A Framework for Optimizing Tall Building Form to Reduce Solar Reflection Impacts

Mahnaz Farahani¹, Mohammadjavad Mahdavine² and Peiman Pilechiha³
¹, ² Pars University of Architecture & Art, Tehran, Iran
mahnaz66f@gmail.com¹, mahdavinejad@modares.ac.ir ²
³ Tarbiat Modares University, Tehran, Iran
p.pilechiha@modares.ac.ir ³

Abstract: Reflection of sunlight from tall buildings covered with glass facades creates many problems for residents and pedestrians in urban environments. Proper design in the early stages of construction can eliminate or reduce most of these problems and it can also considerably curb the environmental consequences and post-construction costs. Most of the research conducted in this field is focused on the façade materials to reduce or eliminate reflection and the existing body of research scarcely consider the design solutions in the early stage of design to minimize the effects of reflection. This study aims to provide a framework for simulation and optimization of solar reflection effect caused by the façades of tall buildings. The reflected sunlight from the studied façade of parametric forms were traced. Then the reflected points on surrounding and distances between them studied for each form. Finally genetic algorithm is adopted to find the optimum found with maximum distance between reflected points. The innovative proposed method can be applied to similar cases and it enables researchers and designers to analyze and optimize reflected sunlight.

Keywords: Glare; Solar Reflection; Ray-Tracing; Optimization.

1. Introduction

Buildings can influence the environment through the design of their façades. Reflective surfaces on the building façade can reflect the sunlight in urban environments and lead to different problems like over-reflection. The reflected sunlight from the façades can bother drivers, pedestrians, and residents and, in some cases, can lead to visual disorders. Development of new glass technologies has led to an increasing usage of glass on the façade of the buildings. Furthermore, high-reflection façades are increasingly used by designers to reduce energy consumption and facilitate cooling of the building during summer. The visible sunlight, which is beneficial for the indoor spaces, are mostly absorbed through the window glasses, but the solar rays are unwantedly reflected from the surface of the window. Hence, the sunlight is reflected in the street and the surrounding environment. Lack of precise material analysis can increase the reflection chance and create annoyance for the neighbours. In some extreme cases, there have been reports about burning of people’s hairs or melting of plastic glasses (Whitely, 2010). In most cases, these reflections are only an annoying sunlight, but these reflections have caused serious damages in recent years (Hayward, 2012), such as property damage (Wornick, 2012).

Despite potential dangers due to reflection, these problems are rarely considered in the early stages of the design. This is due to the fact the reflection effect from the façade of the buildings is a relatively new phenomenon and the process of testing the reflection has been difficult and almost impossible in the past years (Danks and Good, 2016). There have been growing concerns regarding light-reflection-related issues, especially in crowded cities with high glass-façade buildings (Schiler and Valmont, 2005). It has been noted that the façade of the building has various influences on visual and thermal comfort of the residents and the reflection poses threats to the comfort of the people living outside the building.
1.1. Review of Existing Literatures Regarding Reflected sunlight

Some media reports have shown that sunlight reflected from newly-constructed buildings has caused various problems. Vdara Hotel in Las Vegas is another instance that reflects a considerable amount of sunlight off its southern façade, which has turned to a serious concern for the health and comfort of hotel customers near the pool (Mayerowitz, 2010). Walt Disney Concert Hall (WDCH) is another example of light reflection discomfort. Since its completion in 2004, WDCH has been a source of thermal and visual discomfort for residents. Research has shown that the temperature is more than 58°C near the building in the roadbed focal point (Suk, Schiler, et al. 2016). Other example include the Walkie-Talkie building, This building is a 160 m high skyscraper, located in the financial district of the City of London The construction work finished in 2014. News about plastic parts (wing mirror, panels, and badge) of a car parked at street level near the building being melted was first reported in early September 2013 (Verity, 2013). The south façade of the Walkie-Talkie has a concave shape covered with highly reflective glass panes to reduce the energy consumption inside the building. The architect of the building at 20 Fenchurch Street told the media that he knew reflected sunlight could cause problems but that there was a lack of tools and software to assess and prevent these problems. The actual temperature of hotspots induced by the building was more than twice as high as the estimated temperature (Wainwright, 2013) reports are suggesting that fixing the problem could cost millions of pounds. Potential long-term solutions could include treating the glass, applying an external film, adding external shading elements, or replacing one or more of the facades. The estimated costs of the solutions range from £60,000 to several million pounds, reported Building magazine. It seems that due to the problems caused by the reflection of sunlight during the day, these and similar buildings have been offered post-construction solutions, but these solutions create a lot of costs and it also affects the design of the building aesthetically, so providing solutions before construction and in the design, phase can prevent these problems.

