Using genetic algorithms in parametric building facade design to create different atmospheres

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Abstract

In this project, genetic algorithms (GA) are combined with parametric building facade design and daylight optimization systems to create different atmospheres. The parametric design will dictate how sunlight is transmitted into a room and the end will influence how a room is perceived. In this project 3 parametric designs are implemented in Rhino and Grasshopper and the daylight measurements are done through Ladybug and Honeybee using lux measurement. In this project a total of 3 test scenarios was conducted in order to determine whether this method would be effective in creating different lightning scenarios. In general, the evaluation shows that this method is useful in terms of creating different lightning scenarios that will impact how a room is perceived. However, to fully confirm the capabilities of this method in terms of creating different atmospheres further research is needed.

1 Introduction

Creating atmospheres in real time experiences such as video games is important in order to convey a message or invoke certain feelings. Böhme describes atmospheres as something that like a haze fills up a space and evokes “a certain tone of feelings” (Böhme, 1993 [1]). A lot of parameters can influence an environment’s atmosphere and one of the most impacting is the light. It has been shown that light has major impact on how interior spaces is perceived [2, 3, 4]. For an interior space sunlight plays an important role and the shape, size and patterns of the windows will influence how the sunlight transmits through and in end how a room is perceived. It will also influence how the artificial light inside should be arranged to complement that. This is a major topic in architectural design where buildings are designed to preserve the sunlight and decrease the need for artificial lights. However, it also important to minimize the visual discomfort caused by glare [5] , and therefore in the typical design goal is to create with an environment bright diffuse light setting and no visual discomfort caused by glare. This type of lightning scenario is common in modern workplaces and being present in this type of environment one might find oneself enveloped by an atmosphere. How this atmosphere is perceived might differ from person to person, but in nevertheless this type of lighting scenario certainly does play a major factor on the impression of the room space.

Balancing between daylight saving and glare probability is a typical optimization problem in architecture. In parametric building design this optimization problem can be addressed in a more effective way since it allows the designer to change certain parameters of the design in a virtual environment and then observe the outcome instantly. However, observing all the possible scenarios is time consuming and for complicated designs the amount of possibilities are near infinite. Genetic algorithms (GA) provide an agile solution for this because they facilitate a search-oriented design that will improve over time and in the end find an optimal solution to a problem, based on a fitness criterion. In recent years several architectural studies has used genetic algorithms to solve this specific optimization problem, whether it is in regards to building facades, building geometry/shape [6, 7, 8], or the placement of multiple buildings. [9]

One of the strength of the GA is its versatility and it can be used for many different purposes. In video games GA can be used as an algorithm to make procedural generated content, based on a fitness criterion set by an artist or game designer, which might be an optimization problem different from the one concerning daylight savings. Lightning design in games might serve different purpose as for example highlighting certain areas in an environment with the light or creating different atmospheres. Regardless of the design goal this method of using GA in parametric building design has a strong potential usage for environmental and lighting design in games. This project will make use of the daylight measurements used in architectural design and use GA's to procedural generate parametric building design that will radiate different atmospheres. The initial problem statement of this project is:

> How can genetic algorithms and parametric building design be used to create different atmospheres in games?

2 Background

2.0.1 Atmospheres

Defining atmosphere is a complicated subject and is beyond the scope of this project. The understanding of an atmosphere in this project is derived from Gernot Böhmes definition. Böhme describes the qualities of atmospheres by saying "[t]hey seem to fill the space with a certain tone of feeling like a haze" (Böhme [1], 1993: 113-114) that is "conceived as ecstasies". He defines atmosphere as something with gas-like qualities as it surrounds the humans, objects or the environment. As such one can find oneself enveloped by an atmosphere when entering a room or a an environment as it radiates a certain atmosphere as for example friendly, warming, tense or anxious [10] The same way another human or even an object might radiate a certain atmosphere that is perceived by the observer. It is difficult to define atmosphere as something subjective or objective as Böhme notes ambiguous status of atmospheres.

> ...atmospheres are neither something objective, that is, qualities possessed by things, and yet they are something thinglike, belonging to the thing in that things articulate their presence through qualities – conceived as ecstasies. Nor are atmospheres something subjective, for example determinations of a psychic state. And yet they are subject like, belong to subjects in that they are sense in bodily presence by human beings and this sensing is at the same time a bodily state of being of subjects in space (Böhme, 1993: 122 [1])

Being present in any kind of environment will affect one's emotional state based on the atmospheric qualities of that environment. While it can be difficult to describe atmospheres in general it seems straightforward to exemplify when describing a room. As an example a sunny day might be described as joy full and a relaxed [11, 12, 13] and a grey day might be perceived as sad [14]. Knowing how to create different atmospheres is important in the artistic field. If the artist wants to convey a message or evoke certain feelings it is important that the atmosphere substantiate this. Regardless whether it is a video game, a film, an art installation, or painting or anything else, it is important that the artist is aware of the topic atmospheres, and being able to control this means that the artist is able to do his job well.

