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Research Article

Investigating the Effect of Stained-glass Area on Reducing the Cooling Energy of Buildings (Case Study: Ankara)

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Keywords

Cooling Load,
Energy Consumption,
Stained-glass,
Energy Simulation,
Optimization.

Abstract

The harmonious relationship of sustainable architecture with nature is one of the first things to be considered. In this regard, reducing the cooling load of buildings, especially in hot weather is very important. For this purpose, the use of different glass types in order to reduce the solar transmittance has become widespread. Among various types of glass used to reduce the solar transmittance, stained glass has been used for hundreds of years. The purpose of this article is to investigate the effect of paint level on transparent facade and reducing the cooling load of the building in summer. For this purpose, the level of these colors in glass has been modeled and optimized on two case examples of office buildings in the continental climate of Ankara. Simulations of these samples were performed for July and April using Rhino-grasshopper software. By optimizing the total minimum lighting energy and cooling load using the Galapagos plugin, the percentage of use of each color was determined. The obtained results can be evaluated according to the spatial orientation and the amount of radiant energy. According to the results, the area percentage of blue color in the window surface was found to be higher than other colors in the month of July (75% in the first case sample and 60% in the second case sample) and the purple color was found to be higher in the window surface as compared to other colors in April (30% in both samples). Yellow and orange colors in both samples had the lowest surface area percentage in the month of July (5% in both samples).

1. Introduction

Transparent materials transmit definite wavelengths of sunlight which are in invisible part. Glass can reflect, bend, transfer, and absorb light, all with great accuracy. The glass combinations display various physical, chemical, and optical attributes as shown in Table 1 [1]. The architectural glass comes in three different strength categories [2]: “Annealed glass, heat-strengthened glass, and fully tempered glass.” Generally, Annealed glass is the most advantageous glass in architectural buildings. It has a good surface flatness because it is not heat-treated. Therefore, it does not undergo any degradation that is typically observed during hardening of the glass [3].

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Table 1. Common commercial glass types and their applications [1]

Glass Type	“Primary Component”	“Linear Thermal Expansion”	“Thermal Shock Resistance”	“Chemical Resistance”	“Applications”
Borosilicate	SiO_2, B_2O_3	-30-60*10^{-7}/ºC	Average - High	High	“- Industrial equipment - Exterior lighting - Laboratory and kitchen glassware.”
Soda – Lime Silicate	SiO_2, Na_2O, CaO	-80-100*10^{-7}/ºC	Low	Average	“- Food and beverage containers - Windows - Lamp envelopes”
Phosphates	P_2O_3	-90-110*10^{-7}/ºC	Low	“Low/ except high resistance to hydrofluoric acid”	

The glass is produced from natural materials, e.g., sand, limestone and plant ashes. So, the changes in color occur by adding heavy metals. “In the Middle Age, stained glass was made by melting a mixture of washed siliceous sand and a flux. The flux used was either mineral (natron) or plant-based beech or fern-ash. The staining was attained during the fusion process by the addition of variable amounts of different metal oxides such as Co, Mn, Cu, Fe, etc.” [4-7].

Traditional building technologies have taught us a lot about how to design. Orosi glasses (Stained-Glasses) are known to be one of these technologies. The function of stained glass is essential for the environment, health and energy efficiency [8]. There are some new researches on conventional hydrochromic materials [8-10], photochromic materials [11-13] and thermochromic materials [14-16] which show that by researching the effect of different colors of the transparent surface of the building facade on optimizing energy consumption, a solution can be given for the development of nanomaterials.

This architectural element has kept its importance for ages. It has protected Iran against burning, complex and violent sunlight. It has been understood that Orosi lenses play an essential role in protection against solar rays as these severe solar rays damage Iranian woven fabrics, which are very valuable and easily deformable. The Orosi glasses were actively used until the end of the Qajar period in 1930 and as modern architectural practices began, the place was left to the widely used glass.

According to the results of the research by Haghshenas et al. [17], the transmission specimen did not match the human susceptibility curve in glass specimens. Blue and Red glasses were the colors with the highest human susceptibility. However, the yellow glasses were proven to be the lightest; they passed the yellow-orange spectrum, and the full range was between 62-75 nm, which did not include people’s visual sensitivity. The highest transmission spectrum for green glasses was also suitable for people’s visual senses and was considered the most appropriate color according to the optimum daylighting transmission of the glass [18].

In the study of different Orosi samples, it was found that colored and simple glasses were used together in all of them. Colored glasses included blue, red, green, and yellow colors. The amount of colored glass used was different; however, in 91% of them, the glass area was colorless. More than 50% of the glass area tends to be colorful in the samples of cold climate [19] and 100% of the glass area tends to be colorful in models of hot climate [18]. In an experiment carried out to determine the light transmittance at various wavelengths of colored and simple glasses belonging to Qazvin houses, the percentage of light passing through simple glasses and yellow glasses was higher as compared to the blue, red, and green samples [19]. Therefore, considering the high percentage of use of colorless and yellow glasses and high light transmission in them, it was determined that one of the factors influencing the selection of colored glass in Iranian architecture was attention to the climate. In the cold cities of Iran, there was a greater need for sunlight in order to provide comfort to inhabitants than in the central and desert towns of Yazd and Kashan.