Several strategies, such as changing the façade materials or adding louvre to the façade, have been applied to decrease the damaging façade reflections after it’s initially being noticed. Officials have enacted regulations to eliminate the problem of façade reflection in some countries and most of them are based on controlling the amount of reflected light from the construction materials. Several Australian cities have restricted the amount of reflection from the glass façade to a maximum of 20% and Sydney has achieved the highest restriction for the façade materials (Council, 2012).

On the other, researchers have proposed different methods for the evaluation of sunlight from the façade. Shih proposed a computer model for the absorbance of sun light reflected from the glass façade of the buildings. Border of Reflection Area has been proposed as a functionality index to evaluate the glare which could simulates the received reflections. Quantitative evaluation finally led to suggestions like employing inclined walls. The limitation of this method is that reflectivity of façade material is not considered in the calculation and only simple massing geometry could be analyzed.

Analysis conducted by Hassall in 1991 estimated the brightness range for the comfort of drivers of vehicles 500 cd/ m². In addition to drivers and vehicles, this area will be satisfactory for pedestrians. In the study, the effect of glare on the residents of neighboring buildings has also been investigated (Hassall, 1991). In this method, the facades of a constructed building are imaged and the areas that are affected by the reflection of sunlight are identified. The application of this method is limited to built buildings and therefore can not predict the potential problems caused by sunlight reflected in the design phase. Another limitation of this approach is that it ignores the amount of time that reflections occur on adjacent buildings.

Due to the problems and lack of methods for simulating the reflection of sunlight from the facades of buildings, most of the research of researchers has been done on the built buildings and after the problems caused by the reflection of the sun and little research has been done on the pre-construction stage. Despite the expansion of high-rise buildings with glass facades and the emergence of problems mentioned earlier, one of the factors that can be considered in the design phase of such buildings is the study of the effect of light reflection from its facades. So there is a lack of a way to simulate and study the effects of light reflection.

1.2. Visual Glare

Glare is a visual condition in which the discomfort of the capacity reduction to see the details of things is caused by the inappropriate distribution of light in the luminance threshold or the existence of high contrasts. Glare is a direct result of distribution of light in the eye, which reduces the luminance contrast of the eye (Brotas and Wienold, 2014). The glare in outdoor space is a topic worthy of attention, since not any acceptable indicator measuring the reflection glare in the outdoor space has been introduced. Glare in the outdoor space is the result of the unwanted light reflection from the façade, which leads to thermal and visual discomfort. This definition is similar to that of excessive light or light pollution produced by unwanted light in urban areas.
A Framework for Optimizing Tall Building Form to Reduce Solar Reflection Impacts

during the night (Schiler and Valmont, 2005). Researchers believe that glare happens when the eyes are exposed to a distracting or blinking light. It is also a well-established fact that surfaces with higher luminance lead to glare regardless of the contrast level. Reflection is also classified as a bothering discomfort. Discomfort can be discussed in three parts: the process which creates the glare, the amount of glare perceived by the person, and the results of the glare (Jakubiec and Reinhart, 2010).

While excessive light and light pollution affect comfort, productivity and health at night, glare during the day also affects thermal or visual comfort and, in some cases, can influence both of them. Light pollution is appropriately discussed in the studies on current buildings and several regulations have been proposed, but the issue of glare in outdoor spaces has not been thoroughly discussed.

