2 area, costing over 180,000 dollars. Additionally, Burbank (2005) reports that there are 12,500 individual metal pieces on the surfaces of the museum while only 833 panels had to be treated with mitigation techniques.

Figure 3. 6. Various surfaces of Walt Disney Concert Hall with different remediation techniques: fabric covered, brushed and sanded next to the original polished surface. (Source: Schiller and Valmont, 2006)

3.2. **20 Fenchurch Street**

Building Information

Location: London, UK
Architect: Rafael Vinoly
Construction date: 2010-2014
Building Function: Commercial
Building Mass: Concave
Building Skin: Glass Curtain Wall
Building Height: 160 m.
Energy Label: BREEAM Excellent

Figure 3. 7. Southeast view of 20 Fenchurch Street, also known as 'Walkie-Talkie' with the building information. (Source: https://www.cbre.co.uk/services/industries-and-specialties/london/investment-properties-highlight-transactions/articles/20-fenchurch-street-ec3)

20 Fenchurch Street is located in the financial district of London and has become one of the most prominent landmarks of the city due to its 160 m. height and unique shape, joining the other landmarks of the city such as the Gherkin, the Shard and the Cheesgrater. This distinctive top-heavy form has been nicknamed 'Walkie-Talkie' by the people, but later it was changed to 'Walkie-Scorchy' due to its scorching effects on the environment. (Marszal, 2014) Designed by a world-renowned architect Rafael Vinoly, the construction of Walkie-Talkie ended in 2014. However, before its completion date, it was considered as an "architectural sin" due to the news item exposing the highly powerful glare effect of the façade and nominating it as the worst building in the UK. (Blair, 2015)

The Problem

The south façade of 20 Fenchurch Street has a concave shape covered with highly reflective glass panes, acting as a parabolic mirror. The reflected sun light converges in a hotspot across the street as could be seen in the schematic illustration below (Zhu, Jahn, & Rein, 2019). It is indicated by the developers of the building that the temperature reaches to 91.3°C on the exposed surfaces and the effects last two hours of the day for two to three weeks a year due to the sun's path. However, the occupants of the surrounding buildings and pedestrians experience discomfort more than that. (Verity, 2013)

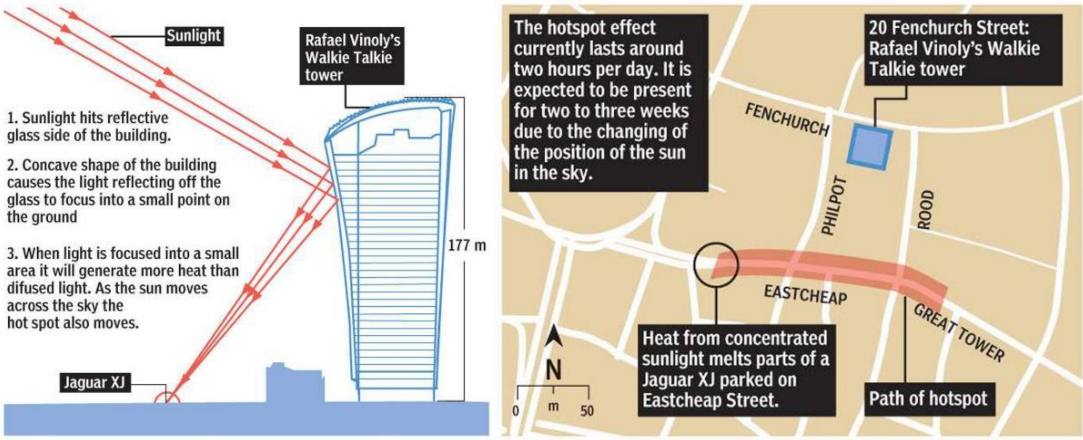


Figure 3. 8. Schematic drawings of the area where solar reflection impacts. (Source: https://nationalpost.com/news/london-skyscrapers-deathray-reflection-is-melting-cars-burning-businesses-but-also-cooking-eggs)

Frearson (2013) reports that Rafael Vinoly accepts his fault and further explains that they had foreseen the problem however, they were unable to determine the precise effect without the necessary tools or software. He also elaborated that they predicted the temperature would rise to 36°C at its maximum, while the real number is up to 72°C where the solar reflection hits, causing significant visual and thermal discomfort that could even melt the body of a car.

Figure 3. 9. The glare reflecting from Walkie-Talkie and the hotspot created by this glare across the street. (Source: https://www.dailymail.co.uk/news/article-2409710/Walkie-Talkie-building-melting-bicycles-Light-reflected-construction-City-skyscraper-scorches-seat.html)

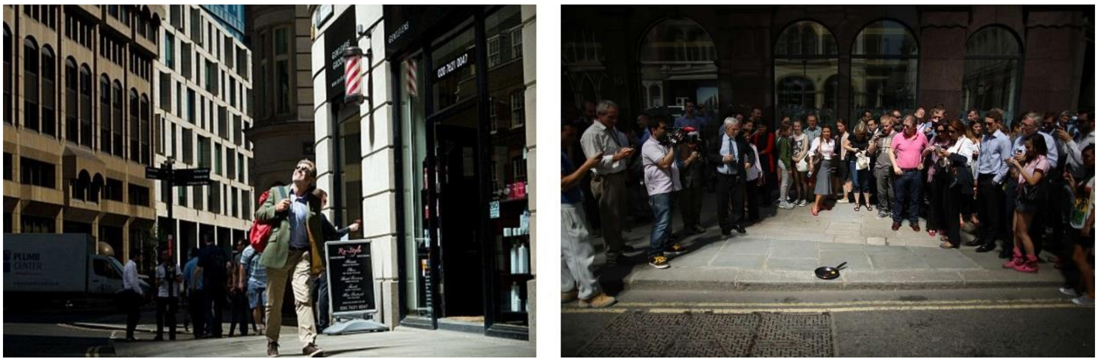


Figure 3. 10. People on the hotspot created by the glare of Walkie Talkie. (Sources: a) https://www.dailymail.co.uk/news/article-2786723/London-skyscraper-Walkie-Talkie-melted-cars-reflecting-sunlight-fitted-shading.html and b) https://nationalpost.com/news/london-skyscrapers-deathray-reflection-is-melting-cars-burning-businesses-but-also-cooking-eggs)

As it was noted by Bornoff (2015), this highly news-worthy case was modelled in a newly developed CFD tool FloEFD by implementing the building form, material properties, the environment and the car, exactly the same in the simulation. The results that supported the incidence of car damage due to the reflected heat from the building are represented in the figure below. The color coded image shows the total heat flux on solid surfaces.

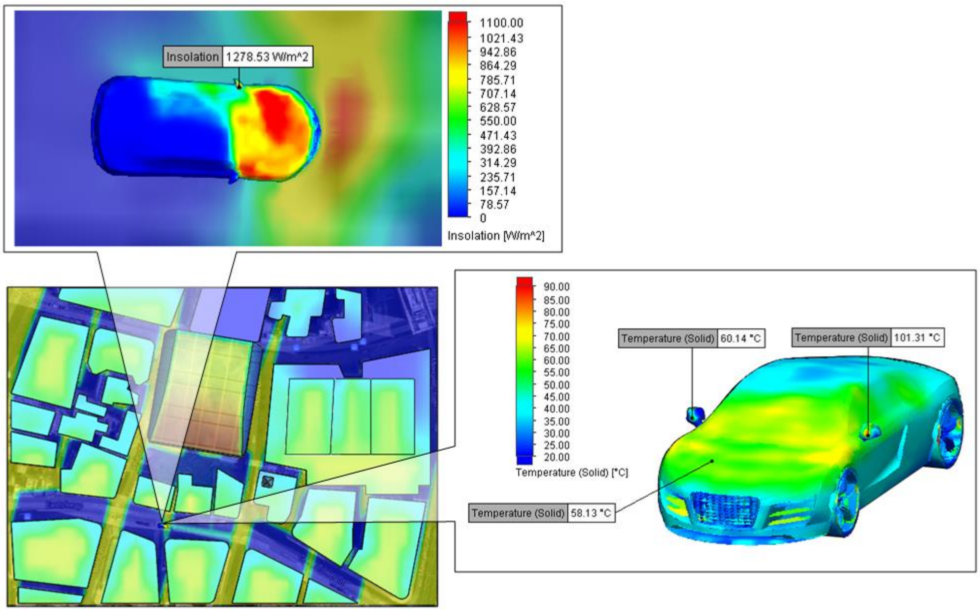


Figure 3. 11. Thermal image of the buildings and the car that was affected by the solar radiation. (Source: https://blogs.mentor.com/robinbornoff/blog/2015/03/05/angry-building-melts-car-with-focused-sunlight-weapon/)

The Solution

It is reported that the developers decided to use brise-soleil shading devices, in order to absorb and diffuse sun light, thus preventing it from being reflected. The brise soleil consisted of horizontal aluminum fins, which was designed by the architect and solar glare experts, and placed from the third floor up to the 34th floor, nearly covering all of the south façade. They announced the cost of the project as nearly £10 million and the construction phase lasted 6 months.(Morby, 2013)

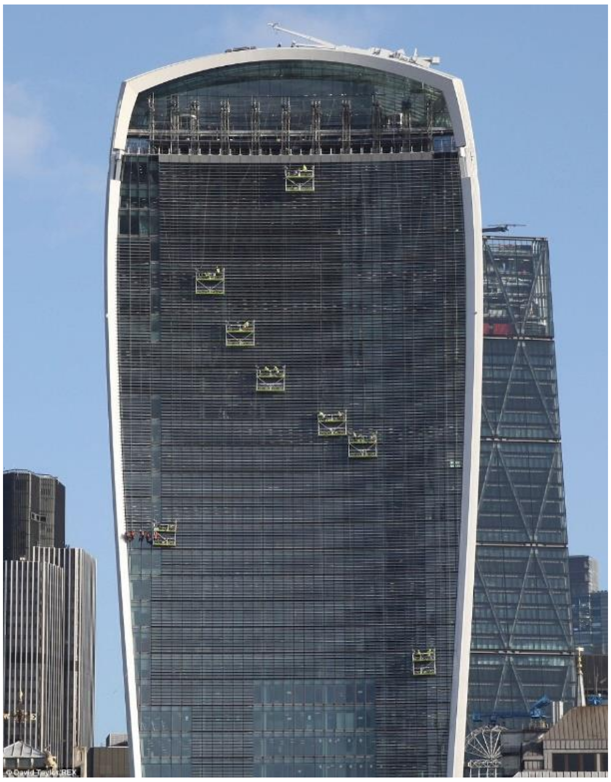


Figure 3. 12. Brise soleil installation on the south façade of 20 Fenchurch Street. (Source: https://www.dailymail.co.uk/news/article-2786723/London-skyscraper-Walkie-Talkie-melted-cars-reflecting-sunlight-fitted-shading.html)

3.3. **Vdara Hotel**

Building Information

Location: Las Vegas, Nevada, USA
Architect: Rafael Vinoly
Construction date: 2006-2009
Building Function: Hotel
Building Mass: Concave
Building Skin: Glass Curtain Wall
Building Height: 170 m.
Energy Label: LEED Gold

Figure 3. 13. Vdara Hotel with the building information. (Source: https://www.dailymail.co.uk/news/article-1315978/Las-Vegas-hotel-death-ray-leaves-guests-severe-burns.html)

The building is located in Las Vegas Strip in Nevada, USA and was completed in 2009 as a part of a mixed use urban complex. It has 57 stories reaching the height of 170 m. Designed by none other than the architect of 20 Fenchurch Street, Rafael Vinoly, which can not be considered as a coincidence, the building has three different sections sliding onto each other creating sleek and curved façade. The crescent shaped form of the building is defined by the three parallel arcs with varying heights by recessing from one another. The horizontally striped façade of the hotel is a combination of alternating bands of reflective glass and acid-etched spandrel glass in black and white. (Lomholt, 2019)

The Problem

The building had received several prestigious international awards and a LEED Gold certificate, however it did not stop it from being considered as an "architectural sin" and referred to as a 'Death Ray'. Sustainable features that aimed to reduce urban heat island effect such as light colored surfaces on pool deck and roof turned out to be the contributers to the problem. The fully glazed concave façade causes a major discomfort which is reflecting light beams and converging light onto a specific area creating hotspots. (Whitely, 2010)

Figure 3. 14. The scorching glare of Vdara Hotel. (Source: https://www.businessinsider.com/the-vdara-death-ray-hotel-is-still-burning-people-in-las-vegas-2016-6)

In this case, the affected area was the hotel's swimming pool. As stated by Montes-Amorros (2015), the temperature rise in the affected area is measured as 11.1°C creating an un-inhabitable area at certain times of the day for the customers of the hotel. Hotel guests claimed that the pool was affected by the glare, which also singed their hairs, burnt their skins and melted plastic bags and cups, making it impossible to use the pool during majority time of the day.

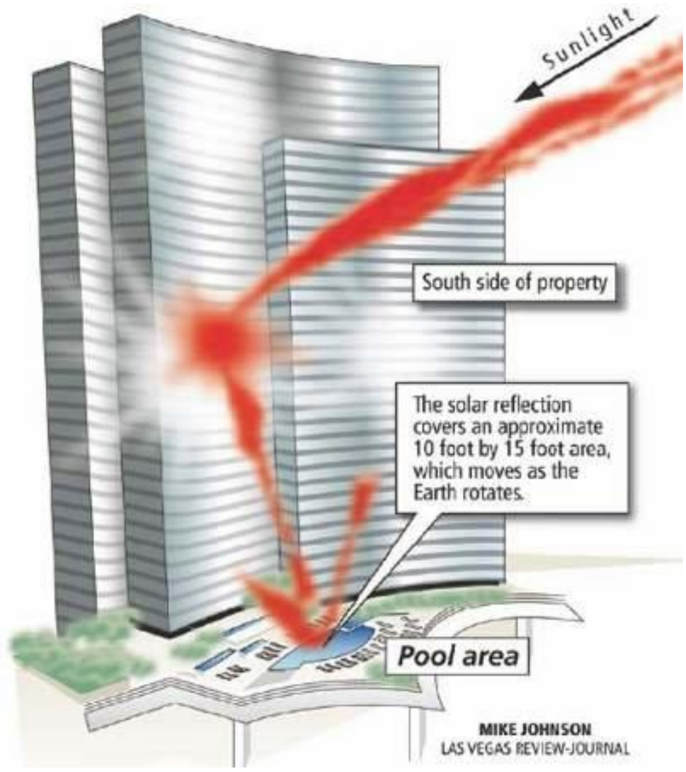
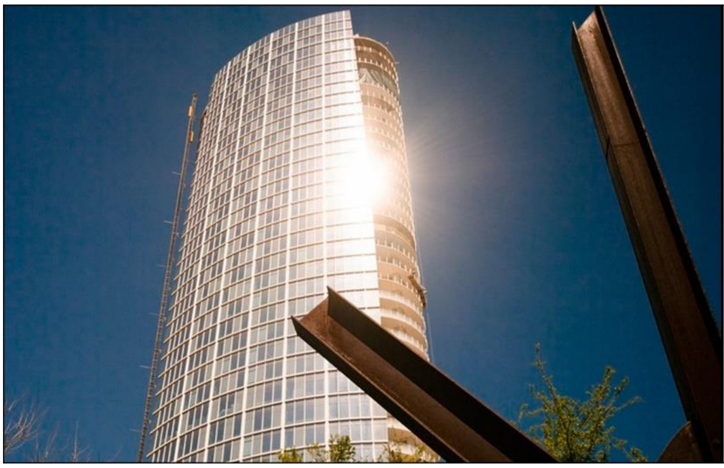


Figure 3. 15. The diagram of sunlight reflecting from concave façade of the hotel converging on the pool area. (Source: Montes- Amorros, 2015)

The Solution

Even though, during the construction stage, in 2008, 3000 glass panes from the façade that face the pool were covered with thin films in order to prevent the effects of sun light, which makes it clear that façade designer did foresee the problem, it was not effective. Increasing complaints from guests at the hotel led to another ineffective and temporary solution that is covering the pool area with giant umbrellas. (Garfield, 2016)

3.4. **Museum Tower**



Building Information

Location: Dallas, Texas, USA
Architect: Scott Johnson
Construction date: 2010-2013
Building Function: Residential
Building Mass: Convex
Building Skin: Glass Curtain Wall
Building Height: 171 m.