The data obtained from the research conducted by Haghshenas et al. [6] shows that in 91% of the studied Orosi samples, more than 50% of light was found to be at wavelength of 555 nm, which is considered as the most sensitive value to the human eye, and this light passes through Orosi glasses. The point that needs to be taken into consideration is that in half of the total Orosi samples, this amount was more than 60%. The transmission spectrum of Orosi when compared with the spectrum of three bronze, colorless and blue glasses made according to the preferential spectrum, it was determined that the light transmission at 555 nm wavelength in these glasses is less than 60%. As a result, it can be concluded that, in general, the studied Orosi glasses are more suitable for the human eye in terms of light transmission as compared to the afore-mentioned three glasses [20]. The percentage of energy passing through the visible area in each Orosi shows that about 28% to 81% of the solar radiation energy in the visible area does not pass through the Orosi glasses and does not directly enter the interior spaces [5] [6] [21]. Therefore, considering that about 46.41% of the total solar radiation energy is in the visible range, the percentage of energy absorbed and reflected by Orosi glasses will be significant. Due to a relatively cold climate, during which there is a high need for internal space heating in winter, the observed amount of radiation energy passage is an acceptable value.

2. Methodology

Increasing energy consumption in buildings has paved the way for ecological designs of buildings that use energy efficiently [22]. In order to reach this point, there is plethora of energy simulation software programs used to design the future more efficiently. The required data for simulations and outputs may vary in different software programs, but their inputs and outputs are as follows [23]. It should be noted that the methods regarding information receiving and display vary in different software programs. The input data of simulator software are as follows:

Climate Data: It is the basis of all heating simulations. This data is inputted into the software for a given period of time or for a complete year.

Building Geometry: Form, size and surrounding of thermal zones, openings, shelters, the position of a building against sun, and other related information for building volume are all specified by defining the building geometry for the software. In some cases, the initial geometry of the environment may be drawn using other software such as CAD and then inputted into the simulator.

Construction Type: This includes the type of structure, materials, and other specifications of the geometry of a building.

Type/Amount of air conditioner equipment usage: Inputting this data is one of the most challenging steps of working with simulators by architects. Considering the direct effects of air conditioners on heating issues and energy consumption rate in buildings, it becomes necessary for some simulators to define the specifications of the related equipment. In contrast, in some other simulators, there are default values.

Occupancy and information of the resident: The rate of internal loads is specified with an hour-hour schedule.

The software also requires the type of coverage and individuals' activities in these periods for simulations as well as the kind and rate of other equipment usages like lighting.

Additional information: This information may vary for different cases, for example, the open/close status of openings.

After simulating, simulator software may have various outputs as follows:

Rate of humidity and temperature of each thermal zone

The temperature of other surfaces in thermal zones

Variables for air conditioner equipment

Rate of energy consumption of all components or whole building

Rate and kind of thermal behavior between neighbor thermal zones

Rate of receiving solar energy

2.1. Energy-Plus Software

Energy-Plus [24] is one of the most critical simulations and Energy Analysis Software products for buildings. This software can calculate cooling and heating loads using primary data such as physical structure, residents, mechanical and electrical systems, and annual climate data. It can also calculate the air temperature or all building spaces based on its specifications, mechanical systems, and topography in any time interval.

The software has no Graphical User Interface, and its inputs and outputs are textual. On the main page of this program, there is one window specified for row list in which different data describing all buildings elements are classified and listed. Users have to define and insert required data fields to make it possible for the software to simulate the building's heating performance and produce related outputs for the user [25].

Although the lack of Graphical User Interface [26] in the software makes its usage difficult to some extent, the software can be used along with many GUI programs as a powerful simulator motor. In other words, users can use other GUI software programs to provide text inputs for Energy Plus and facilitate their required results [27]. This software is considered one of the most popular ones in building energy simulation, having different options for simulating passive and renewable systems such as photovoltaic panels [28].

The Energy-Plus Software combines two valid older software programs, namely DOE-2 and Blast [29-31]. Typically, this software simulates buildings' hourly conditions. By considering different air conditioners and other existing equipment in the buildings, the software presents the accurate needed energy content. The output of Blast software can be used to calculate the biological cycle cost of the building [24]. However, the Energy-Plus Software has some limitations for the number of heating and simulation areas, which should be known before starting the simulation process.

2.2. Other Applications of Energy Simulator

Some energy simulator software specially designed for architecture development can simulate renewable energy effectiveness and passive systems. These software programs are useful for initial designs and applicable scales.

In other words, the software can use energy simulations as input data to analyze new outputs, for example, costs and bills, life cycle cost, etc.

However, there are some specialized software programs used for this purpose. BEES [32] and Athena [33] are the two most common software which can calculate cost and bills and life cycle cost from construction to destruction. However, it should be noted that the input data of these software programs are based on regional information. Verifying building life cycle cost will suggest the building aspects such as economic resistance and environmental issues in their life cycle.

2.3. Lighting Simulation

Lighting simulation is one of the most commonly used simulations in architecture design. Reinhart et al. suggested the usage of lighting simulator software for the initial design [34]. Considering the image nature of these simulations, they have more uses than energy and thermal software.