There are many things can contribute to an atmosphere in an environment such as light, sound, object materials etc. A.Felnhofer et. al [15] investigated how different virtual environments affected the user. In their study they created five different virtual park environments each intended to elicit a specific emotion: joy, sadness, boredom, anger and anxiety. By examining how other studies were able to elicit the aforementioned feelings, they were successful in the creation of the 5 park environments as they were able to elicit the intended emotions. A similar project by R.M. Baños [14] played with a binary configuration of two different park environments intended to evoke happiness and sadness respectively. The idea was to switch between the two environments in real-time and see if the changes would affect the mood state of the user. Their results show that it was possible to achieve this.

In these two examples a lot of different measures were used to achieve a specific atmosphere and elicit different emotions of the users. Incidentally this shows that with a lot of parameters any atmosphere can be achieved. However, it also possible to achieve this by only changing one parameter, as it has been shown that light can influence how an atmosphere is perceived, as M. Naqshbandi and R. Munir [4] found that lighting was the most influential factor on the impression of hotel lobbies.

A. Naz et. al [16] investigated how light properties such as brightness (bright and dark) and color (blue or orange) in cooperation with material properties (smooth or rough) had an influence on how a virtual space was perceived in both active and inactive setups. They found significant difference between the colors and how they felt. The orange light felt warmer and blue light felt cooler.

In terms of brightness they found that brighter light settings made the space seem more spacious, and the darker light settings more suited for resting. In addition to this the brightness of the light also has an influence on the materials used in the virtual space. In darker areas the participants preferred smooth material when working. The brightness also has an influence on the perceived warmth of the room in the active setup. This result shows that while color has a significant influence on the perceived space the brightness also has an influence, which was also found by C. C. Countryman and S. Jang [2]

D. Ayşe et. al [3] investigated how different light arrangements and different levels of illuminance could give different impressions of a room in terms of clarity, spaciousness, relaxation, privacy and pleasantness and order. In their study they had 3 different types of lightning arrangements: general lightning, wall washing and cove lightning and two different levels of illuminance: 500 lux and 320 lux. Their results show that there are a significant difference between the impression of the room and the lightning arrangements and lightning levels respectively. This underlies the importance of lightning design as it will affect the perception of any kind of space, and thus being able to optimize a building design through an algorithm is very powerful. It allows the designer to set a criteria based on e.g. lux measurements, and then the genetic algorithm will optimize the building design to meet that criteria. In this project the ambition is to create different atmospheres based on a given fitness criteria that states the target lux value in different sections of a room space. Being able to optimize a design to fit this kind of criteria can be very useful not only in architectural design but also in game design or when designing any kind of virtual environment.

2.1 Genetic Algorithm

Genetic algorithms are a computational model based on the theory of evolution. The theoretic discussion of genetic algorithms can be dated back to the 1975 where John H. Holland first proposed the idea [17]. and has been developed for machine learning and optimization problems [18, 19, 20] and in a conceptual process [21].

They are useful to solve optimization problems where there are several parameters to consider. As an example, in architecture the optimization problem could reduce the need for artificial light by allowing more sunlight to pass through without causing visual discomfort such as glare. These two goals are in some sense contradicting and for this GA can be used to optimize the design such that both criteria are fulfilled. This is known as a multi-objective optimization, but the GA can also be used for a single-objective optimization, which is in this case would be to optimize either of the two criteria alone. The basic structure of a GA can be seen in Figure 1.

Population The GA starts of with a population of possible solutions often based on a random selection of the given parameters. The success of each individual solution determines how likely it is to be used to create offspring in the next generation of solutions. This follows the evolutionary principle of natural selection or "survival of the fittest", which in this case ensures that critical information is preserved and used in a re-combination with other successful individuals. The assumption here is the combination of the good characteristics from two or more successful individuals will produce an even more successful offspring. This way the population will grow to become more suited for their task, which is defined by the fitness score.