Figure 3. 16. Glare reflecting from the convex façade of Museum Tower with the building information. (Source: https://www.dailymail.co.uk/news/article-1315978/Las-Vegas-hotel-death-ray-leaves-guests-severe-burns.html)

Museum Tower is located in Dallas Arts District in Texas, USA, reaching the height of 171 m. with 42 stories. The building is designed as a residential complex by Johnson Fain Partners and the construction is completed in 2013 costing over $200 million. It has an elliptical floor plan consisted of 4 living units with direct access to the elevators. This elliptical floor plan gives form to its sleek concave façade which later become the main factor that leads to solar reflection.

The Problem

This fully glazed convex façade led to intense solar reflections causing both visual and thermal discomfort to its surroundings. Its convex façade is causing diffused solar reflection which is not similar to convex façades converging light beams into singular hotspots, as can be seen in Figure 3.17. While creating visual and thermal discomfort for its surroundings, the most affected building from this problem is Nasher Sculpture Gallery and its garden, which also functions as an outdoor display area, and which is located right across the street from Museum Tower. (Abdelwahab, Elhussainy, & Labib, 2019)

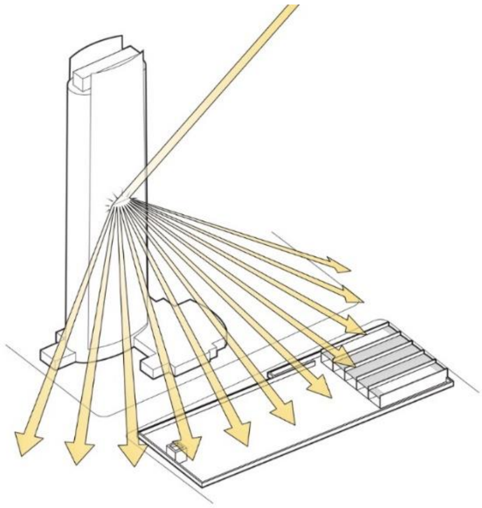


Figure 3. 17. Diagram of sun lights reflecting from convex façade of Museum Tower into Nasher Sculpture Center. (Source: https://rex-ny.com/project/surya/)

To be able to understand the magnitude of the problem in this case, the building that causes solar reflections and the one that affected by it should be studied together due to its architectural significance since; it is designed by Renzo Piano, one of the most celebrated architects of our time.

Nasher Sculpture Center

According to Abdelwahab, Elhussainy and Labib (2019), the museum has 5 identical and parallel rectangular pavilions whose volumes are divided by walls. The feature that intensifies the problem of solar reflectivity is its original and patented roof design. The ceiling of the museum consists of 5 glass vaults placed on top of the walls that are dividing the space, while extending over the pavilions. An aluminum shielding system which consists of 223,020 three dimensional elements called occuli is located above these glass vaults, which can be seen in Figure 3.18. The aluminum occuli that function as a sunscreen are designed only to let soft light into the museum according to the exact longitude and latitude of the museum and sun path diagram of Dallas for every hour of every day in a year,. This feature creates visually pleasing and safe display conditions for artwork, since it is exposed to the harsh climate of Dallas. (Rogers, 2012)

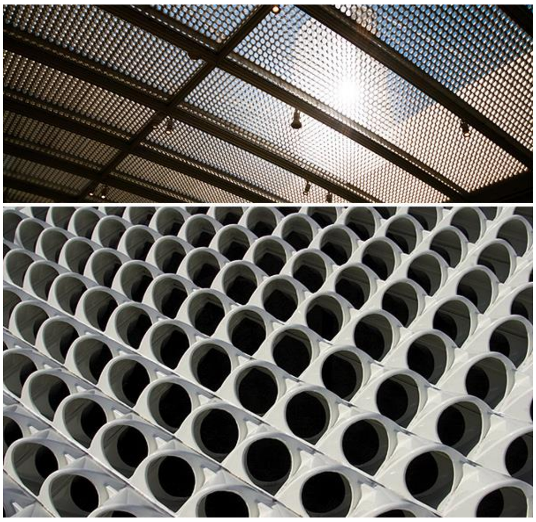


Figure 3. 18. The patented oculi from inside and outside of Nasher Sculpture Center. (Source: https://www.dmagazine.com/publications/d-magazine/2012/may/museum-tower-the-towering-inferno/?single=1)

The controversy of Museum Tower might not be the most discussed one due to the size of its effect but it certainly has raised great concern among the community of arts district because it has the potential to destroy the art objects. The museum is designed with a perforated roof surface in order to bring natural light to accentuate the art works. However, the tower is located near the museum and sending light beams directly onto it, conflicting the very idea of the museum's design concept. As can be seen in the figure below, very important works of art, such as paintings by Picasso and sculptures by Rodin are being affected by this solar reflection from the problematic building. (Pogrebin, 2012)

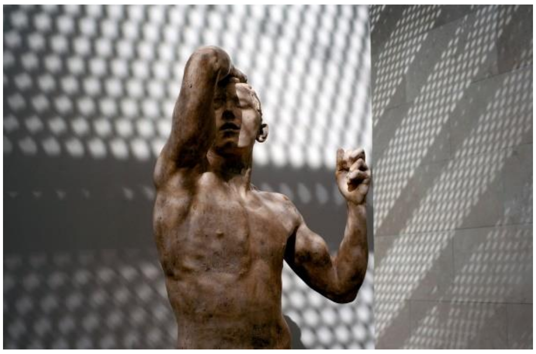


Figure 3. 19. Glare penetrating through oculi and resting on Rodin's 'Age of Bronze'. (Source: https://www.nytimes.com/2012/05/02/arts/design/renzo-pianos-nasher-museum-in-dallas-has-sunburn-problem.html)

The Solution

Granberry (2016) reports that the Museum Tower case has also remained unresolved due to the conflicts between the developers of the tower and the architect of the art gallery, Renzo Piano. Several methods have been discussed between the developers of Museum Tower and the museum officials and over $1 million has been spent on research and project development. During the process, four major proposal were suggested in order to minimize the effects of solar reflection but they were all rejected for different reasons:

1. Using Spray: Spraying a nanotechnology material used in military vehicles to diffuse light was proposed and tried onto the façade by the developers yet the results were not promising.
2. Revisions to the Nasher roof: The developers also suggested that the cone-shaped perforations of the roof should be reoriented. Both the officials of the museum and Renzo Piano rejected this proposal due to architectural concerns and also since this proposal disregards the damage to the garden.
3. Using Louvers: Nasher officials suggested that 1000 glass panes of the façade could be covered with computer controlled louvres reacting according to wind and sun in order to prevent the glare. However, it was denied due to its added structural load and cost of $7.5 million.

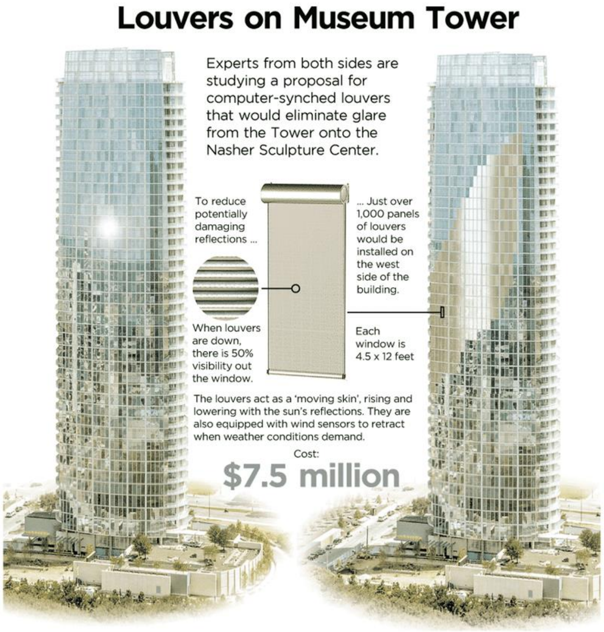


Figure 3. 20. Louvre proposal for the façade of Museum Tower. (Source: https://www.dallasnews.com/arts/museums/2016/09/25/fights-fantasy-fixes-fbi-museum-tower-nasher-still-odds-glare-five-years)

1. Constructing Surya: A new structure to prevent the glare reaching to the museum was suggested, which is the most unorthodox solution that has been discussed on this issue. Since, the common solutions were not efficient nor accepted due to architectural or structural considerations, the idea was put on a trial and commissioned to Rex Architects. The final version of the structure, which can be seen in Figure 3.22. is designed as a ferris wheel holding several umbrellas placed strategically to block the glare aiming at the Arts District with its original and functional design. According to the simulation results based on the sun-path along the façade and the height of the tower, the new structure has to reach 122 m height and be located at a high proximity to the museum, which raised concern from both Renzo Piano since it would overwhelm his design and developers of Museum Tower, since it would decrease the real estate value of condos. Also, the cost of this proposal which was kept confidential, may have been one of the reasons for rejection. (Granberry, 2016)

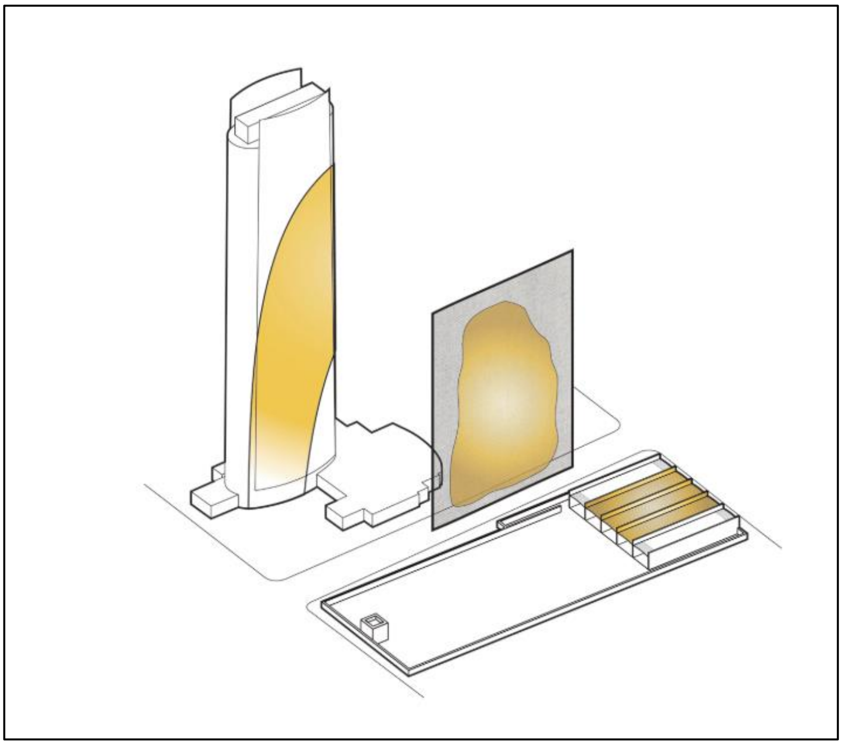


Figure 3. 21. Diagram of how the dimensions of Surya is determined according to the movements of glare on the façade. (Source: https://rex-ny.com/project/surya/)

Figure 3. 22. Rendering of Surya. (Source: https://rex-ny.com/project/surya/)

CHAPTER 4

MATERIALS AND METHOD

This chapter explains the two major parts of the study: materials and methodology. As material, the selected case from Ankara is analyzed in detail regarding its function, form and façade characteristics, building skin materials, architectural drawings and exterior photographs. In the first part, the chosen case study, the software and the equipment that are used in order to obtain the data is explained. In the second part, the method for carrying out the study is further explained.

4.1. Materials

To confirm the deductions that is made from literature review, a high rise building with a curved glazed façade in Ankara was chosen for further analysis. The aim was to analyze the solar reflection caused by a sample building. Therefore, a number of different materials that were used for this study which are listed below.

-Several websites to obtain building's architectural and constructional information

-Weather data to determine the ideal site visit dates

-Canon Powershot A3100 IS camera for exterior photographs

-Adobe Photoshop CC to adjust brightness and exposure levels of glare and to visualize solar reflection path and volume diagrams

-www.sunearthtools.com to obtain sun path diagrams

-Google Earth Pro to obtain the exact coordinates of the building

- Autodesk AutoCAD Architecture 2015 to determine the locations of hotspots and solar reflection paths that are created by sun rays reflected from the curved façade of Yıldırım Kule.

Case Study: Yıldırım Kule

Yıldırım Kule is designed by the collaboration of Fazlıoğlu Mimarlık and İki Derece Mimarlık. The construction was completed in 20015 by Fertaş Construction Incorporated Company. It is located on Konya Yolu highway that is considered as a north-south axis of Ankara. The building sits in a 46000 m2 area which is located at following coordinates: 39°52’56.4” N, 32°48’45.6” E.

Figure 4. 1. A rendering of Yıldırım Kule from northwest perspective. (Source: https://www.ozaymuhendislik.com.tr/pg_193_yildirim-kule)

The building functions as a mixed use building consisting of 108 offices, 25 stores and 2 ball rooms. The building façade is designed with a slightly concave, fully glazed form in a location that provides no obstructions to solar insolation, since it is located right across an open green area, METU Forest. This feature was an important criteria for selecting Yıldırım Kule as a case study in order to analyze the impact of solar reflectivity from its façade. In other words, there are no buildings in the vicinity that may cast shadows or solar reflections bouncing off of from their façades at any given time of the day.

Figure 4. 2. Northwest, west and southwest views of Yıldırım Kule showing its concave façade from different perspectives.

This 36 story building with a height of 130 m. has multiple typical floors due to its form that consists of four different section with different heights as can be seen in the figure above. The typical floor plan for each section gets smaller as it reaches to the next section and all of them have different numbers of office spaces which is showed in the figures below.

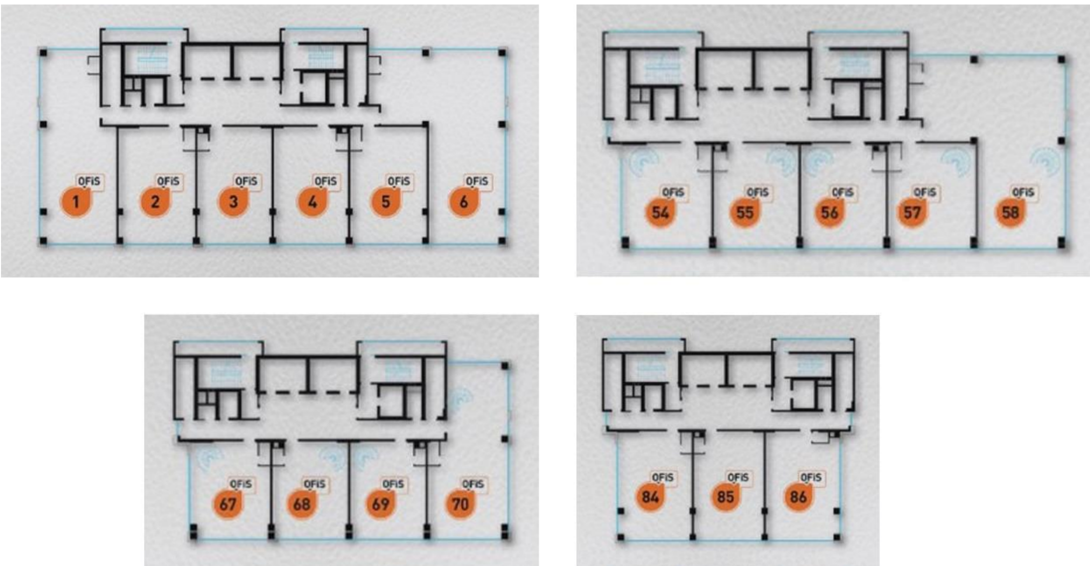


Figure 4. 3. Schematic drawings depicting the f our typical floor plans of Yıldırım Kule. (Source: http://www.remaxtower.com/proje/yildirim-kule)

The building skin of Yıldırım Kule was constructed by Reynaers Aluminum using their curtain wall product ‘Concept Wall 60 (CW 60)’. This product is specially designed for sloped or curved façades with the ability to carry large glazing units which makes it a great choice for the west façade of Yıldırım Kule. However, the glass used in CW60 is Guardian Sunguard Super Neutral 70/41 and High Performance Neutral 60/40 which carry high reflectance rates. Their detailed technical properties for both visible and infrared lights are shown in the table below.

Table 4. 1. Glass properties of the curtain wall façade of Yıldırım Kule.