Lighting simulation is significant in the initial steps of design. In the Curve, Reinhart [35] has presented different changes after good lighting design for buildings. These changes include many design elements.

In lighting simulation, the electrical lighting and natural lighting should be considered simultaneously. Factors such as natural lighting (direct, scattered, and reflected light) received from outside of a building, space geometry, space coverage material, form, location and surface of openings, shelter type, and materials and other lighting equipment have all direct effects on the quality of internal space lighting.

Two standard methods for lighting simulations are Ray Tracing and Radiosity, respectively [36].

In the Ray-tracing method, the software emits some rays from the observer point and then images their reflection when they reach different subjects in a room on an imaginary plane [37]. This process is repeated until all rays in the room are be imaged.

In the Radiosity method, the software converts all planes into smaller ones and calculates the lighting transfer rate between them [37]. In this method, lighting starts from light sources, and its reflection paths are followed in internal space.

Simulation software can use either one or both of these methods. There are different outputs for these software programs. These outputs can be numerical, imaginary, colored images or imaginary outcome and its imaged information [38].

The lighting simulation software is most commonly used in a daylight design and a design for artificial lightings. Generally, at initial architectural design, architects do not consider artificial lighting. They focus on natural lighting as it is critical. Daylight analyzer helps architects in this regard. In many software programs, lighting simulation has the same quality as photographs. Additionally, these images can be analyzed.

The drawn lines suggest the margin of regions with the same illuminance level. These two images together enable the designer to percept the lighting quality and quantity simultaneously.

There are several software products available for lighting simulation. One of them is AG132. The software can input DWG and DXF files for rendering and analyzing artificial and natural lighting. Lighting conditions can be measured for a given time and interval using AG132 (Figure 1) [39]. One other advantage of this software is the discount it provides for students and academicians.

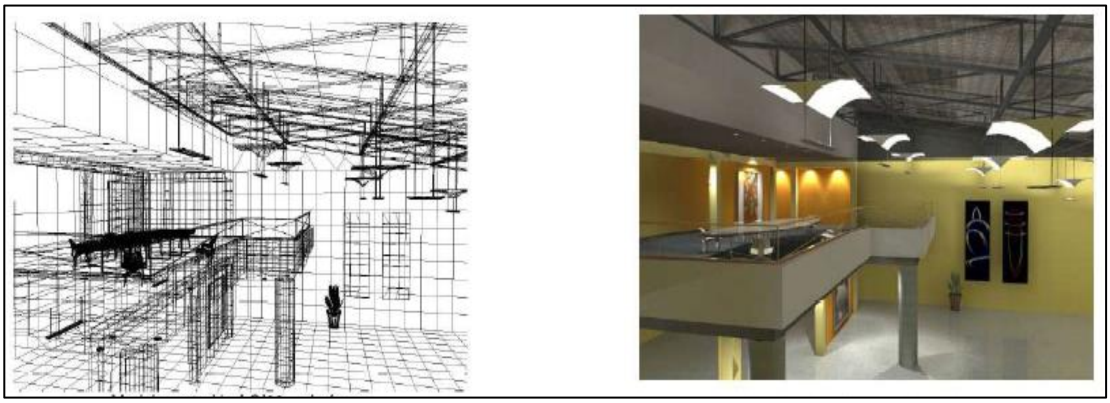

Figure 1. Sample of AG132 outputs [33]

Radiance [40] is the other simulation motor used which is highly applicable in lighting processes. This simulator motor working under Windows and Linux is free of cost and can be used for lighting simulation of different spaces and materials. Other software programs such as IES Radiance [41], Daysim [42], Rayfront [43], Echotect, etc., use Radiance for lighting simulation. Form Z RadioZity [44] and Lumen Micro [45] are other available lighting simulator software programs. At first, the copyright of these simulation software programs was owned by US Energy Department and Switzerland Federal Government; but now, their copyright is owned by California university [46]. A sample of radiance software outputs has been shown in Figure 2.

Figure 2. Sample of radiance software outputs [40]

Radiance is a set of analysis and lighting design display software. Space geometry, material, reflector surfaces, time, date, and sky status are the inputs of this software for lighting simulation. Using calculated values, the software results can be presented as 3D color images, numerical values, and some other information can also be displayed as images [40].

One of the most critical aspects of this software is the non-limitation of space geometry and diverse materials in simple lighting simulation. Radiance can be used to simulate lighting quality and test or rate innovative design methods in research centers. This software presents different procedures for problem-solving, which can be used for performing time-saving and accurate simulations.

2.4. Coding in Rhino Grasshopper

Geometry is one of the most fundamental architectural infrastructures by which the relationships between forms, currents, spaces, their sizes and proportions, the composition of components, and the relationship between them and their features are examined. Since it is presented in computer, space and geometry can communicate with the programming language within 3D software modeling. Establishing the relationship between programmer bases and geometry in 3D software has led to algorithmic processes in the design of shapes and volumes.