1.3. Glare-Causing Factors

Unwanted reflection of sunlight can be considered as sun glare. However, the reflected light has several distinct features that distinguishes it from the sun as a glaring source. The features are as follows: The reflected sunlight happens unexpectedly in some situations, while the location and movement of the sun are predictable. The highest glare is due to new buildings and the people who have never experienced any problems before the establishment of the building encounter unexpected visual and thermal glare from the reflection of light from the building’s façade (Schiler and Valmont, 2005).

The height of the neighboring buildings and their façade should be considered simultaneously according to the movement of the sun to obtain the potential sources of the reflection. The location of neighboring buildings, the geometry of the building, its nature, and occupancy type are among the vital issues and the method used for analysis is of the highest importance (Danks, Good et al. 2016). So the following key factors contributing to glare:

- The location of the sun in the sky
- the location of the observer
- the angle of reflection, type of the material

The location of the sun in the sky is one of the most important factors regarding glare. Unwanted reflections are mostly in low degrees of the sunlight. The reflections meet the sightline of the pedestrians and drivers lead to potentially dangerous eye distortions (Jung, 2010). As well, unlike an overhead solar angle, a glancing reflection will potentially travel further from the façade affecting a larger area of the surrounding urban areas and thus have a greater potential for offending neighbours. Therefore, the most “unruly” reflections from a visual glare standpoint will often occur while the sun is lower in the sky in the first few hours before sunset or after sunrise. Conversely, this also means that the impacts of visible reflections from overhead (southern, midday) can be less problematic as the angle of incidence is less likely to align with the required line of sight of a pedestrian or driver. However, it is important to note that the thermal impacts of reflections during midday periods are more of a concern due to the greater intensity of solar insolation at these times (Danks, Good et al. 2016).

Glare is also dependent on the sun angle and the angle from which the building is observed. The chance of glare is higher when the reflected light is in line with the viewing angle of the drivers. The reflection increases by up to 15% in the double-glazed glass. If the angle of the sun and the façade is 45 and 60 degrees, the reflection will be 22% and 49%, respectively. Existence of a glaring source on one side or higher than observer eye level can also increase the chance of glare. Generally, glare source positioned upper than 25° compared to the sightline can reduce the glare effect. The worst condition happens when the drivers move directly toward the building. In this condition, the light is directly reflected in the driver’s eyes. This usually happens in the lower sections of the building (Corporation, 2017).

When there is a reflection in the façade, the reflected area may be a relatively small due to the ray concentration. This area creates various side-effects: damage to the eyes of people, especially the retina; burning of the skin due to touching fences or doorknobs; higher temperature in the building; damage to the paint of the cars. The reflection can also affect plastic, rubber, tar, and asphalt of the road and it is possible to see damages to the trash cans and other tools in the street. In some extreme cases, the reflection can lead to a fire. There is little convergence cause for the sunlight. This only happens when the building has elements with a concave form, which converge the light. This element can be in the plan or the cross-section of the building. Flat and convex façade can also lead to glare, but they do not converge the light. It should be noted that the reflections from concave façades are called deadly rays. Convex facades it should be noted that the reflections from concave façades are called deadly rays. Convex facades create scattered reflections and can affect various locations during the day. It should be noted that depending on the façade form glare can affect various.
locations during the day. Although this kind of reflection affects less heat-related issues, it can lead to glare annoyance in a large area because of scattered light (Danks, Good et al. 2016). The flat façade reflects the light but does not concentrate it. The concave façade reflects the light but its reflection radius is different. The Concave façade converges the light and the reflection is concentrated on one location. Facade slope is another contributing factor that should be taken into consideration. For vertical facades, the worst condition happens when the sun approaches the earth. The façade with a backward slope can reflect the sunlight in more angles. This form is very acute since it is not expected by the drivers and the sunlight does not end until reaching the windshield of the car. The façade with a forward slope creates less reflection (Dwyer, 2013).