	Visible Light Properties			Infrared Light Properties					Thermal Properties
	Transmission (%)	Reflection Outside (%)	Reflection Inside (%)	Solar Factor [g](%)	Direct Transmission (%)	Reflection Outside (%)	Absorption (%)	UV (%)	U Value (w/M2k)
Sunguard High Perfor-mance Neutral 60/40	60.10	24.60	20.10	40.50	38.00	35.30	26.70	32.90	1.10
Sunguard Super Neutral 70/41	70.00	11.00	12.00	40.95	39.00	33.00	28.00	27.00	1.12

(Source: https://www.guardianglass.com/tr/tr/products/markalar/sunguard/high-performance/neutral-60-40 and https://www.guardianglass.com/tr/tr/products/markalar/sunguard/superneutral/70-41)

4.2. **Method**

Ankara is a rapidly growing city where numerous high rise buildings have been constructed and are being under construction along the axes that divide the city from north to south and east to west. Being a capital and a financial center, Ankara is surrounded by tall buildings constructed with the purpose of commercial interest and state affairs which many of them located alongside these said axes. Especially on Konya Boulevard which is also known as Mevlana Boulevard and on Eskişehir Boulevard which is also known as İsmet İnönü Boulevard, there are a great number of commercial/office buildings with fully glazed façades which now can be considered as a city statement.

First of all, these axes that shape the city's growth are examined. After examining these axes and tall buildings located alongside these boulevards, several tall buildings with fully glazed façades and curved forms are identified due to the requirement of the research. As it is mentioned in the Materials section, Yıldırım Kule was chosen due to its form and reflective façade. Another important criteria for selecting Yıldırım Kule is that it is located rather isolated from other high rise buildings, away from surrounding reflections that may fall onto its façade. In the near vicinity, there are only low to mid-rise buildings and a large green area which can be seen in Figure 3.3. This feature helps to obtain more accurate results since it is quite easy to be affected by other glares when the building is located in a dense site surrounded by many high rise buildings. It also helps to get direct sunlight without any obstructions that may block sun rays from falling onto the façade.

Figure 4. 4. An aerial view of Yıldırım Kule with its surroundings. (Source: http://www.yildirimkule.com.tr/)

Five different dates were chosen in order to understand how the light reflects from the curved façade of Yıldırım Kule. These are March 21st being the spring equinox, June 21st being the summer solstice, September 23rd being autumnal equinox and December 22nd being the winter solstice; the fifth date was selected for being a suitable day when the data on reflections and glare calculated from the façade geometry could be supported by visual data from photographs demonstrating solar reflection problem. As a first step, before the site visit, the local weather data was acquired in order to understand the weather conditions. Thus, hourly weather data for a period of time in August was collected from https://tr.fremeteo.com website and 23rd of August was chosen as the most suitable day for observing solar reflection. Also, by using the exact coordinates taken from Google Earth Pro, chosen dates and hours and time zone for Turkey, a sun path diagram was generated on the website of https://www.sunearthtools.com/.

By analyzing sun path diagrams for the chosen dates, two different time periods were chosen; i.e. 3:00 pm and 6:00 pm. The reason for choosing 3:00 pm as a base point was because, on all of the evaluation dates, the sun rays began to fall on the curved façade around that time. Also, the rush hour on Konya Highway peaks at the time between 5.30 pm to 6.30 pm. Therefore 6.00 pm is chosen in order to evaluate the levels of glare discomfort, when it makes the most noticeable impact on the surroundings, in this case, the drivers commuting to their home from work. However, it should be noted that the glare effects exist all year round and their duration can change according to the various reasons.

During the site visit, several photographs were taken from different viewpoints with Canon Powershot A3100 IS camera in order to assess the intensity of glare forming on the façade and find the focal points that may occur in the reflection volume. Northwest, west and southwest viewpoints of the building were photographed at every hour to support the findings derived from the sun path diagrams.

After the site visit, the solar reflection path and volume were determined by using Autodesk AutoCAD 2015 in order to identify the problematic areas. To identify the path of solar reflection, elevation and azimuth angles of sunrays that were obtained from sun path diagrams were used. The pictures of sun path diagrams were inserted as raster images. The floor plan of Yıldırım Kule was also inserted and placed on top of sun path diagram in order to draw incoming sun rays at certain angles (azimuth angles). By drawing sun rays hitting falling onto the façade with and reflecting from the façade, the path of reflected rays was identified. This process was also repeated on the building's silhouette, in order to find focal points for the reflection volume. Due to the curved form of Yıldırım Kule, focal points occur on specific areas throughout the year. By drawing sun rays coming at specific angles (elevation angles) to the curved façade, focal points were created. Furthermore, the area between focal points occurring at 3.00 pm and 6.00 pm also constitutes the reflection volume. This process was repeated for every 3.00 pm and 6.00 pm hours of every date in order to understand the path of reflection and location of the focal points.

For a better understanding of the methodology used in this study, a flow chart was generated and can be seen in the figure below.

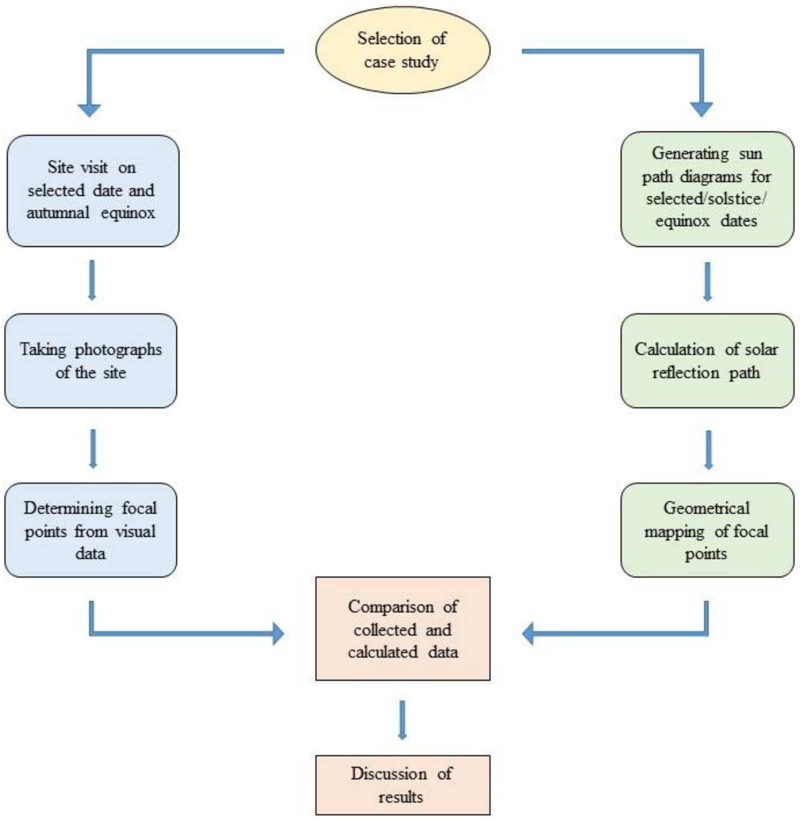


Figure 4. 5. A flow chart showing the steps taken during the study.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, the results from the selected date and solstice/equinox dates are presented and later evaluated. Moreover, the case studies around the world elaborately reviewed in Chapter 2 and the local case study from Ankara presented in Chapter 3 are compared with each other. Finally, architectural responsibilities that should be taken in order to avoid solar reflection problems are discussed.

5.1. Environmental Conditions

In this section, the accessed data and information on weather conditions such as air temperature, sensible temperature, humidity level, air pressure, precipitation and wind speed from ‘freemeteo’ website are presented in Table 5.1. This table shows ideal weather conditions to take photographs of the site and the building in order to observe the hotspots occurred in the vicinity and the glare reflected from the façade of the building.

Table 5. 1. The accessed weather data about weather condition.

Date	23.8.2019			
Hour	9.00 am	12.00 pm	15.00 pm	18.00 pm
Weather Condition	Clear	Clear	Clear	Partly Cloudy
Air Temperature (°C)	22	26	28	28
Sensible Temperature (°C)	21	26	27	27
Humidity (%)	48	35	31	34
Wind Speed (Km/h)	11	16	20	21
Air Pressure (mb)	1015.5	1014.8	1013.0	1012.6
Precipitation (mm)	0	0	0	0

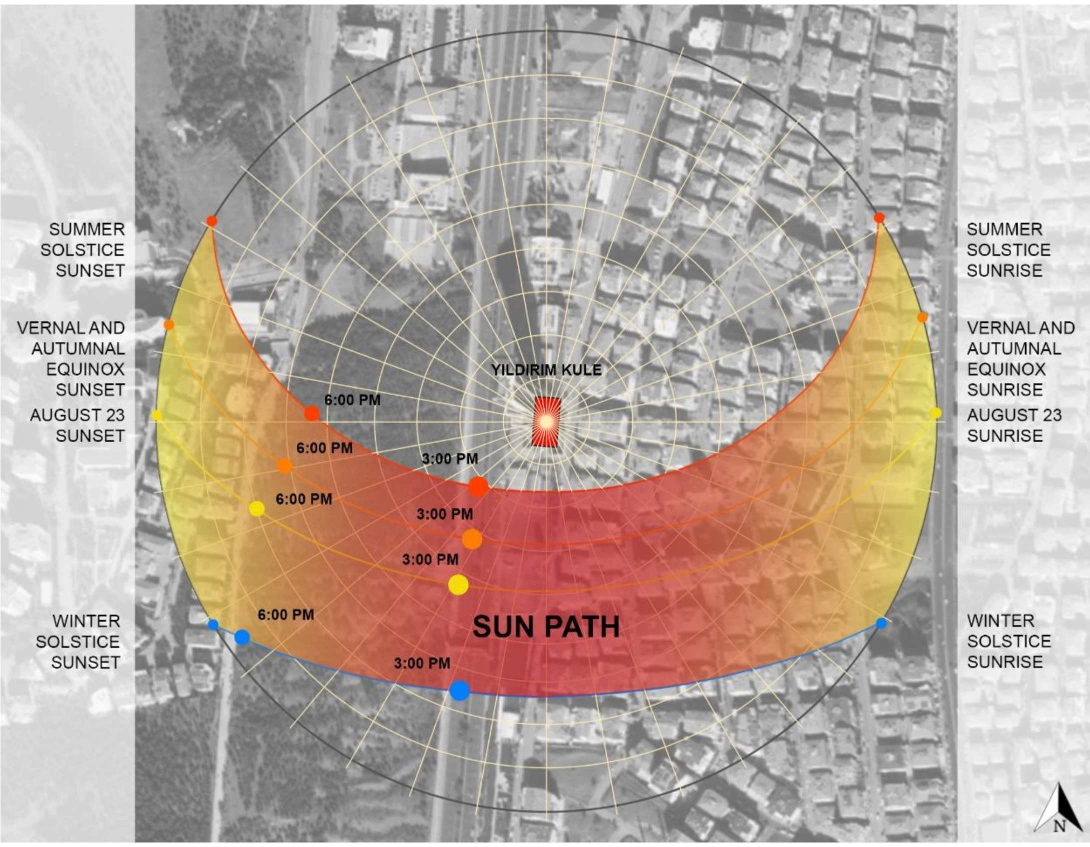


Figure 5. 1. Visualization of a sun path diagram for Yıldırım Kule

In the figure above, a sun path diagram for Yıldırım Kule, on the selected dates which are vernal and autumnal equinox, summer and winter solstices and August 23rd can be seen. It is visualized for a better understanding of the movement of the sun throughout the year. The position of the sun in the sky is marked with different colors for each selected time period. For each date, these marks show the position of the sun at sunrise, sunset, 3:00 pm, and 6:00 pm. Also, the sun path for the entire year is covered with a gradient color block suggesting the intensity of sun rays at noon with the color red and at sunrise or sunset with the color yellow.

Moreover, derived from the sun path diagrams generated for each scenario, elevation and azimuth angle of sun rays are listed in the table below and used to determine solar reflection paths and approximate locations of hotspots. The sun path diagrams for

August 23rd are shown in Figure 5.3. and Figure 5.4. while sun path diagrams for solstice and equinox dates are listed in Appendix A.

Table 5. 2. Table of elevation and azimuth angle of sun rays on the selected time periods that are obtained from the sun path diagrams.

Date	Time	Elevation Angle of Sun Rays	Azimuth Angle of Sun Rays
March 21st (Vernal Equinox)	3:00 PM	47.94	203.11
	6:00 PM	22.55	250.07
June 21st (Summer Solstice)	3:00 PM	68.36	225.38
	6:00 PM	36.14	271.79
August 23rd (Site Visit Date)	3:00 PM	58.06	211.50
	6:00 PM	29.14	260.15
September 23rd (Autumnal Equinox)	3:00 PM	46.45	208.11
	6:00 PM	19.61	252.50
December 22nd (Winter Solstice)	3:00 PM	24.58	197.62
	6:00 PM	4.03	234.63

5.2. **Results for site visit date**

As mentioned in the Method section, due to time limitations and clear weather conditions, 23rd of August is chosen for observing the solar reflections caused by the glazed façade of Yıldırım Kule. The orientation of the building according to the north direction is shown in the Figure 5.2.

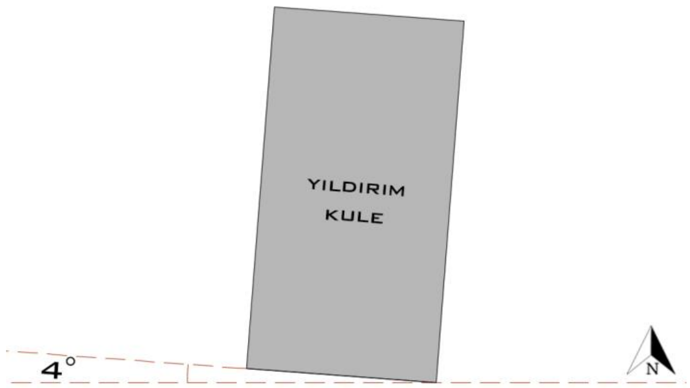


Figure 5. 2. The orientation of Yıldırım Kule according to north direction

The sun path diagrams generated for August 23rd are shown in the figures given below. The azimuth and elevation angles of sun rays and the position of the sun for that specific time period are marked in each diagram in order to highlight the data that were used in the next step.