Algorithmic architecture attempts to determine the parameters affecting the physical behavior of the building in the process of continuous analysis in order to impact architecture at the right time and correct the design in feedback loops. A designer's insistence on advancing a former concept and the engineering team's coercion to build that design is no longer the best way of architecture design. Algorithmic design-analysis cycles investigate and produce the options, and after completing various analyzes on the design, they resolve the deficiencies and problems [47]. The design consists of a repeatable process of influencing and weighing parameters, generating options before analyzing and receiving feedback, re-applying them to design parameters to produce revised options, and then repeats itself to eventually achieve a desirable result as the final output. The software used in this study is defined in three broad sections—generator algorithm section, Heating section, and lighting section, which perform a process of optimization to reduce energy consumption.

The algorithm of producing the model's geometry needs to be defined first in order to investigate all possible scenarios and create sample spaces which are known as the generator algorithm. Generator algorithms in the architecture can produce all design scenarios. These algorithms cover special issues related to space design and architecture in CAD software combined with its features and commands. Also, these algorithms perform a change in the percentage of colored glasses by selecting several input items and controlling them. Moreover, by changing the parameters, all permutations produced by the combination of different rates of colored glasses can be made. The Rhino [48] software and the Grasshopper [49] plugin were used to define the generator algorithm and geometry in 3D space.

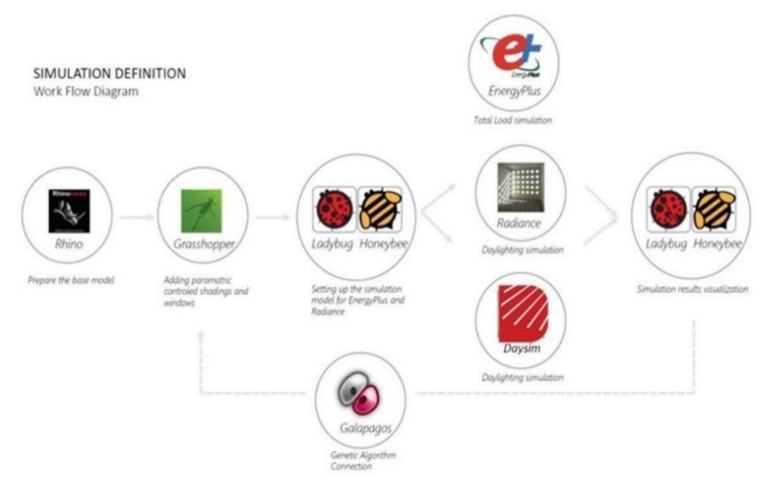

Figure 3. Samples simulation diagram in Rhino- Grasshopper

A parametric model can be produced with this plugin and its specifications can be changed by modifying its constituent parameters. To determine the thermal effects, the Energy Plus software engine, the lighting effects of the computing engine, the Radians, and Daysim software programs were used. The Honeybee [50] add-on and the computing engine's graphical interface were selected to transfer information between the generated geometry in the Grasshopper header and the computational engine. In the optimization section, the Galapagos [51] solution plugin was utilized. Figure 3 shows the workflow diagram of simulations of samples in a software environment.

3. Case Study

Grasshopper program has been used to investigate the effect of color in reducing radiant energy and cooling loads of the building on transparent outside facades. Two rooms on different sides of the office building have been simulated. The percentage of yellow, orange, red, green, blue, and purple colors with a minimum of radiant energy transmission and maximum light passage were optimized. The colors on the glass surface were assumed to be vertical, and the minimum percentage of colors was found to be five percent.

Two estimated samples were investigated in Ankara (Tepe Prime Office Block), located in the northern hemisphere where the sun follows an arc, rises in the east and sets in the west. Tepe Prime project consisted of curtain wall systems and glass panel covering elements [52]. As regards, the essential facades for solar heat gain are known to be south and west. Therefore, the 1st sample selected was located on the south facade, and the 2nd one was located on the west facade (Figure 4).

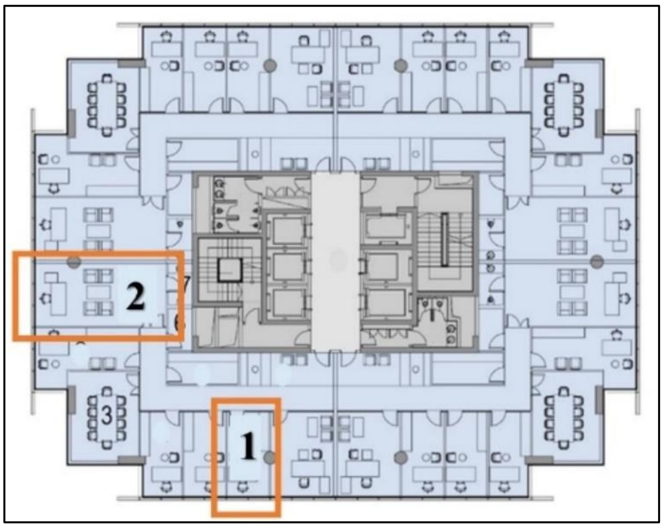

Figure 4. The plan of 15th floor of A block (official building) of TEPE PRIME [53] and the location of 1st and 2nd samples

4. Results and Discussion

Colored glasses have different thermal and lighting properties, and the effect that the colored glass has on energy consumption is the result of thermal effects and brightness. The scripting of starting parameters (user-defined parametric inputs) was listed in Figure 5.