However, all buildings with concave façades do not lead to problems and the existence of different forms of facades differentiates them from other façades. Lack of uniformity in the façades creates several focal points instead of one significant point. These points usually reflect the light to the roofs of other neighboring houses and they are usually outside the pedestrian area. This can be done by changing the radius of the façade curve, using balconies and shades (Danks, Good et al. 2016). According to the literature, the methods currently used can increase the post-construction costs. It is possible to analyse and choose a suitable form to reduce the adverse effects of the reflection.

According to what was mentioned above, the shape of the building, the position of the sun and the position of the observer are important and influential factors on the reflection of light from the building. By parametric simulation of these factors, the reflection of light from the building can be tracked and examined and a solution can be provided to reduce the reflection of light.

2. Methodology

2.1. Research Framework

This study provides a framework to simulate sunlight reflection of studied building façade on its surroundings. Figure 3 illustrates proposed 4-step optimization framework. The first step is dedicated to identifying studied building form variables in a parametric model. This step helps considering various parameters, such as impure area, the height of the building, and the ratio of the area to volume to study their impacts on urban glare. Parametric model in this study is simulated in Grasshopper which is a visual programming language runs within the Rhinoceros. Selected form parameters in this study are the coordinates of the façade points in different levels. In the second step, sunlight simulation is conducted for each generated form and its surroundings. Sunlight simulation is the process in which the sun rays are followed before reaching the façade until they reflect on the surrounding area. This simulation helps identifying the sunlight reflected contact points on surrounding and studding the distance between them. The greater the distance between these points, the less glare this generated model produce. To Study the sun rays and their reflectance, Ladybug plugin used. So, the optimization objective in the third step is set on the maximum average distance between the second step points. This step is conducted by the Galapagos, adopting Genetic algorithm to find the optimum form. In the final step after the optimization process ends, the objective, parameters and the solutions are investigated more.
2.2. Case Study Building

To test the proposed framework a case study in Tehran, Iran has been chosen. Geographically, Tehran is located in the B category of the Koppen climate classification (dry), like most parts of Iran. The weather file used in this research is belongs to Mehrabad International Airport with the latitude of 35.683 and longitude of 51.317, located in an elevation of 1190.0 m. Figure 4 is illustrate a sun path diagram of Tehran, shows that the lowest altitude angle of the sun is 30 degrees which occurs in December 21. It is also noteworthy that on this day before 7:00 AM and after 4:45 PM, the lowest altitude angle is exist. The studied site area is 2813 m² and is located near the main street and an alley (Figure 5). There are various commercial, residential, and official buildings in surroundings. The studied building has twenty-five storeys with 4 m height for each. The façade is covered by glass. The surrounding area is highly dense and the reflection effect of the glass façade can have negative visual effects on the surrounding buildings.

Figure 4: Sun Path Diagram for Tehran (www.HarvestingRainwater.com.)
2.3. Objective Simulation and Optimization

In this study, Rhinoceros 3D and its Grasshopper add-on were adopted to simulate several building form. Rhinoceros add-on lets designers discover various creative and new forms without having any programming knowledge. Changing the complex form using main parameters facilitates obtaining desired forms by the architect. It is interesting to note that the building form created by this software can be transferred to other energy analysis software thanks to Ladybug tools which is set of several environmental analyse tools.

Through Ladybug, ray tracing simulation method is adopted to evaluate the reflected sunlight from the façade. The colour, intensity, and orientation of the sunlight changes at different times and this makes it difficult to analyse it after reflection from the façade. Ray tracing is very useful in this situation and identifies the places that have been under the influence of the reflected sunlight. This method can trace the light all day and it can provide information about the amount of reflection in different seasons or each hour of day.