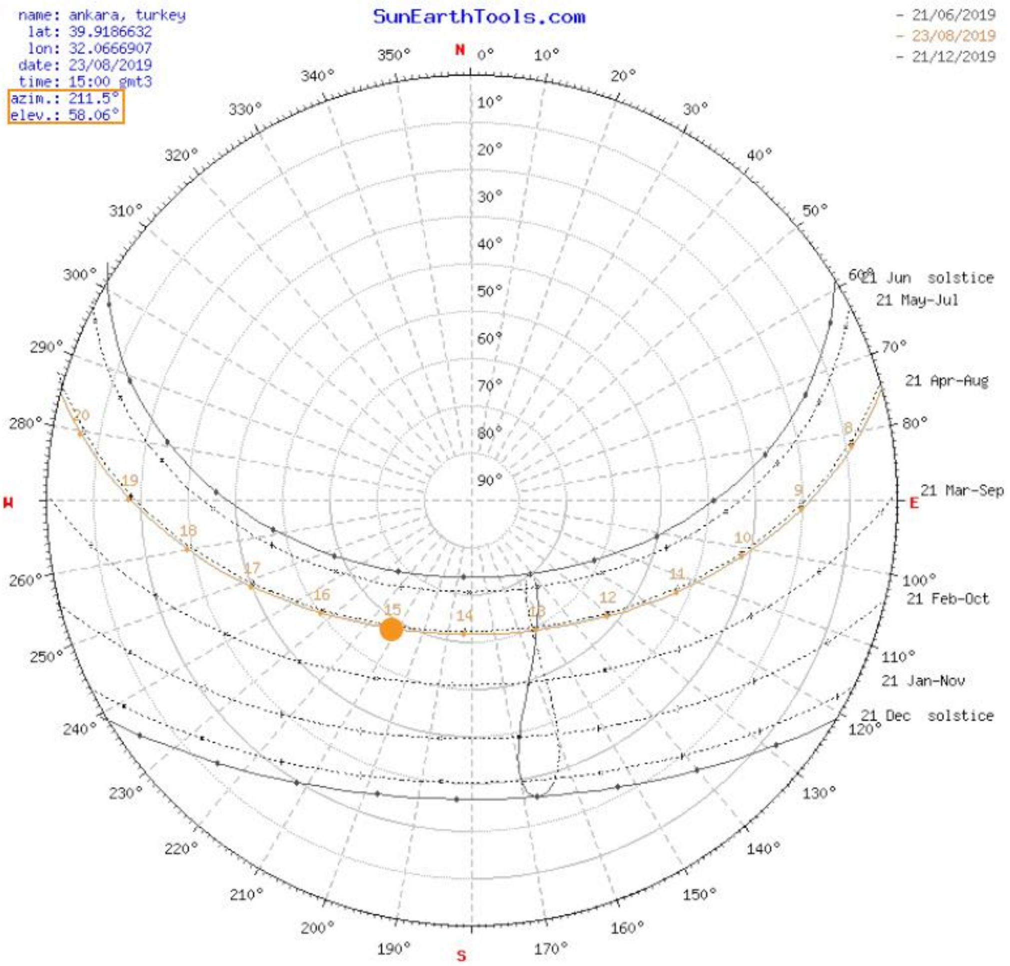


Figure 5. 3. Sun path diagram for 3:00 pm on August 23rd

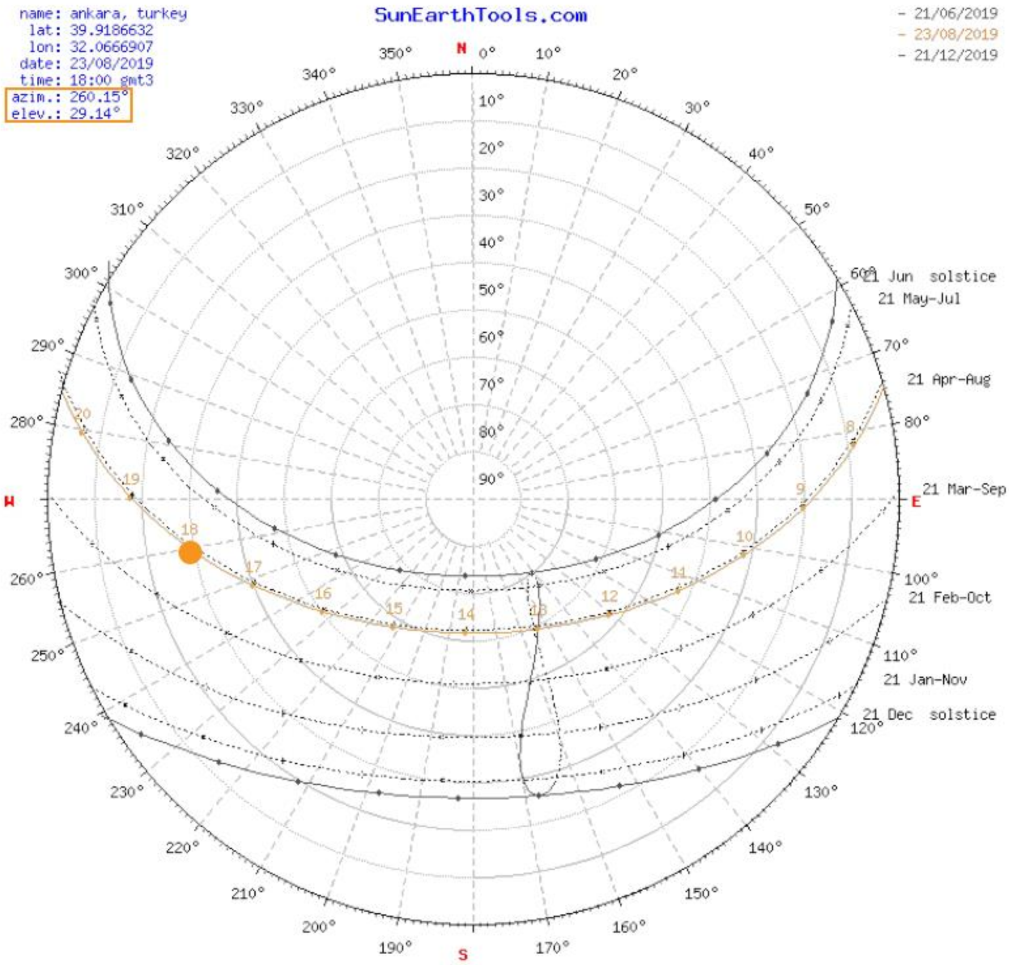


Figure 5. 4. Sun path diagram for 3:00 pm on August 23rd

Using the azimuth angle, the path of incident rays falling onto the façade and the path of reflected rays bounced off of the façade at 3:00 pm and 6:00 pm are drawn in Figure 5.5. and Figure 5.6. Later, these paths are combined in a single diagram which is Figure 5.10. to show the volume of sun rays traveled in the vicinity between these hours.

Figure 5. 5. Reflection path at 3:00 pm on August 23rd

Figure 5. 6. Reflection path at 6:00 pm on August 23rd

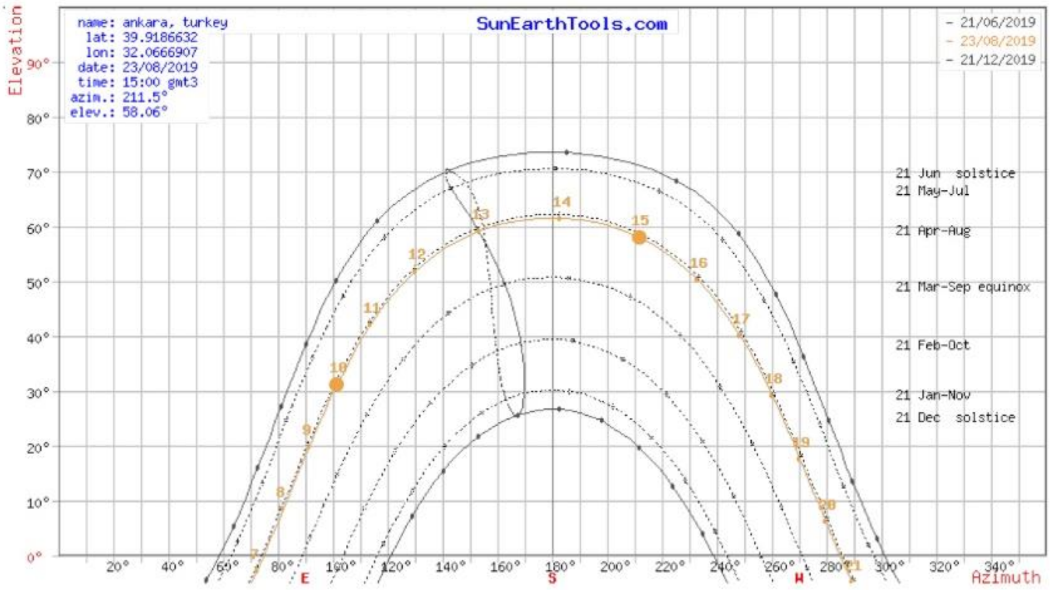


Figure 5. 7. Table of elevation and azimuth angle of sun rays at 3:00 pm and 6:00 pm on August 23rd

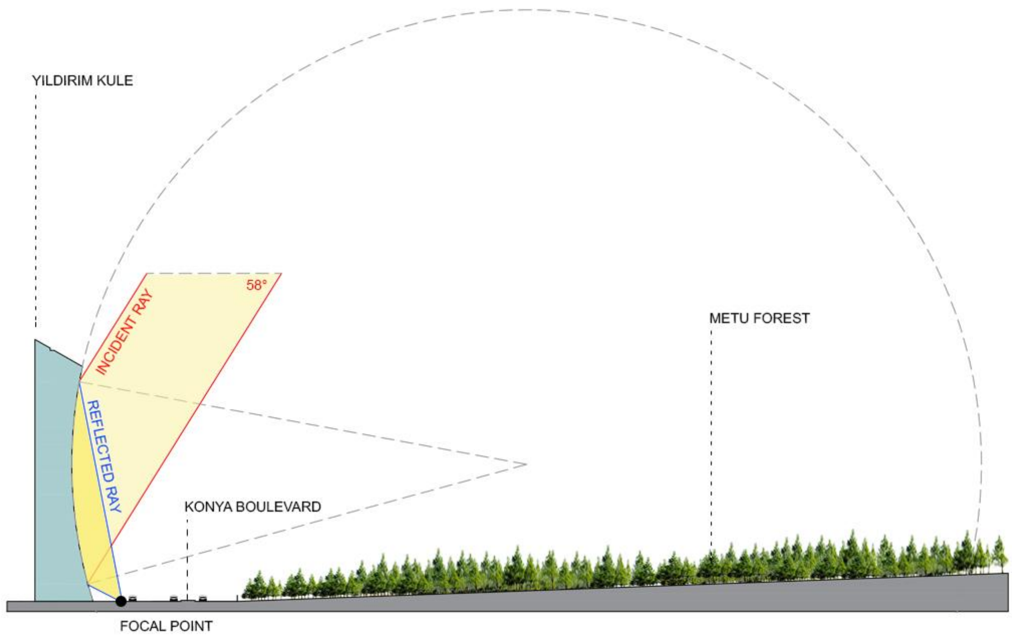


Figure 5. 8. Diagram of sun rays reflecting from Yıldırım Kule and converging on a focal point located on Konya Boulevard at 3:00 pm on August 23rd

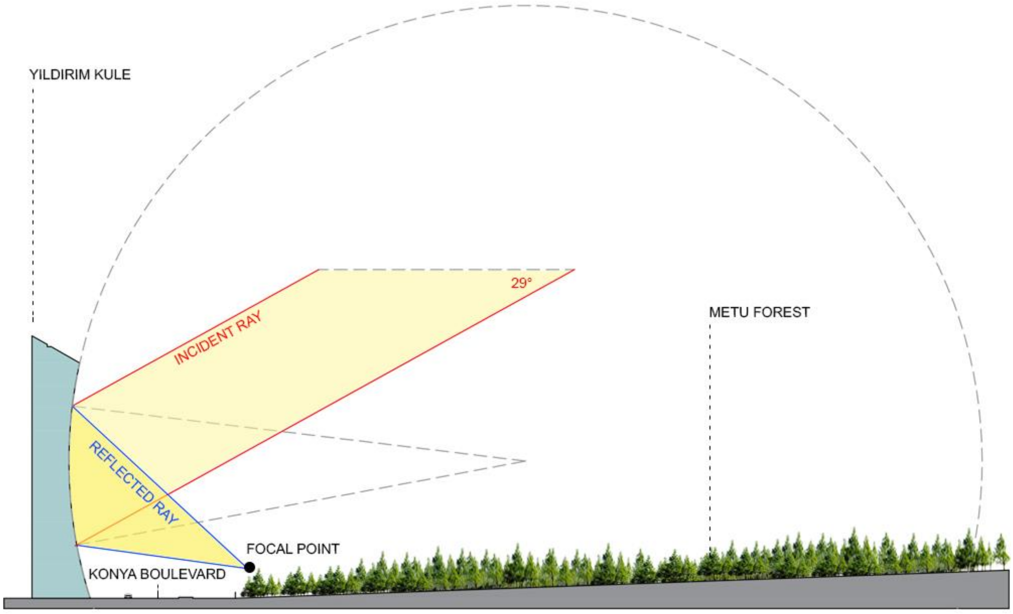


Figure 5. 9. Diagram of sun rays reflecting from Yıldırım Kule and converging on a focal point above METU Forest at 6:00 pm on August 23rd

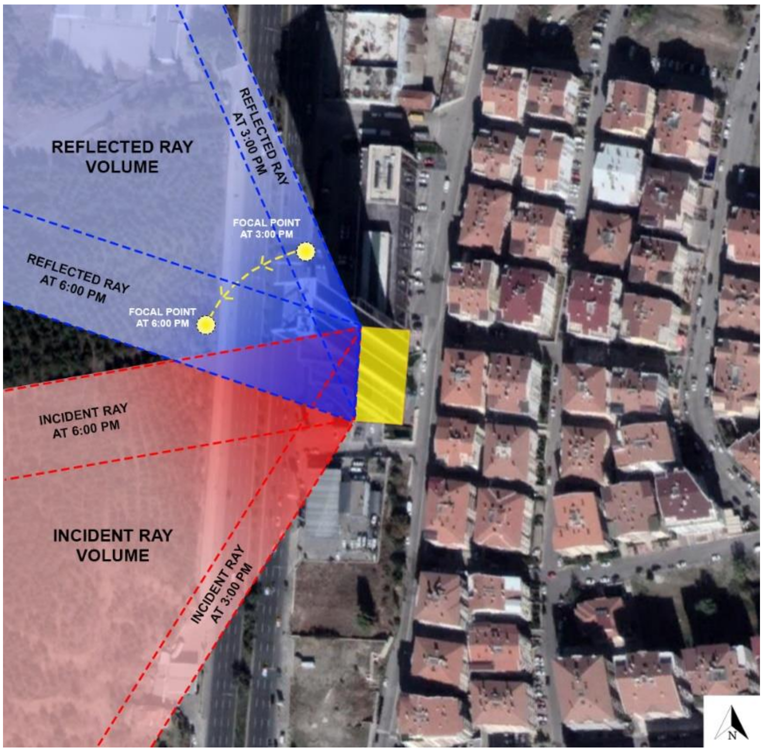


Figure 5. 10. Sun reflection paths and movement of focal points on August 23rd

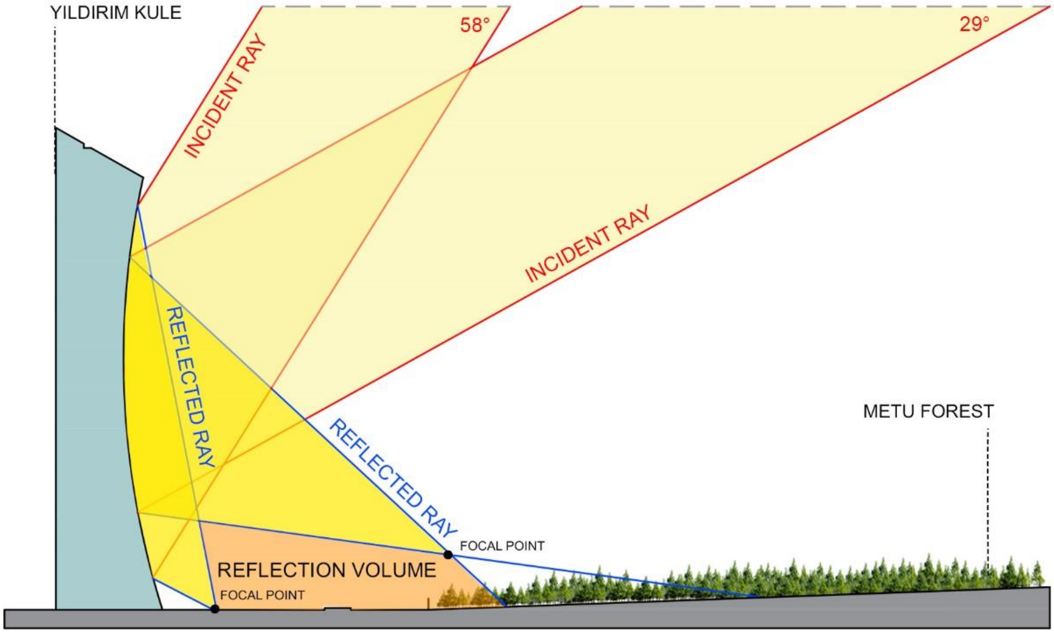


Figure 5. 11. Reflection volume and focal points occurred at 3:00 pm 6:00 pm on August 23rd

The focal points started to occur on the boulevard at 3:00 pm as can be seen in Figure 5.8. and as time goes by, it starts to move towards METU forest area, creating a reflection path on the boulevard depicted in Figure 5.9. The movements of hotspots are rather clear in Figure 5.10 in the plan form and in Figure 5.11 in the section form. It could be stated that parked cars in front of the building, users of various shops located at the ground level of the tower, drivers passing the boulevard and pedestrians using the sidewalk at the edge of the forest area are being affected by these focal points between the hours of 3:00 pm and 6:00 pm.