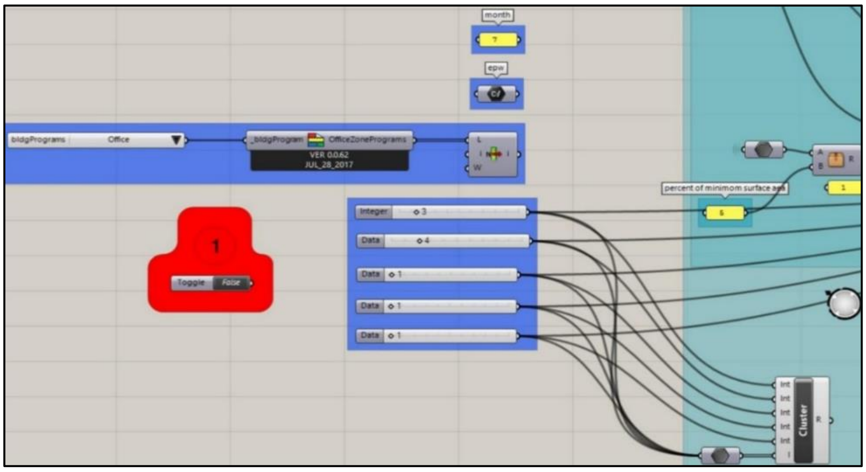

Figure 5. Starting parameters: User-defined parametric inputs

In the next step, with the aid of thermal and lighting simulators, the effect of change in the percentage of colored glasses on energy consumption was calculated, and the results were analyzed. The Radians and Daysim software programs, and the Energy Plus software engine were used to determine the thermal effects, and the computing engine's lighting effects, respectively. The Honeybee add-on, which is the graphical interface of the computing engines, was selected to transfer information between the generated geometry in the Grasshopper header and the computational engine.

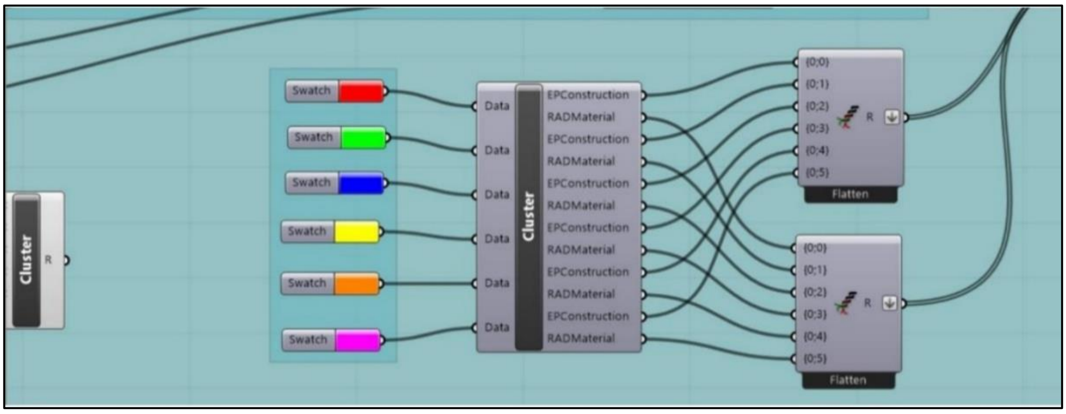

Figure 6. Algorithm for colors and glass properties

The thermal analysis uses the thermal properties of materials. These specifications in colored glasses include thickness, thermal conductivity, and transmittance rates of radiation at various frequencies. In this study, the thickness of the glass was 2 mm, and the conductivity coefficient was 0.9 w/mk. The transmission rate of the received radiation also varied according to the glass color (Figure 6).

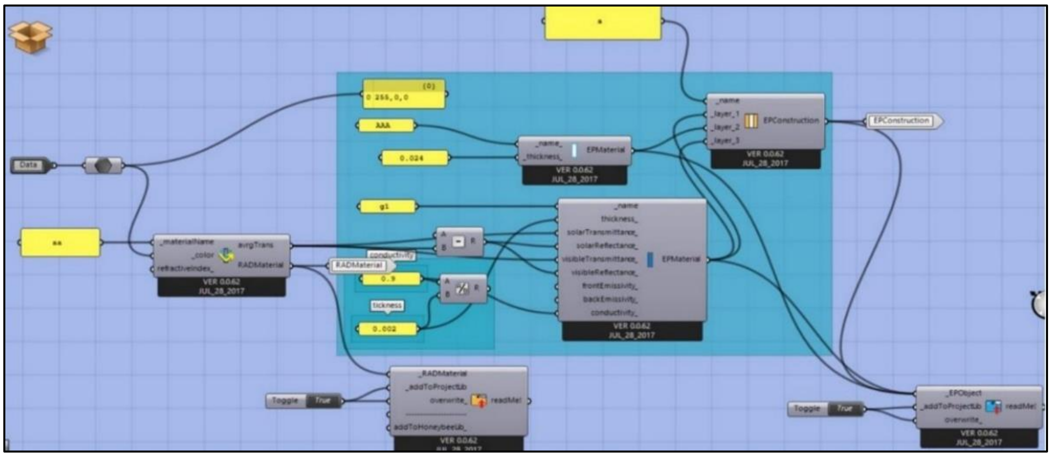

Figure 7. The inside parameters of material cluster

The middle part of algorithm is a cluster that contains the material properties such as glass thickness, solar and visible transmittance for each color as shown in Figure 7.