Calculate fitness score Regardless of whether it is a single- or multi-objective optimization problem, the success of each solution in the population is calculated based on a fitness function. The fitness function is defined by the designer, and it describes the optimal target in the optimization problem. The comparison between optimal target and a given individual solution determines its fitness score and thus its success. Those solutions with the highest value in the fitness function will be more likely to create offspring in the crossover phase. The rest will be not be considered in the crossover phase and will “die out” and thus the term “survival of the fittest” applies.

Crossover In this step the characteristics from the best solutions will be recombined in different ways to create offspring for a new population. The selection of the best solutions can be based on many different determinations. There is absolute elitism that only takes the two best solutions, and there are others method that breeds from several solutions. None of these are necessarily superior as they have their pros and cons. Breeding a generation from few solutions might lead to faster convergence but might result in inbreeding and thus produces a local maxima and not an optimal solution and breeding from a larger population might result in the opposite.

Mutation A way to prevent inbreeding and ensure that the GA won’t reach a local maxima is to use mutation. Mutation expands the search space and ensures diversity in the population by altering or “mutating” the solutions by a random factor. The mutation is set by a mutation probability, and the value of that dictates the same balance as the crossover breeding method. A low mutation probability might result in the GA reaching a local maxima and a high probability might lead to slower convergence and essentially a mutation probability set to 100 or close to eliminates the idea of GA as all solutions would be randomly generated.

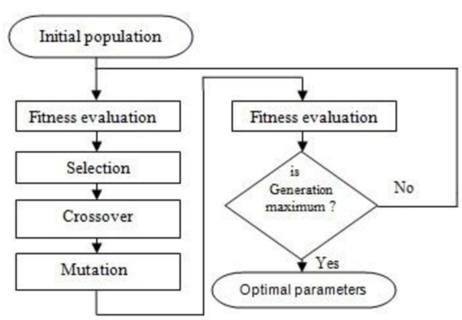

Figure 1: A figure showing the overview of Genetic Algorithms [22]

These steps encode for one generation in a GA. This process is repeated and thus the GA runs for several generations unit it meets the fitness criteria. If correctly implemented the population will improve with each generation and the average fitness in each generation will increase towards the global optimum. One of the strengths of the GA is its versatility as it can be applied to many different optimization problems [18]. With GA it is possible to find optimized solutions for complicated problems and allows for a fast search-based optimization.

2.1.1 Parametric Building facades

Building facade design is an important field in architectural design and it has a lot of influence on the building properties such as energy consumption [23], daylight systems [24, 25], exterior noise [26] etc. The building facade not only dictates the visual appearance of building but also the window placement and size and thus how the sunlight transmit through and illuminates a room space. A common goal in architectural design is to preserve the incoming sunlight and reduce the need for artificial. However, allowing to much sunlight to transmit through might cause visual discomfort such as glare. This creates a design challenge since accomplishing one of these goal might reduce the chances of accomplishing the other. In addition that the key to a great architectural design is create a building design that also have a visually aesthetic exterior whilst maintaining the goal of having a visually comfortable lighting scenario on the interior. Achieving both of these is difficult and it might take countless of design iterations to reach that. Luckily this process has been optimized significantly with the method of parametric building design.

Parametric systems have made it easier for an architectural designer to produce countless of iterations. By adjust a set of parameters in a virtual environment, the designer can investigate many different variations of a building design. However, investigating all the possibilities would be near impossible, which is why genetic algorithms are useful. Genetic algorithms provide a framework which allows for a search of the optimal solution in an infinite generative field of variation as W. H. Ko [7] describes. In this sense the parametric system becomes the genome, the field of possibilities becomes the population and the designer's goals becomes the fitness function. In this sense the parametric system becomes the genome, the field of possibilities becomes the population and the designer's goals becomes the fitness function.

Genetic algorithms have been used a lot for architectural purposes where to optimize daylight systems. With genetic algorithms is possible to simulate the many possible outcomes in a more effective way and thus increases the usefulness of parametric design in architecture. D.Tuhus-Dubrow and M. Krarti [6] used GA to investigate different geometrical shapes for buildings; rectangle, U-Shape, H-shape, L-shape, T-shape Trapezoid and cross shape. In addition to this the wall, roof and window configurations were also considered in the optimization.

This project investigates optimization of the building shape which alienates the design projects where the geometric shape is given beforehand and the goal is to optimize the façade of this building. Making a parametric design that focuses on the facades extends the usage of this method to even more projects.