5.3. Results for solstice and equinox dates

- March 21st – Vernal Equinox

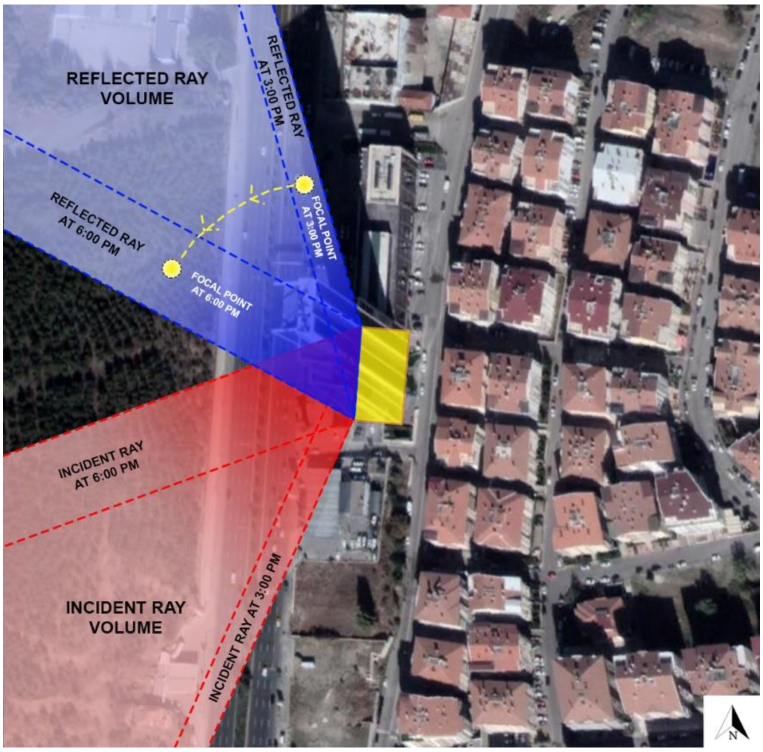


Figure 5. 12. Sun reflection paths and movement of focal points

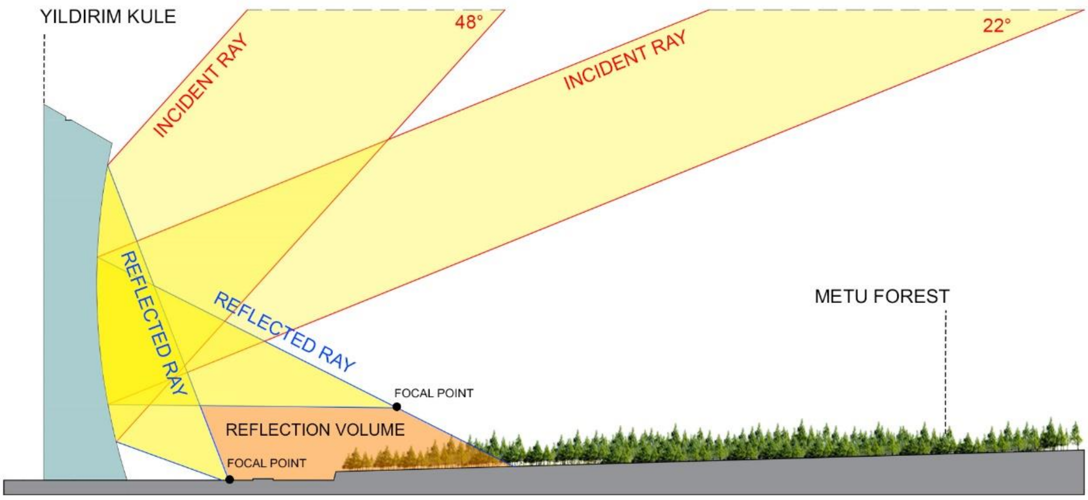


Figure 5. 13. Focal points and reflection volume between the hours of 3:00 pm and 6:00 pm

As can be seen from the figures above, at the vernal solstice date, focal points begin to emerge on the highway at 3:00 pm and slowly moves towards METU Forest passing through the boulevard and disappears above the forest. It only affects the drivers and pedestrians that use one side of the boulevard and the sidewalk in front of the border of the forest. Pedestrians and drivers may feel some temperature rise and visual discomfort while using the area. Also, the trees located on the edge of the forest may be affected by solar reflection. The diagrams showing the paths of incident rays and reflected rays are Figure 0.9 and Figure 0.10 in Appendix B. Moreover, to better understand the formation of focal points at each time period is shown in Figure 0.11 and Figure 0.12 also in Appendix B.

- June 21st – Summer Solstice

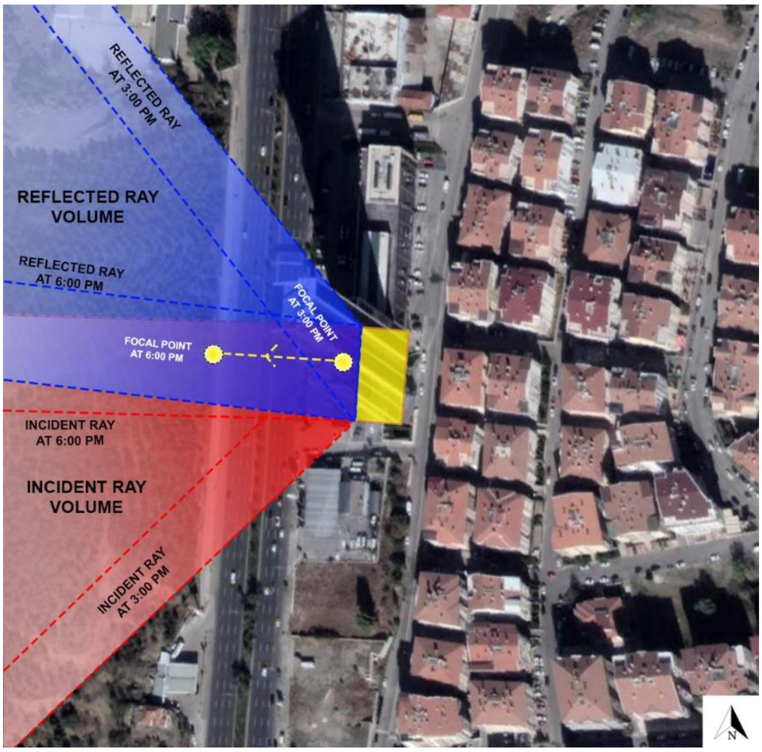


Figure 5. 14. Sun reflection paths and movement of focal points

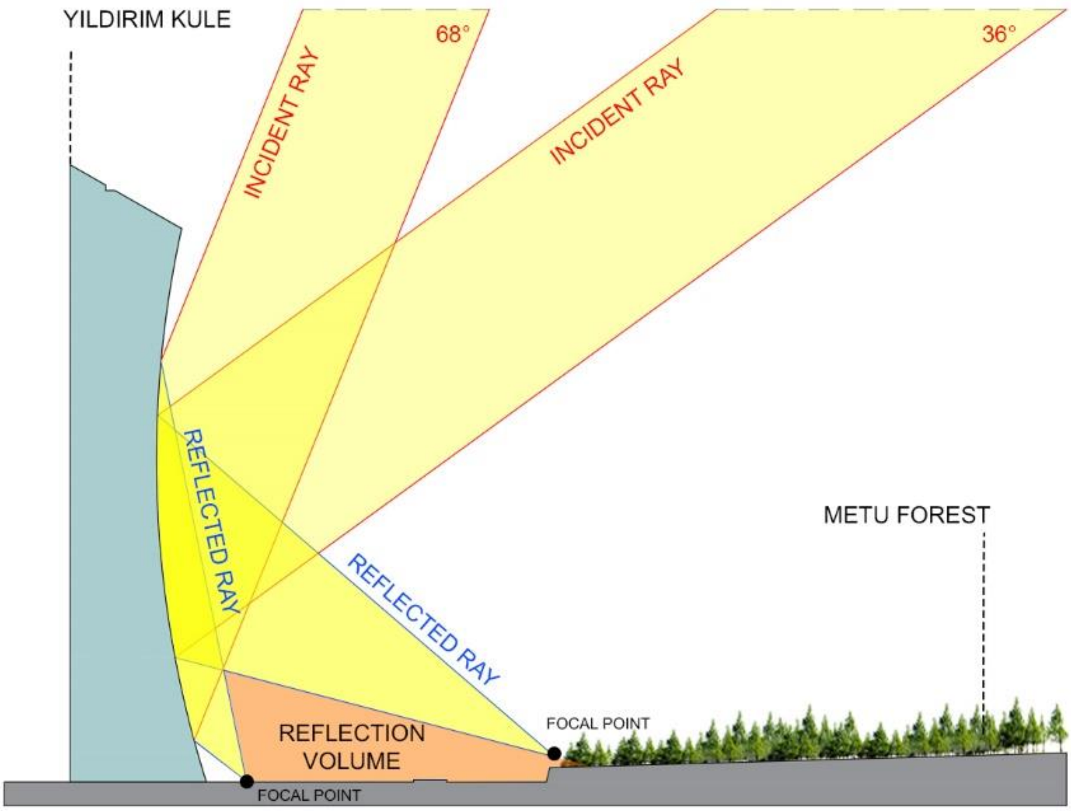


Figure 5. 15. Focal points and reflection volume between the hours of 3:00 pm and 6:00 pm

At the summer solstice, the impacts from the hotspots may be felt at the maximum level due to both their locations and the intensity level. At 3:00 pm the first hotspot starts to occur at the sidewalk in front of the building and travels across the highway towards its final location which is the edge of the forest which is clearly depicted in Figure 5.14. and Figure 5.15. Incident ray path and reflected ray path can be seen in Figure 0.13. and Figure 0.14. in Appendix B with the separate formations of focal points at each time period shown in Figure 0.15. and Figure 0.16. Pedestrians and drivers are exposed to this glare. Furthermore, the parked cars in front of the tower and the users of the several shops located at the ground level may be affected considering their long exposure times to hotspots.

- September 23rd – Autumnal Equinox

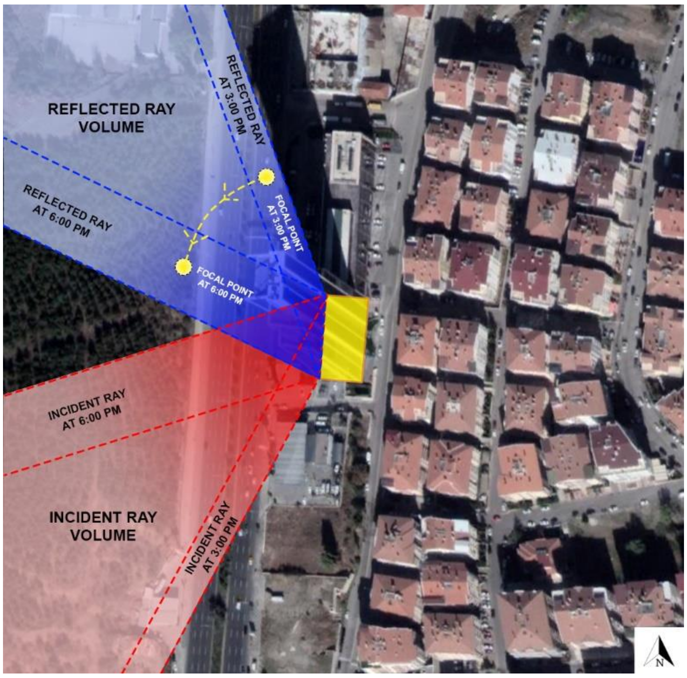


Figure 5. 16. Sun reflection paths and movement of focal points

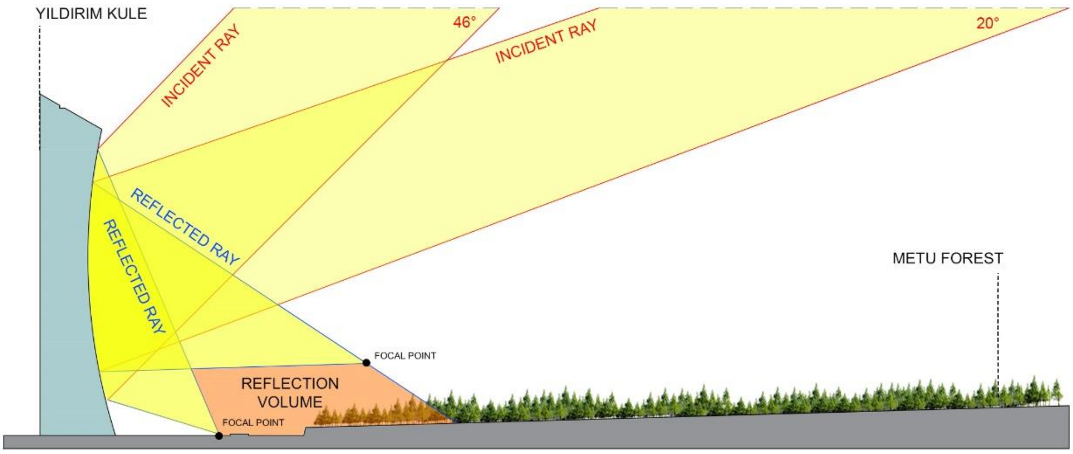


Figure 5. 17. Focal points and reflection volume between the hours of 3:00 pm and 6:00 pm

The locations of the hotspots occurred at the autumnal equinox are quite similar to those occurring at the vernal equinox due to the angles' of sun rays reflecting from the façade being close to each other as can be seen in the figures above and in Figure 0.17., Figure 0.18., Figure 0.19., and Figure 0.20. in Appendix B.

- December 22nd – Winter Solstice

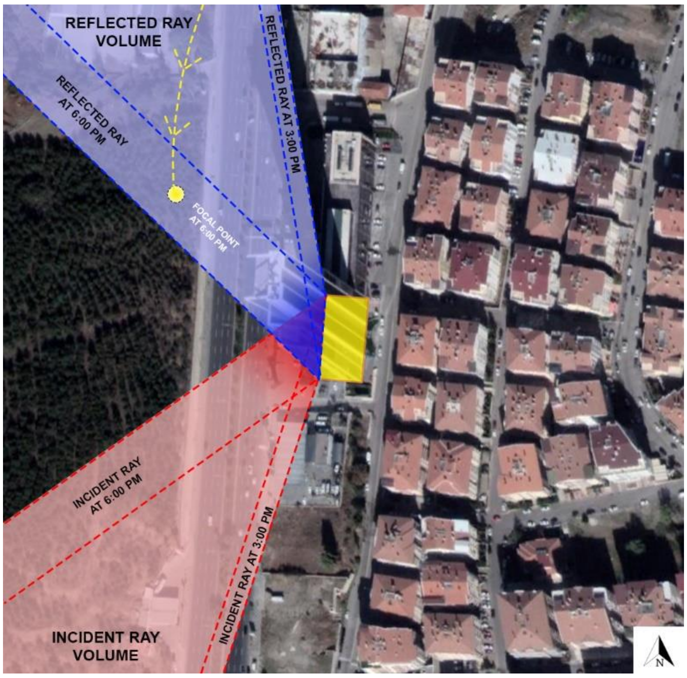


Figure 5. 18. Sun reflection paths and movement of focal points

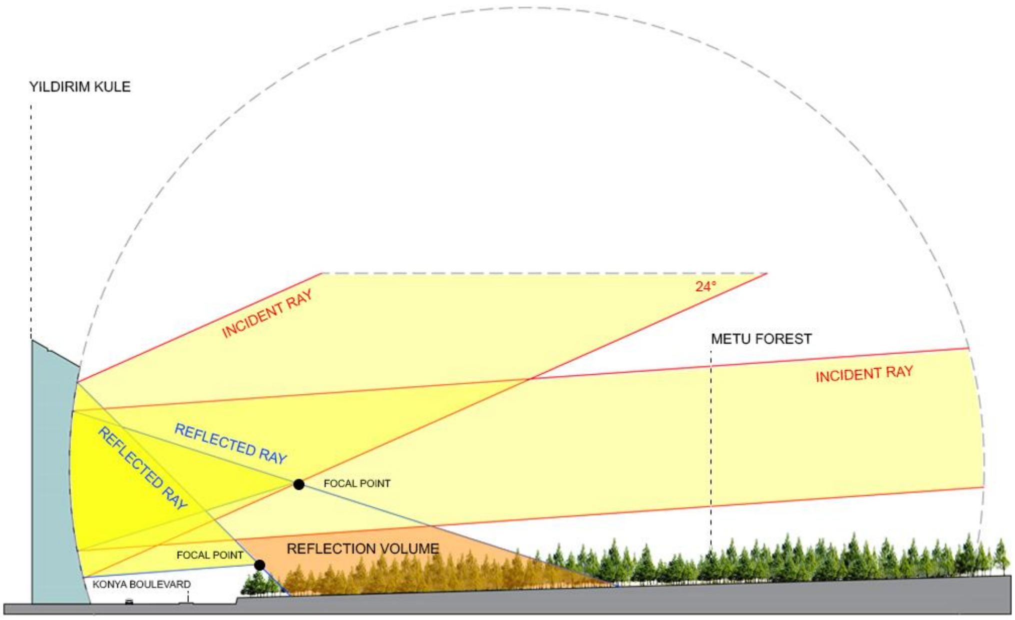


Figure 5. 19. Focal points and reflection volume between the hours of 3:00 pm and 6:00 pm

At the winter solstice date, as can be seen from the diagrams above and in Figure 0.23. and Figure 0.24. in Appendix B, hotspots occur mid-air at both 3:00 pm and 6:00 pm. This translates into zero effects towards people and minimal effect on vegetation because of the location of hotspots and minimum intensity levels of sun rays in the wintertime. Therefore, the environmental impacts of solar reflection can be mostly disregarded between the dates of the autumnal equinox and the vernal equinox.