Since our aim was to estimate the influence of the percentage of colored glasses on energy consumption, the other thermal zone levels were defined as adiabatic in order to exclude heat transfer from the calculations.

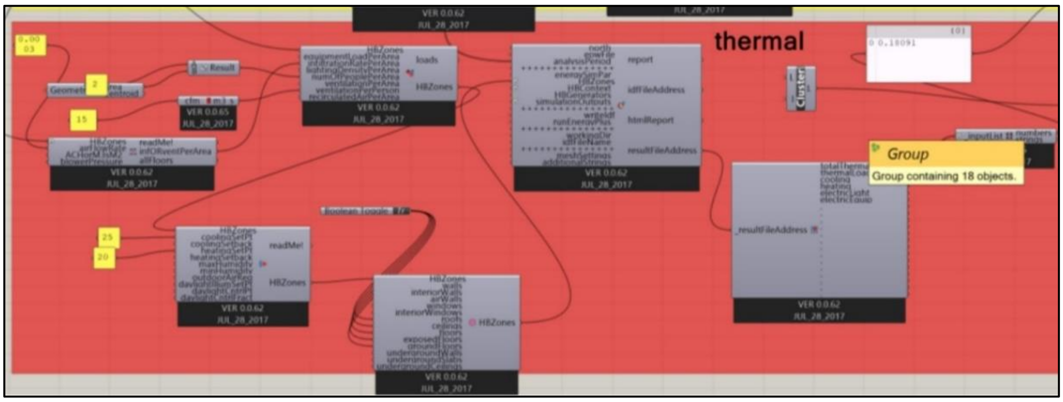

Figure 8. The algorithm of Thermal analysis in Grasshopper

Estimation of energy consumption depends on the amount of operation and the hours of mechanical facility usage. Therefore, the cooling set point and heating set point were defined, respectively, as the thermal zone for switching the mechanical installations on and off at 25 and 20 degrees Celsius. There were two users in the thermal zone, and each needed 15 cfm of fresh air through ventilation. The thermal analysis was carried out for the warm month of a year from 8th to 18th, and also the cooling load factor was calculated. Eventually, the amount of energy consumed by the illumination unit was calculated during the same period by analyzing the radians and the days.

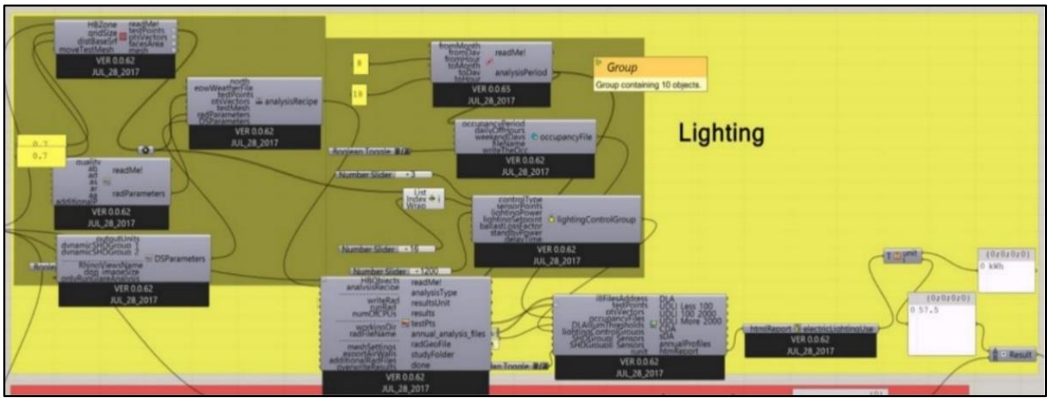

Figure 9. The algorithm of lighting analysis in Grasshopper

In analyzes of lighting, optical properties of surfaces exposed to light are used. These characteristics in colored glasses include refractive index, reflection, and visible light rays, which vary according to the color of the glass. The Radians software calculates the brightness of the light according to the optical properties of the surfaces for a given time, and it can't cover a period. Since the thermal energy analysis is carried out monthly, light analyses should be performed after a monthly interval. In our study, these analyses were carried out by the software Daysim. The Daysim is used for lighting analyzes from the Radians computing engine for a specified range.