The surrounding content of the studied building with a radius of 280 meters was modelled in Rhinoceros. The building has 25 stories with the total height of 100 meters. The geometrical plan of the building is considered a circle with a radius of 20.6 meters divided into 8 equal parts to select 8 points with equal distances. Then those 8 points were connected and created an octagonal structure. This octagon was copied vertically 5 times with a distance of 20 meters. The points on each curve were connected and the base form was made (Figure 4). These points are capable of moving from 0 to 3 meters in vertical and radial orientation. This has led to 192 different building forms.
After modelling the surrounding area and the building form, reflection simulation was conducted through Ladybug. The weather file (EPW file) of Tehran imported to Ladybug-Sunpath to trace the sun rays. As noted earlier, the lower the sun angle (winter and a couple hours after the sunrise and also before the sunset), the greater the chance of glare. Hence, the simulation times were set on the 22\textsuperscript{nd} of September for 7, 8, and 10 AM and also noon and 2, 4, 5, and 6 PM (Figure 7). The reflected points were identified tracing the sun rays. The chance of glare are directly related to the density of the points on the surrounding surface. Increasing the distance of the point and reducing the density leads to a reduction in the heat effect. Hence, the distance of the points in the algorithm was calculated and the average distance of them was used as a function for optimization.

Figure 7: Ray Tracing after Hitting the Building and its Reflection on the Surrounding Area

Figure 8: The Reflection Angle on the Base Form at 7 AM, 12, and 4 PM.
Optimization was conducted in Galapagos which uses evolutionary algorithms to solve the problems. In this research, the genome are the surface points of the studied building, creating the several forms. The average distance of the points on surrounding area was set as fitness objective in the Galapagos set to be maximum. The location of the surface points, were captured and illustrated as graphs after optimization to find the best optimum form (Figures 10 and 11).
3. Results and Discussion

The initial results of the base form simulation showed that the reflected point distribution in surrounding area were in radius form and point’s accumulation in some area were obvious. In this model, the lowest distance between two points was approximately zero and the highest was 4197 meters. The average distances after in optimize model are 1154 meters. Figure 9 illustrates the location (0 to 3) of each point (A to F) in each vertical level (1 to 8). Figure 11 compares movements on the levels in optimised form. The highest movement is belongs to the middle and base of the form.

Figure 11-A shows the scattering of the reflected points in the basic form at different times of the day. In this case, the scattering of the reflected points on the surrounding urban space is radial and concentrated in some places. However, in the optimized form of the building, the shape of Figure 11-B is a scattering of points with non-uniform distribution with appropriate distances, which has prevented the points from concentrating in one place. This facade has a zigzag form, which affects the scattering of the sun rays. Adopting different angles reduces chance of glare.

As mentioned earlier, in research and measures, the lack of a suitable criterion for measuring the glare caused by sunlight reflection in urban spaces during the day and the lack of a suitable method for simulating light reflection in the design phase has led to the creation of predictions. Visual Glare is somewhat difficult and impossible in urban spaces. The method and model presented in this study, due to tracking sunlight and measuring the density of reflected points from the building facade in urban space, eliminates the need to have a standard for glare and also provides the possibility to both in the design and after construction. At different times, he simulated and calculated the creation of glare points due to light reflection.
4. Conclusions
This study proposed a method for the simulation of sunlight reflection from the building in urban settings. Furthermore, this study also analysed the optimization of a high-rise building during the initial stages of design to reduce the effect of reflections. The optimization process includes parametric design, sunlight simulation, and form optimization with a genetic algorithm.

This method can generate a form with a less harmful for its surroundings according to the sunlight reflection. The function and efficacy of this method were analysed in a 25-floor office building with a glass façade in a dry climate. The parametric and flexible form generating method of this building made it possible to analyse the different distribution of sunlight reflection by a genetic algorithm.

The proposed framework in the Rhinoceros and Grasshopper helps the designers and researchers to have a better evaluation of the sunlight reflection from the façades at different times of the year. The result of the evaluation can be expanded and improved in the future, which can be done by adding various materials in the façade, analysis of different geometric shapes on the basic form, the influence of shading of buildings in this process, and applying this process to the building before its construction, problems caused by glaring and light reflection, and the addition of the heat produced due to the light reflection in the algorithm.

References
Wainwright, O. (2013). "Walkie Talkie architect “didn’t realise it was going to be so hot””. The Guardian 6.