5.4. **Evaluation of Results**

It should be noted that solar reflections occur at other times of the day and other days of the year also. Additionally, depending on the earth's rotation and local weather conditions, the duration of solar reflection can vary from seconds to hours. However, in this study, one particular date for observing the environmental impacts in addition to the solstice and equinox dates as references, are chosen to see the path of solar reflection in the vicinity. As can be seen from the images in the previous section, the solar reflection path and volume changes throughout the year. Focal points caused by converging reflected sun rays at different times of the selected days, also change. At 3:00 pm, it is mostly placed on the sidewalk and parking line in front of Yıldırım Kule; and it may cause property damage and pedestrian discomfort. Between the hours of 3:00 pm and 6:00 pm, it travels across Konya Boulevard causing discomfort to drivers. Again, at 6:00 pm, it reaches towards the forest which could cause vegetation damage. Some damage can be observed (see drying tree patch in Figure 5.22) and can be attributed to the reflected heat from the building during the period between summer solstice and autumnal equinox.

To break down the pattern of solar reflection, it could be said that solar reflection causes the most discomfort in the summertime, based on the fact that hotspots start to occur at the sidewalk in front of Yıldırım Kule and move to the boulevard creating a more focused reflection volume. In the wintertime, solar reflection hardly causes any discomfort to people since the hotspots only occur above the forest area. During autumn and spring seasons, the reflection volume covers both sides of the highways and a limited portion of the forest causing vegetation damage along with nuisance to pedestrians and drivers.

The glares that occurred on the west and south façades can be seen in Figure 5.20. Also, in the figures down below obtained from Google Earth Pro (see Figure 5.21 and Figure 5.22), solar reflection can be seen on the retaining wall across the boulevard as well as on the vehicles passing through Konya Boulevard. More importantly, in Figure 5.23 and Figure 5.24 taken on August 23rd and Figure 5.25 taken on September 23rd, the hotspots that occurred on the boulevard and above the forest are clearly seen and in correlation with the results discussed in the previous section.

Figure 5. 20. Glares on the west and south façades of Yıldırım Kule. (Source: https://www.sahibinden.com/listing/emlak-isyeri-satilik-ankara-nin-en-yuksek-is-kulesi-fark-prestij-kalite-mimari-690905406/detail)

Figure 5. 21. Solar reflection on the retaining wall (encircled in red). (Source: Google Earth Pro, June 2018)

Figure 5. 22. Vegetation damage, solar reflection on retaining wall and a hotspot on the highway. (encircled in red) (Source: Google Earth Pro, June 2018)

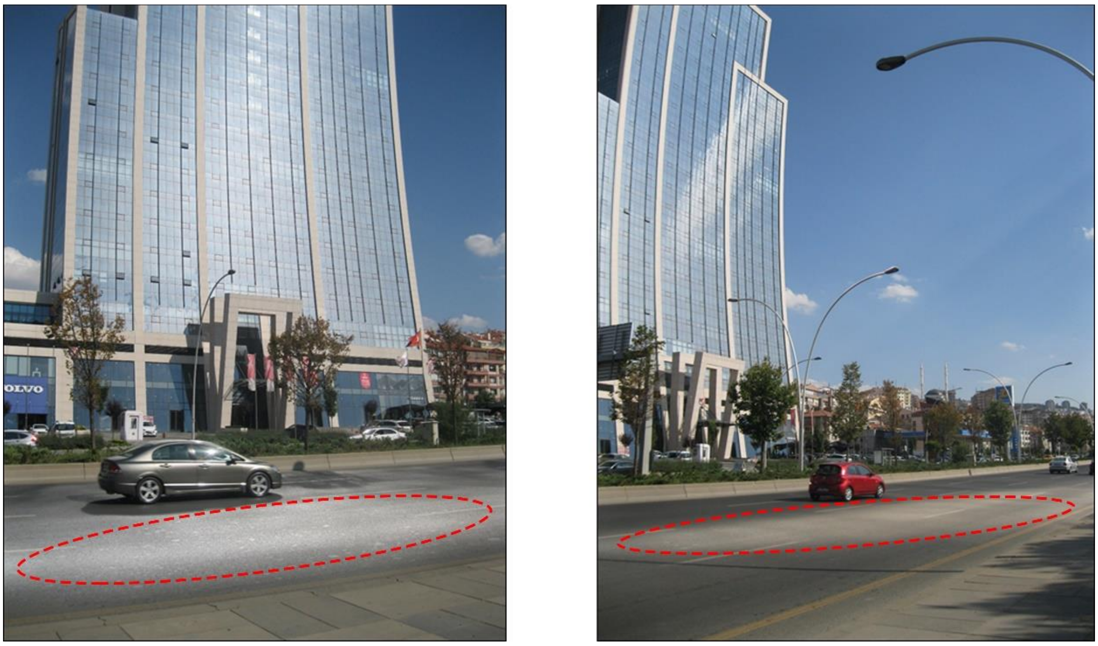


Figure 5. 23. Hotspots (encircled in red) that occurred on Konya Boulevard and photographed around 4:00 pm on August 23rd

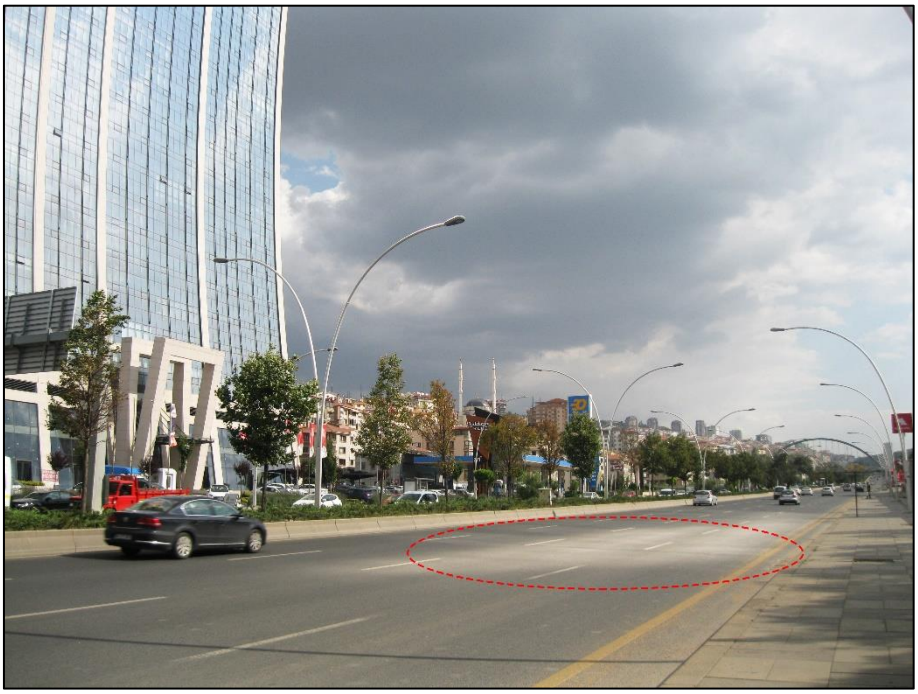


Figure 5. 24. A hotspot (encircled in red) that occurred on Konya Boulevard and photographed around 5 pm on August 23rd

Figure 5. 25. A hotspot (encircled in red) that occurred above the trees of METU Forest and photographed around 6:00 pm on September 23rd

5.5. **Evaluation of Cases**

In the chapter on literature review, four different cases of buildings that are famous for having negative impacts on their environment; namely, Walt Disney Concert Hall, 20 Fenchurch Street, Vdara Hotel and Museum Tower are extensively analyzed based on the information obtained from journal papers, conference proceedings and online newspaper articles covering these buildings. According to the findings, the assessment of case studies is done according to criteria selected from a broad perspective that includes building information, environmental impacts caused by solar reflection and mitigation techniques to prevent these impacts, both proposed and applied. The international case studies presented in the literature review are compared with each other and with the local case of Yıldırım Kule, regarding the magnitude of their problem, similarities, and differences.

As can be seen in the Table 5.3., along with the features that led to solar reflection such as building mass, shape, facade material, height, etc., other relevant building information is also listed from basic architectural and structural details to their energy label, in order to reach valid conclusions. Table 5.4. includes environmental impacts caused by solar reflection and mitigation techniques along with their costs of application for each case. Environmental impacts that are derived from the literature review are listed as nuisance to nearby buildings, nuisance to drivers, nuisance to pedestrians, road and pavement damage, property damage and vegetation damage. Each case is evaluated regarding the presence of these problems. The last one is the mitigation techniques that were proposed or applied onto the problematic surfaces of the case studies.

In Table 5.3., it can be seen that with the exception of one building, all case studies are high rise buildings with highly glazed façades that were constructed in the last decade. The exception is Walt Disney Concert Hall, a low rise building with an undulating stainless steel exterior skin. This case was chosen because of being one of the earliest and most infamous cases that had drawn attention to the solar reflection problems. Other than its considerable harm to the environment, the building is also extensively covered by the media due to the fact that it was designed by Frank Gehry, one of the most celebrated architects of the last decades, as a landmark in deconstructivism style.

Moreover, the buildings are also differentiated on the account of their forms. Some of them have concave, some of them have convex and one of them has both concave and convex surfaces. Another noteworthy detail in the building information Table is that, even though all of these buildings have caused serious environmental impacts and discomfort to people, two of them have high-level energy labels. This controversial information indicates the lack of importance given to solar reflectivity problems in world's leading sustainability assessment certification systems.

In Table 5.4., the environmental effects section is divided into six different categories regarding who or what they have an impact on. Each case is checked whether they affect their environment in the sense of these categories. When information is not available from the literature review or collected data, it is indicated as NA. In the case of Yıldırım Kule, it is only observed that the solar reflection caused by the façade affects visual and thermal comfort pedestrians using sidewalks next to Konya highway, and vehicle drivers that are using the highway. Since in the path of solar reflection, there are no buildings, nuisance to nearby building is marked as NA. Regarding property damage or vegetation damage, it is also left as NA for some cases, since it was impossible to collect data due to time limitations and credibility problems, as it was explained in the literature review.

The last section of Table 5.4 is comprised of several mitigation techniques that are proposed for or applied onto the problematic surfaces of the case study buildings. In some cases, some of the suggested solutions were tried and found ineffective. The list includes these solutions and their costs as well. For further elaboration, in the case of Walt Disney Concert Hall, fabric covering on determined surfaces as a temporary solution cost 6,000 dollars and for a permanent solution, sandblasting cost 180K dollars. For 20 Fenchurch Street, the construction of brise soleil to the entire south façade costs 10 million pounds. For Vdara Hotel, only thin film covering was applied onto the façade during the construction phase, but the cost is remained unrevealed by the authorities. In the case of Museum Tower, none of the mitigation techniques are found useful. Yet, total cost of research and application process as presented in the literature review also, are listed to see the financial burden of dealing with solar reflection problems. Therefore, the importance of precautions that should be taken before the design and construction phase is demonstrated. In the case of Yıldırım Kule, none of the mitigation techniques is used yet. However, in the light of the literature review and case studies, it can be stated that the most applicable mitigation techniques for the building are installing exterior shading elements or implementing ARCs onto the glass curtain wall. By taking the building's form and skin into consideration and acknowledging the fact that the environmental impacts of the solar reflection are relatively minor compared to the other case studies, installing exterior shading elements onto the whole west façade can be considered as extreme measure. Therefore, using glass coatings may be a more feasible solution to this problem. It should also be mentioned that the mitigation applications are mostly implemented due to the negative news items published or aired, about the building or the architect and developers rather than with the aim of protecting the environment.

Table 5. 3. Table of building information comparison between case studies.

Building Information	Building Name	Walt Disney Concert Hall	20 Fenchurch Street	Vdara Hotel	Museum Tower	Yıldırım Kule
	Exterior Image					
	Location	Los Angeles, California, USA	London, UK	Las Vegas, Nevada, USA	Dallas, Texas, USA	Ankara, Turkey
	Coordinates	34°03′19″N 118°15′00″W	51.5112° N 0.0835° W	36°6′34″N 115°10′40.25″W	32.789386°N 96.800248°W	39°52’56.4” N 32°48’45.6” E
	Construction Date	1999-2003	2010-2014	2006-2009	2010-2013	2015-2017
	Architect	Frank Gehry	Rafael Viñoly	Rafael Viñoly	Scott Johnson	Fazlıoğlu Mimarlık
	Developer	NA	Land Securities and Canary Wharf Group	MGM Mirage Design Group	Dallas Police and Fire Pension System and Brook Partners, Inc.	Fertaş Construction Incorporated Company
	Construction Cost	$ 275 million	£ 200 million	NA	$ 200 million	NA
	Building Function	Concert Hall	Commercial/Offices	Hotel	Residential	Mixed use
	Structural Material	Steel	Composite; Core: Reinforced Concrete, Columns: Steel, Floor spannig: Steel	Concrete	Concrete	Concrete
	Building Form	Concave/ Convex	Concave	Concave	Convex	Concave
	Building Skin	Limestone Stainless Steel Polished Steel	Glass Curtain Wall	Glass Curtain Wall	Glass Curtain Wall	Glass Curtain Wall
	Building Height	NA	160 m.	170 m.	171 m.	130 m.
	Floor Count	NA	35+3	57	42	36
	Floor Area	14,585 m2	62,100 m2	180,525 m2	34,375 m2	46,000 m2
	Energy Label	NA	BREEAM Excellent	LEED Gold	NA	NA

Table 5. 4. Table of environmental effects and mitigation techniques comparison between case studies.

		Building Name	Walt Disney Concert Hall	20 Fenchurch Street	Vdara Hotel	Museum Tower	Yıldırım Kule
		Exterior Image					
Environmental Effects		Nuisance to nearby buildings	Yes	Yes	NA	Yes	NA
		Nuisance to drivers	Yes	Yes	NA	NA	Yes
		Nuisance to pedestrians	Yes	Yes	Yes	NA	Yes
		Roads, pavements and water bodies damage	Yes	Yes	Yes	NA	NA
		Property damage	Yes	Yes	Yes	Yes	NA
		Vegetation damage	NA	NA	NA	Yes	NA
Mitigation Techniques	Proposed	Use of vegetation	Yes	No	No	No	No
		Use of paint	Yes	No	No	No	No
		Use of obstruction	No	No	Yes	Yes	No
	Tested	Use of spray	No	No	No	Yes	No
		Surface film covering	No	No	Yes	Yes	No
	Applied	Fabric covering	Yes	No	No	No	No
		Sandblasting	Yes	No	No	No	No
		Exterior Shading Elements	No	Yes	No	No	No
		Cost	$186 thousands	£ 10 million	NA	$ 1 million	NA

5.6. **Architectural Responsibilities to Avoid Solar Reflectivity**

Due to the fact that there aren’t detailed regulations regarding solar reflectivity in the building code, these problems mostly are not considered or foreseen in the design phase. Even though there are numerous examples of unwanted solar reflection cases around the world, legislative mechanisms do not enforce a comprehensive building code on this issue. For example, a solar glare analysis conducted by an engineering company in 2017 to evaluate glare occurred on the construction site was prepared within the guidelines of Seattle’s Land Use Code which have been enforced since 1979 and not been updated to fulfill the requirements of the last decades regarding solar reflection. (EA Engineering Science and Technology Inc., 2017) Even recently updated standards, like in the building code that had been regulated by the department of built environment in the city of London and enforced since 2017, buildings with curvilinear forms are not even mentioned. Only superficial mitigation techniques such as reducing the area of glazed surfaces, using low reflectance films or using external shading devices are listed, while completely excluding complex situations where the solar convergence phenomenon might occur. (Dwyer, 2017)

This shortsightedness of regulatory bodies is causing serious negative and even dangerous environmental impacts. The increase of examples around the world is forcing architects to consider this issue while designing buildings with reflective surfaces combined with curved forms. Granted, the technological incapacities concerning this issue such as lack of software that can give reliable and precise results on solar reflectivity are an important factor yet, it is the architect’s responsibility to consider this issue and take precautions in early design phases to ensure that the façade does not affect the visual and thermal comfort in its surroundings. As stated by Danks and Sinclair (2016), building orientation affected by the sun path should be arranged according to the areas which are most sensitive to solar reflections, such as roads, sidewalks, occupied buildings, local trains or flight paths should be analyzed. Although, mitigation techniques are available after the construction is completed, the risk of adding serious costs and conflicting with the original design concept is always the case. Furthermore, any mitigation technique should be considered in different ways such as added structural load, thermal, visual and acoustic comfort of occupants, snow and ice build-up, etc.