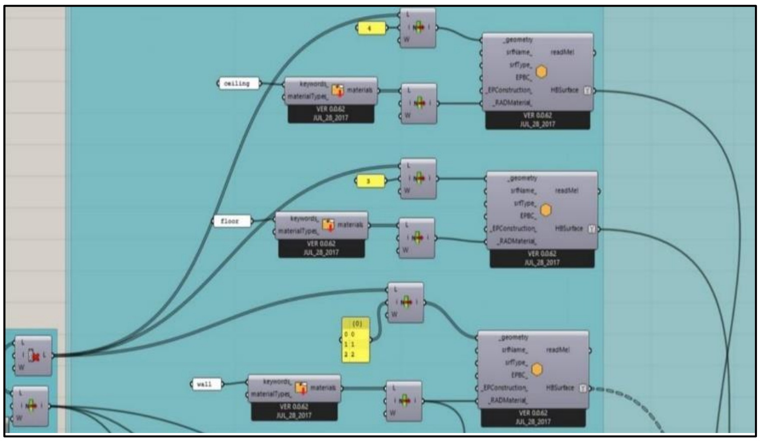

Figure 10. Middle section of code in modeling part

The amount of energy consumed by the lighting unit is estimated based on the usage of artificial light in the absence of natural light. When the natural light level of the room is less than the optimal, artificial lighting turns on and compensates for the lack of brightness. In this way, the number of hours that lamps are kept on is determined, and by determining the power consumption of the lamps, the amount of energy consumed can be calculated. The desired brightness value (set point) was considered to be 300 lux, and power consumption was considered to be 1200 watts. After calculating the energy consumption of the lighting sector, this number was combined with the thermal energy consumption, and the total value obtained was the measure of the optimal layout of colored glasses.

As previously mentioned, in order to analyze the software, we must have a software space as a real test. Therefore, for our samples, the algorithms were written to define parametric objects in "Grasshopper" with "Ladybug" and "Honeybee" connection plugins. To calculate and analyze the solar irradiance, "Energy-Plus" was added, and to test daylighting, "Radiance" and "Daysim" were used. All these plugins can be accessed by Rhino graphic program to see the changes.

The middle part of geometry modeling of samples in grasshopper is shown in Figure 10.

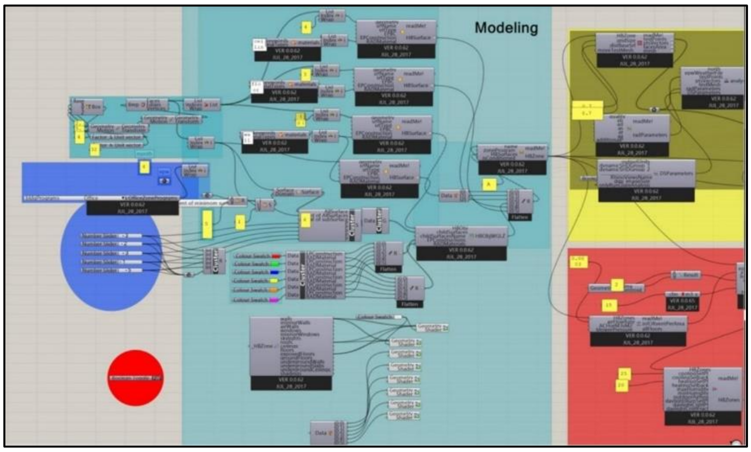

Figure 11. The algorithm of modeling of 1st sample in Grasshopper

Samples were modeled in Rhino-Grasshopper to analyze the results, as shown in a screenshot of modeling in Figure 11. Thermal and lighting algorithms have been added as shown. The results of simulation of electricity consumption and final optimization have also been given below.

The monthly cooling loads of zones were cached, and due to daylighting and cooling energy, the required electrical energy was achieved in "kwh". GALAPAGOS (Genetic Algorithm and Presentation-Assisted Graphic Object layout System) [54] solution plugin was used to optimize countless inquiry responses. Max. Stagnant and Population were selected as 20 and 10, respectively, by selecting initial boost value to be 2 in Evolutionary solver part of GALAPAGOS. The results achieved can be seen in Figure 12.

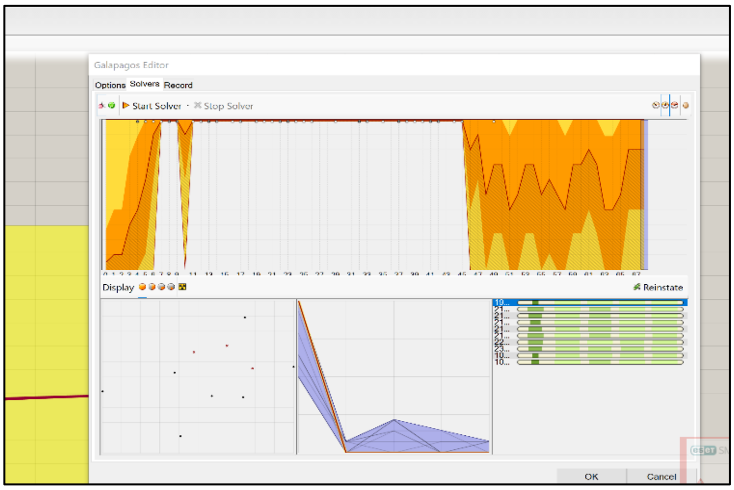

Figure 12. First sample optimization result in July and total energy consumption with Galapagos

The optimization results with the best reply to minimum thermal transmission and maximum daylighting transfer obtained using the Galapagos optimization machine for 1st sample has been shown in Figures 13 and 14.

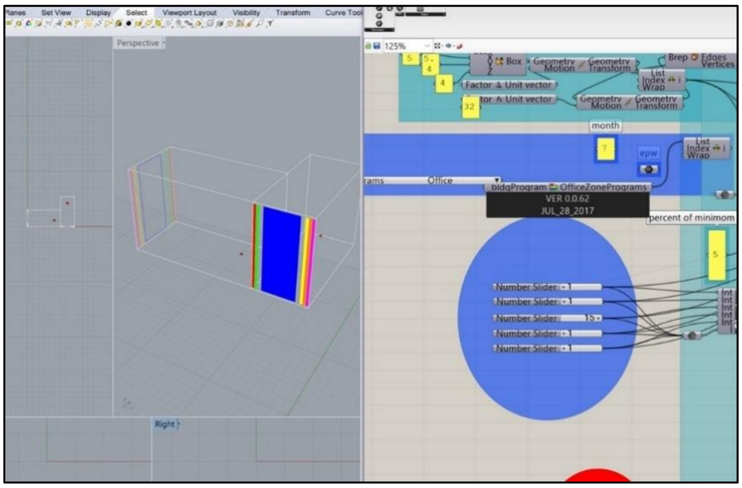

Figure 13. First sample optimization results in July and optimal scheme of colors with Galapagos

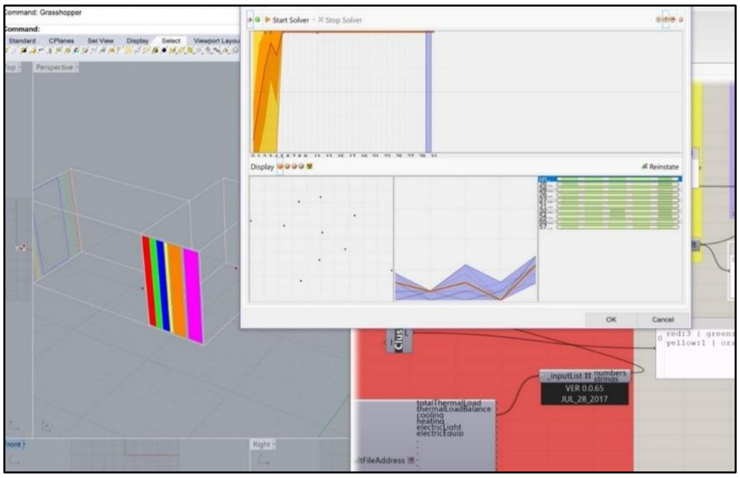

Figure 14. First sample optimization result in April with Galapagos

The simulation results of two samples (for the months of July and April) were obtained using Rhino-grasshopper and the Galapagos plugin [55] was used to determine the optimization in the afore-mentioned continental climate. According to the simulation, the result found was the lowest total amount of lighting and cooling energy consumptions among all randomly simulated phases by Galapagos algorithm, without considering natural ventilation (Table 2).

Table 2. Lighting and cooling energy consumptions of the Two Samples in two months

	First Sample in April	First Sample in July	Second Sample in April	Second Sample in July
Monthly lighting energy consumption (kWh)	0 kWh	32.8 kWh	45.5 kWh	35 kWh
Monthly cooling energy consumption (kWh)	0.18 kWh	105.87 kWh	0.175 kWh	99 kWh

The optimization results achieved using Galapagos optimization machine to estimate the minimum thermal transmission and maximum daylighting transfer for 1st and 2nd samples have been shown in Table 3:

Table 3. Optimization format of color area percent on glass area

	Yellow	Red	Blue	Green	Orange	Purple
1st sample color area In July	5%	5%	75%	5%	5%	5%
1st sample color area In April	5%	15%	15%	10%	25%	30%
2nd sample color area In July	5%	15%	60%	5%	5%	10%
2nd sample color area In April	10%	5%	35%	10%	10%	30%

Yellow and orange colors were found to have the minimum area percentages in July, whereas, Blue had the maximum area percentage in July. In the optimization results of April, the colors were found to have different behaviors in two different orientations originating from medium sunlight in Ankara during April. All the colors have some roles in case study of transparent facades.

5. Conclusion

Stained glasses have different thermal and lighting properties. The effect of glass on energy consumption is the result of thermal and brightness effects. It has been shown in the previously conducted researches that the heat gain is not reduced, and visual comfort can be achieved indoors. These two properties are proved by the percentage of the spectrum passing through the colored glasses (different wavelengths). According to the research, radiation does not only consist of the transition rate in the long-wavelength section. For this purpose, the use of colors on the facades, especially on sizeable transparent glass surfaces, based on colored glasses, was thought to provide these benefits in today's architecture. In addition to coping with these challenges, a design method was investigated in which cooling load could be decreased, and lighting comfort could be provided. This paper aims to develop a new method using stained glass as a sustainable design tool for daylight and radiant energy performance analyses of buildings. The simulation was performed on two samples in Ankara using coding in Rhino-Grasshopper in the months of July and April. The optimization was carried out using Galapagos and considering at least the sum of two variables of lighting and cooling energy consumptions. According to the results, the maximum power obtained for lighting energy consumption was 45 kWh in April, whereas, the maximum power obtained for the cooling energy consumption was 105 kWh in July. The blue color on the southern and western transparent facades had a relatively maximum area. In the previous generation of optimization in Galapagos plugin, the results showed higher area percentage for green color and lower for blue color. For future work, the results of these two colors can be checked in other samples. The study has been conducted without considering natural ventilation. Therefore, natural ventilation may also be considered for future works. Also, the effect of the color of transparent facades on window-to-wall ratio (WWR) can be examined.

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