CHAPTER 6

CONCLUSION

In the past few decades, highly glazed façades are almost becoming a standard for modern architecture. With the help of new technological developments on both construction materials and computational advancements, architects are able to design complex building forms covered with various façade elements. As architectural designs become increasingly complex in shape and geometry, solar reflection studies have gained a lot of importance. However, there is still a lack of industry-wide accepted regulations around solar reflections in the built environment. Therefore, the architects have almost little to none guidance on preventing their designs from inadvertently causing undesired thermal or visual impacts to the environment. Considering the major risks of discomfort caused by solar reflectance and financial burden of mitigation techniques post-construction, the issue should be dealt with during the design stage.

The aim of this research is to analyze how curved façades with reflective surfaces affect their environment in a negative way. To further analyze solar reflection phenomenon, the infamous cases around the world were chosen to study regarding their architectural features that cause the problem. In the selected cases, all of them have common factors such as having a curved form either concave, convex or both at the same time and highly reflective building skin either glass curtain wall or stainless steel. The case studies are further examined on their effects from mild to extreme, to the environment. Moreover, the mitigation solutions that have been discussed, tested or applied onto the problematic surfaces after the building's construction are explained. The precautions that have to be taken early in the design process are stated and the tools that could be used or developed are investigated.

To make a comparison with the case studies around the world, a local building with similar characteristics was chosen to further examine within the Turkish context. The thermal and visual impacts of the building to its environment are investigated with the tools that are available. The collected results are paralleled with the international case studies. Thus strengthening the deduction that curved forms with highly reflective surfaces have the major risk of causing substantial discomfort to the public and to the environment at many levels, such as nuisance to drivers, pedestrians, occupants of nearby buildings, property damage, road or pavement damage, and even vegetation damage.

Apart from being correlated with the international cases, the lack of visual data confirming the results could be considered as a limitation of the work. The study has certain time limits that prevent the researcher from observing the occurrence of hotspots at the summer and winter solstices and at the vernal equinox. A determined site visit date according to the optimum weather conditions and the autumnal equinox date are the only dates that the visual data could be obtained and corresponded to the results drawn from sun path diagrams.

For further studies, with the enlightenment of the literature review and research that was done, it is promising to study early detection methods for solar reflection. Several selected buildings could be modelled and solar reflection caused by them could be simulated for different building orientation settings and for different time periods of the year. Based on the results, a pattern for the factors that cause solar reflection and empirical results of architectural choices such as building form and material for the building skin could be propounded.

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APPENDICES

A. Sun Path Diagrams for Solstice and Equinox Dates

- March 21st – Vernal Equinox

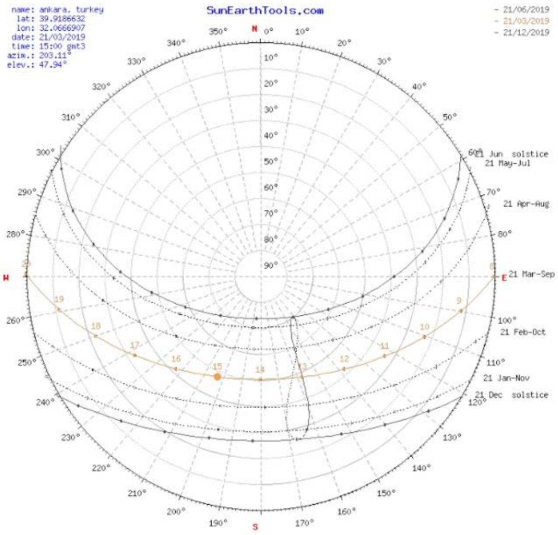

Figure 0. 1. Sun path diagram for 3:00 pm on March 21st

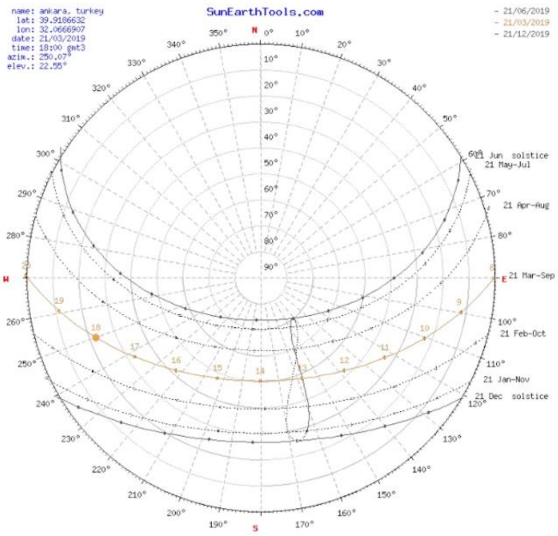

Figure 0. 2. Sun path diagram for 6:00 pm on March 21st

- June 21st – Summer Solstice

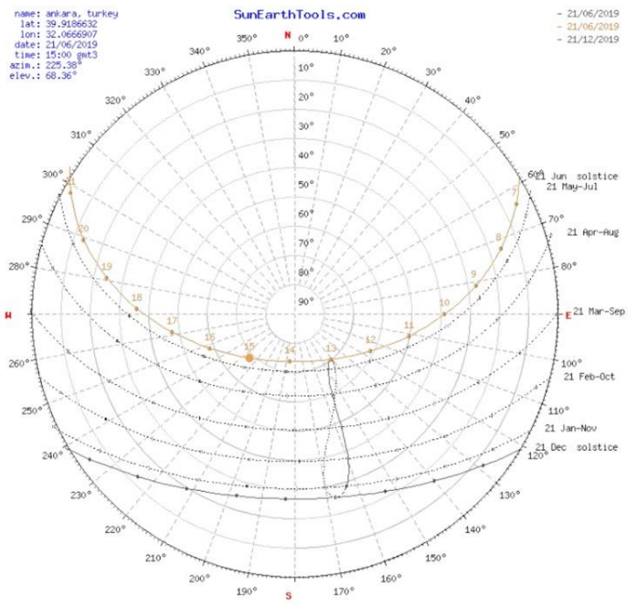

Figure 0. 3. Sun path diagram for 3:00 pm on June 21st

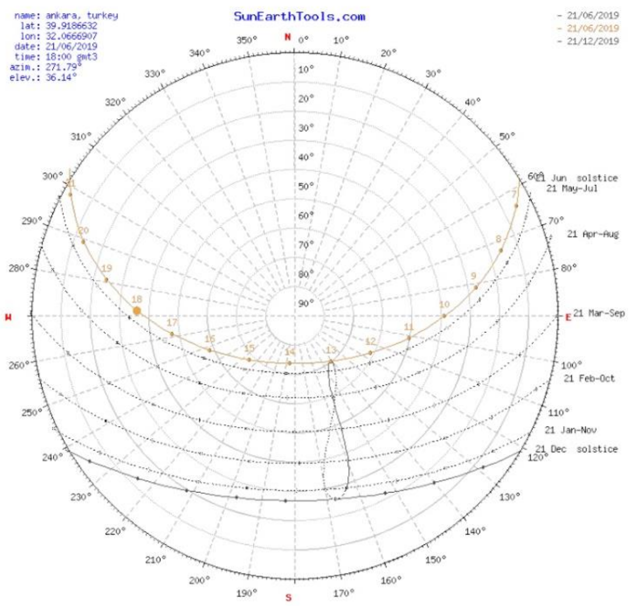

Figure 0. 4. Sun path diagram for 6:00 pm on June 21st

- September 23rd – Autumnal Equinox

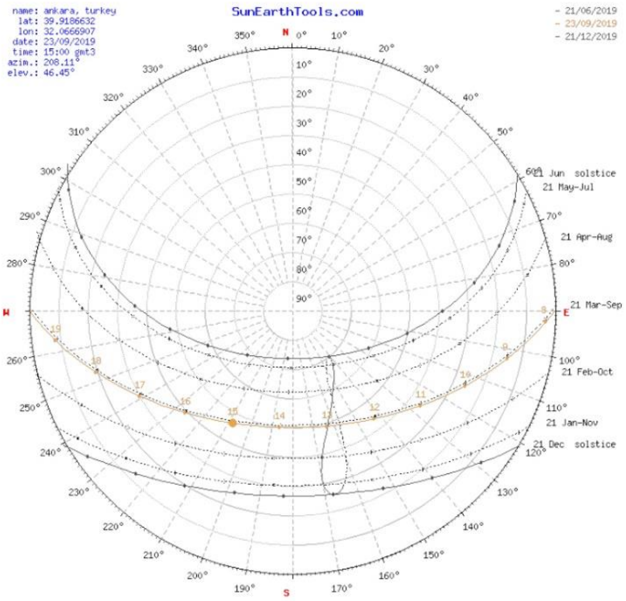

Figure 0. 5. Sun path diagram for 3:00 pm on September 23rd

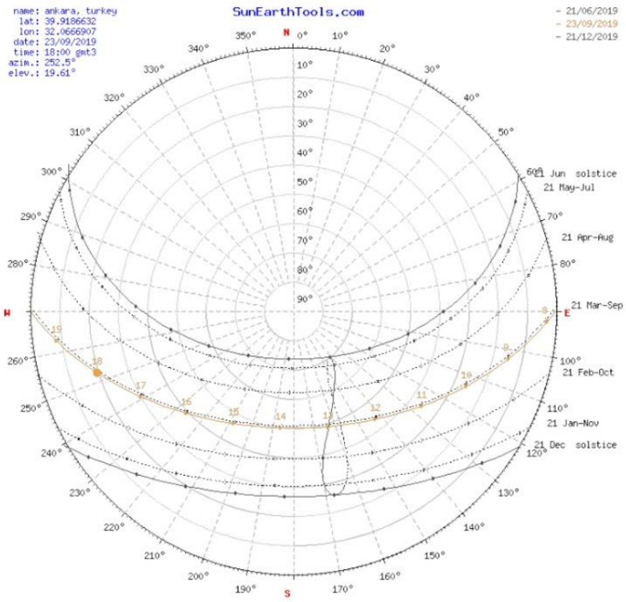

Figure 0. 6. Sun path diagram for 6:00 pm on September 23rd

- December 22nd – Winter Solstice

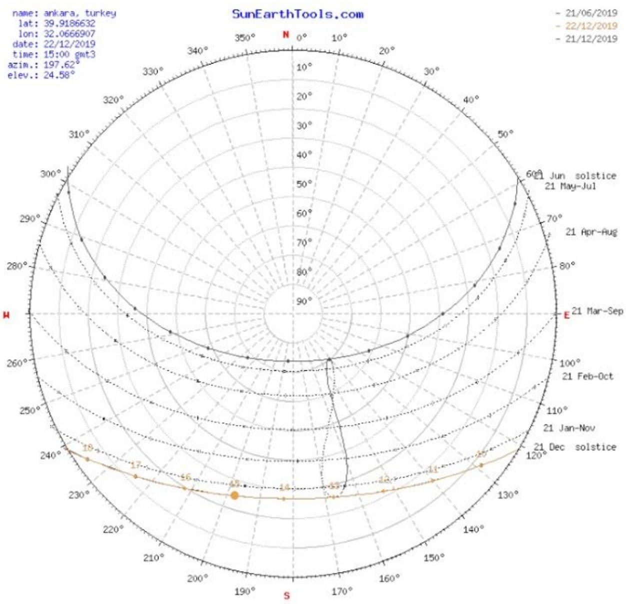

Figure 0. 7. Sun path diagram for 3:00 pm on December 22nd

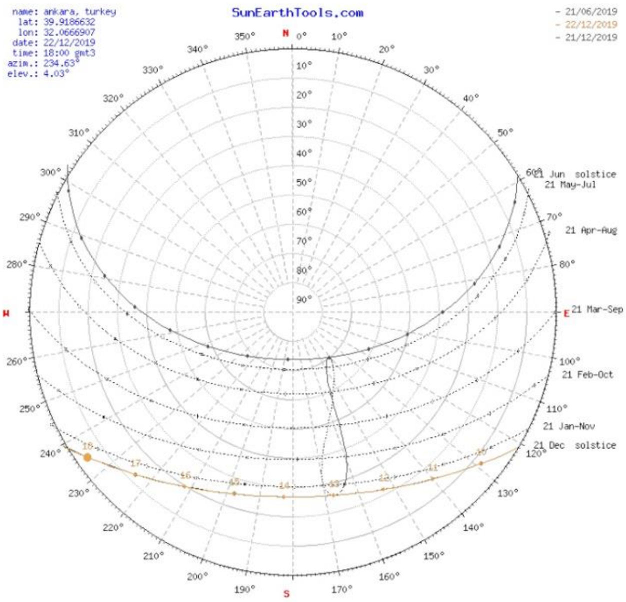

Figure 0. 8. Sun path diagram for 3:00 pm on December 22nd

B. Diagrams of Reflection Paths and Focal Point Formations on Solstice and Equinox Dates

- March 21st – Vernal Equinox

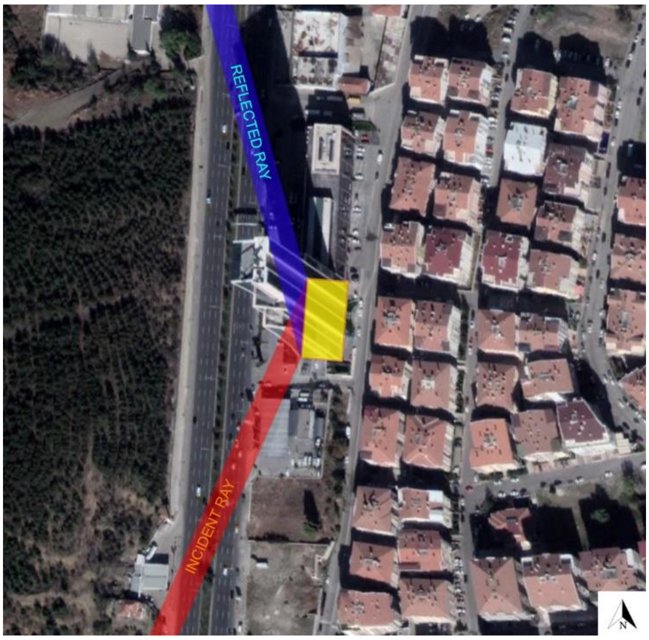

Figure 0. 9. Reflection path at 3:00 pm on March 21st

Figure 0. 10. Reflection path at 6:00 pm on March 21st

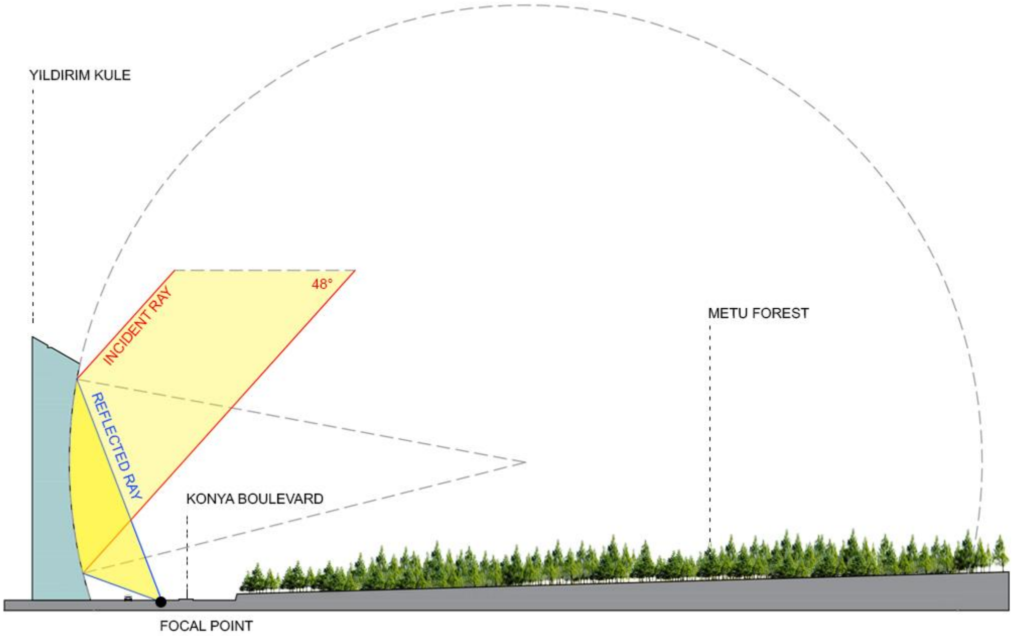

Figure 0. 11. Diagram of focal point formation at 3:00 pm on March 21st

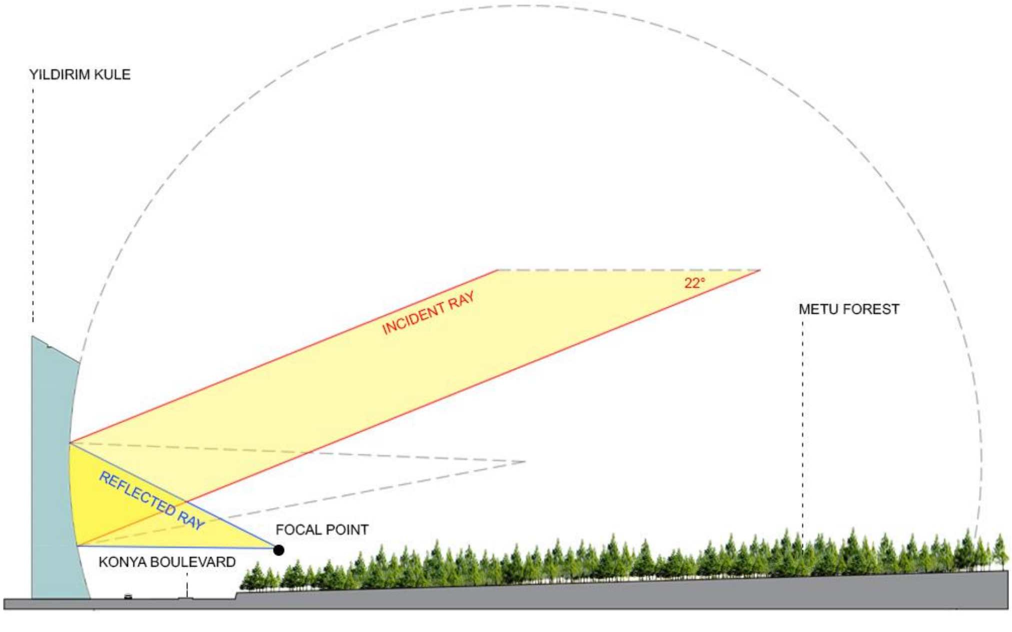

Figure 0. 12. Diagram of focal point formation at 6:00 pm on March 21st

- June 21st – Summer Solstice

Figure 0. 13. Reflection path at 3:00 pm on June 21st

Figure 0. 14. Reflection path at 6:00 pm on June 21*st*

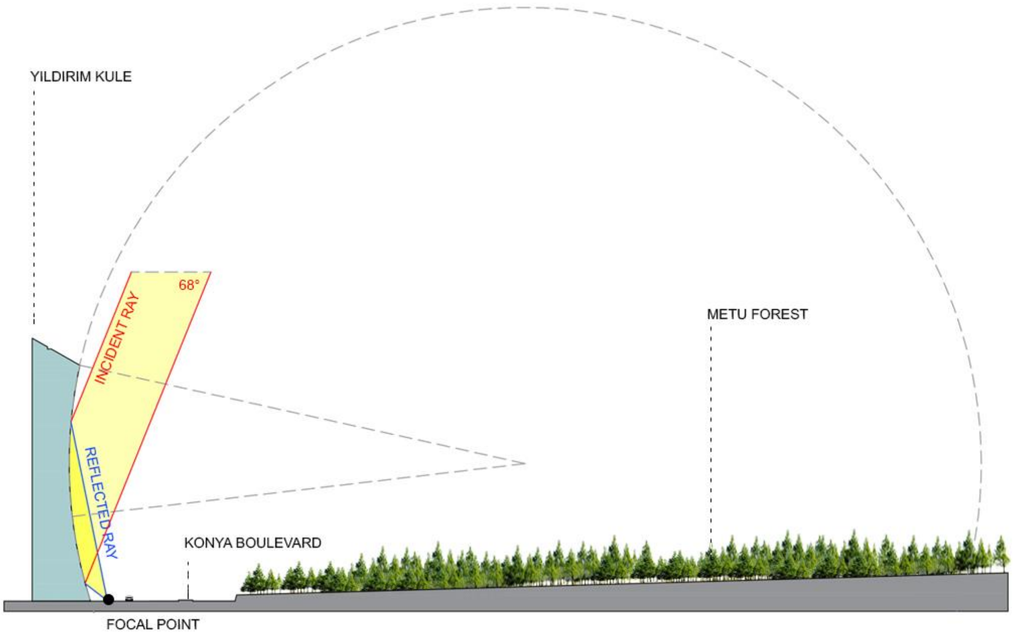

Figure 0. 15. Diagram of focal point formation at 3:00 pm on June 21st

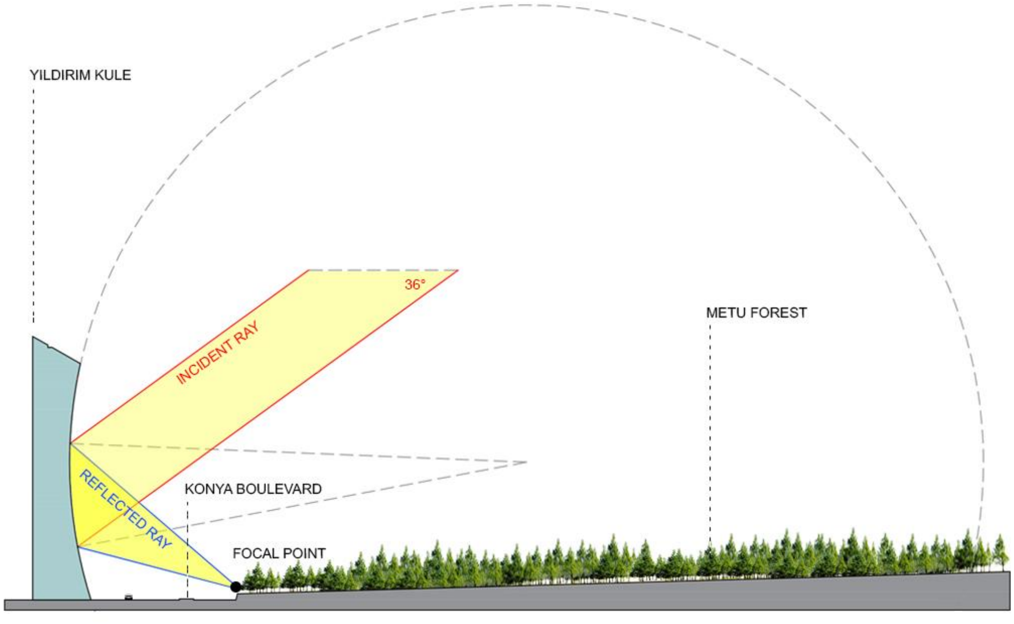

Figure 0. 16. Diagram of focal point formation at 6:00 pm on June 21st

- September 23rd – Autumnal Equinox

Figure 0. 17. Reflection path at 3:00 pm on September 23rd

Figure 0. 18. Reflection path at 6:00 pm on September 23rd

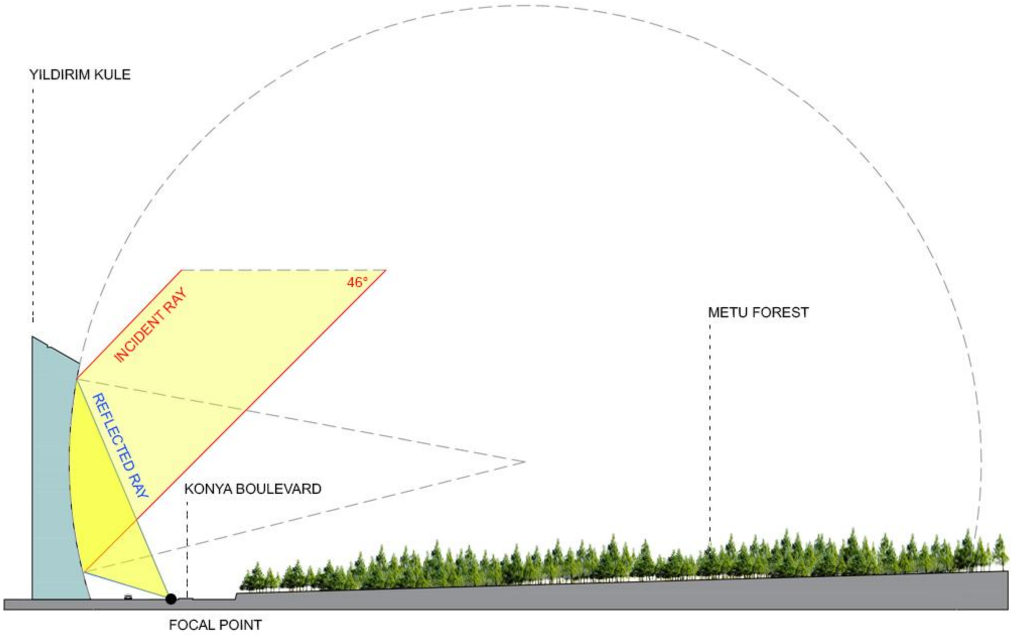

Figure 0. 19. Diagram of focal point formation at 3:00 pm on September 23rd

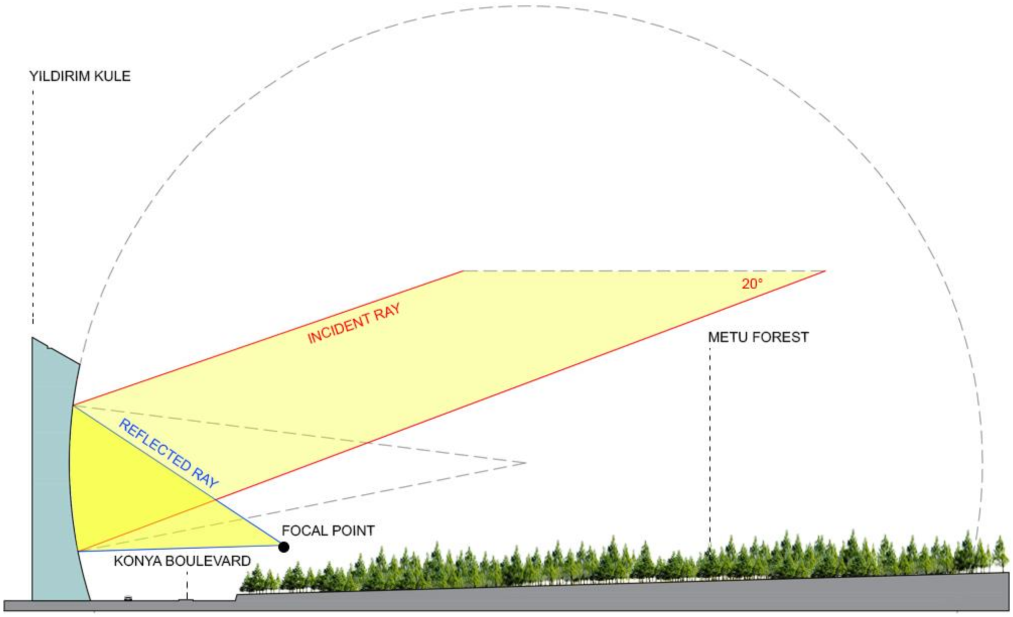

Figure 0. 20. Diagram of focal point formation at 6:00 pm on September 23rd

- December 22nd – Winter Solstice

Figure 0. 21. Reflection path at 3:00 pm on December 22nd

Figure 0. 22. Reflection path at 6:00 pm on December 22nd

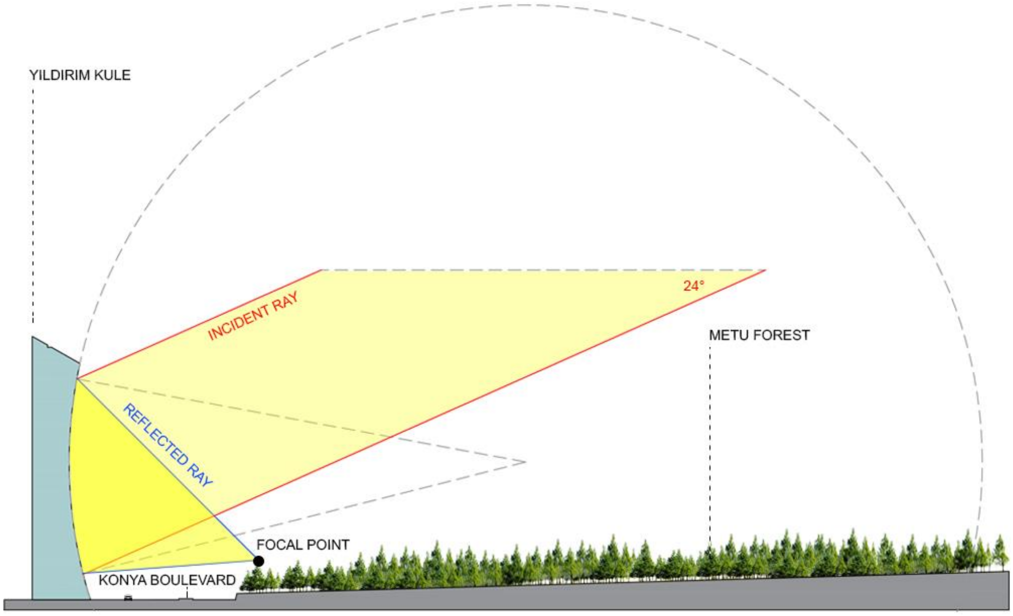

Figure 0. 23. Diagram of focal point formation at 3:00 pm on December 22nd

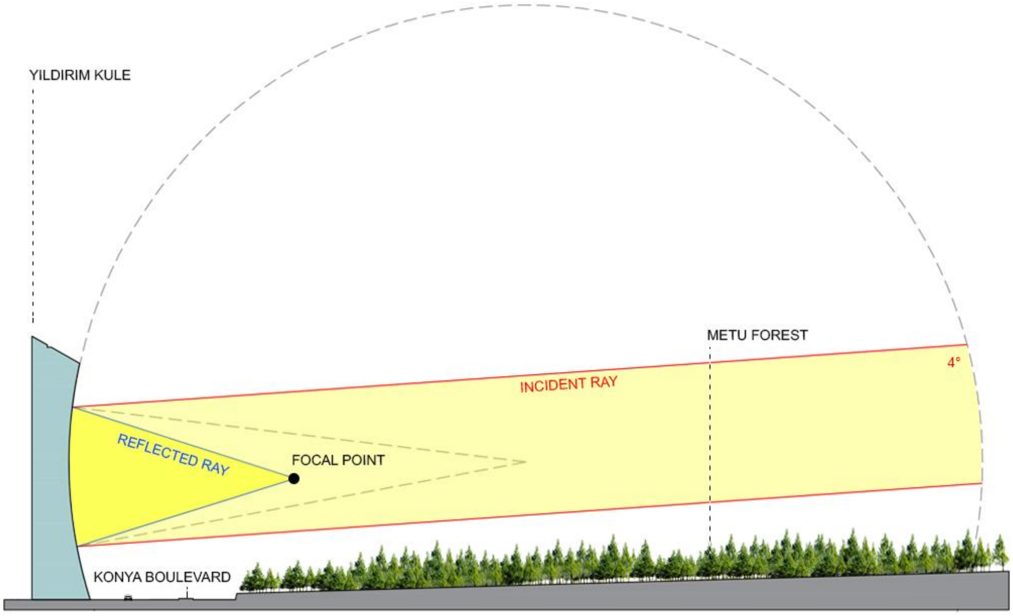

Figure 0. 24. Diagram of focal point formation at 6:00 pm on December 22nd