A simple version of this type of project was proposed by J. Wright and M.Mourshed [27] which had a building split into a series of cells with two possible states; a window or a solid wall. The GA would then optimize the state of each cell to reduce the buildings energy usage and preserve the daylight. This project shows a simple and straightforward way of making a parametric design based on a rectangular building facade. A similar parametric design was proposed by L. G. Caldas and L. K. Norford [28] where the placing and sizing of windows in an office building were controlled by a GA. The investigated the optimal solution for the environmental performance of the building: lighting and thermal.

S. Torres and Y.Sakamoto [24] presented a more complex parametric design of a building facade. Their parametric design consisted of 21 parameters which in combination encoded the sizes, number and position of the windows. Their results show that genetic algorithms are a consistent and reliable method for optimizing this problem. They found consistency in several runs of the design, which ensures an optimized solution to the problem and not a local maximum. One of the downsides of using genetic algorithms is that they can become computationally heavy since even 1 generation might contain a lot of simulations. They tried to reduce this by only using a sub-set of their meteorological data and not the entire annual data. In addition to that, they also used absolute elitism when picking the individuals used for breeding in the next generation. In order to avoid local maxima three randomly picked individuals were also picked and included in the breeding group. This paper supports the motivation of using genetic algorithms for parametric building facades as the test results determines its applicability. In addition to this the paper also approaches several optimization techniques for genetic algorithms that are important to consider in this project.

J.M. L. Gagne, and M.Andersen [25] made a similar project that where GA was used to optimize the design of a building facade. They assumed that the shape of the building would remain the same and only the building facade would change based on the parameters. They set up 10 different parameters for the windows properties of the building including the properties of the glass and measured the illumination percentage and the glare probability. They ran two tests which demonstrated the GA applicability for both one-dimensional (illumination only) and two-dimensional (glare and illumination). The test results showed that GA were applicable in both cases. F. Bre et. al [29] made a building design based on an actual residential house in Argentina. The multi-objective optimization goal of the building design was to reduce the need for air conditioning and thermal discomfort due to high temperatures. The building design had 21 parameters including transmittance, solar absorption and thermal capacity of the walls and windows configurations.

2.1.2 Grasshopper & Galapagos

Grasshopper is a parametric tool used in the architectural design industry. Grasshopper builds on top of the modelling tools in Rhino and allows the user to explore generative design with a user-friendly design that does not require any prior programming knowledge. Grasshopper has a built-in evolutionary problem-solving component called Galapagos, which is based on generative algorithms, and can be used for optimization of a parametric designs systems. In addition to this daylight calculations can also be made in Grasshopper through add-ons: *Ladybug* and *Honeybee*. This provides a great framework as all the components necessary are combined into the same environment. This has been used in several research projects relating to parametric building design.

Y. Huang et. al [30] used genetic algorithms to optimize the building massing in the conceptual design phase. The goal of this project was to use GA to find the optimal shape of a building in the densely populated city Taipei in Taiwan, that lived up to a series of legal requirements. It is argued that evaluating the building massing is one of the most important tasks of architectural design, whereas the use of GA for optimization is important. J. E. Gerbo and E. Salikis [31] used Galapagos to minimize the weight of a building's columns and diagonal braces whilst also minimizing the lateral deflection of the roof. J. Jin and J. Jeong [32] used GA to optimize the shape of a free-form building in order to conserve thermal energy. Their results show that this approach was able to predict and optimize the outcome of the parametric design.

Using grasshopper for this project seems like a natural choice as it facilitates the parametric design, the daylight calculations as well as the GA solver. Grasshopper has integrated all the necessities related to this project and thus it seems like the obvious choice for generating the content. This purpose of this project is to use this method to create different atmospheres in a room space based on the building facade design. Both the exterior visual appearance and the interior lightning scenario has an influence on the perceived atmosphere of the room space, and being able to control this with a genetic algorithm is powerful tool. The possibilities of this method extends beyond architectural design and can also be used in virtual environments in games or any kind of real time experience, which substantiate why investigating this is important. The final problem statement of this project is:

> How can genetic algorithms be used to generate different lightning scenarios with parametric building facades that will radiate different atmospheres in a room space?

3 Design

3.1 Parametric Design

Parametric design is a way for the designer to play around with many different parameters when designing a building. This gives the opportunity of testing out many different possible outcomes of a building in a virtual building before carrying it out in real life. A simple type of parametric design for a building facade would be a set of squared windows similar to what is seen by . In figure 2 a simple parametric design is shown. In this parametric design there are two changeable parameters: The sizing and the amount of windows, both whom will have an impact on the daylight analysis. The sizing of the windows will determine how much light is transmitted through as larger windows will result in a higher lux measurement. The amount of windows will determine the distribution of the transmitted light, and will create visually different results.

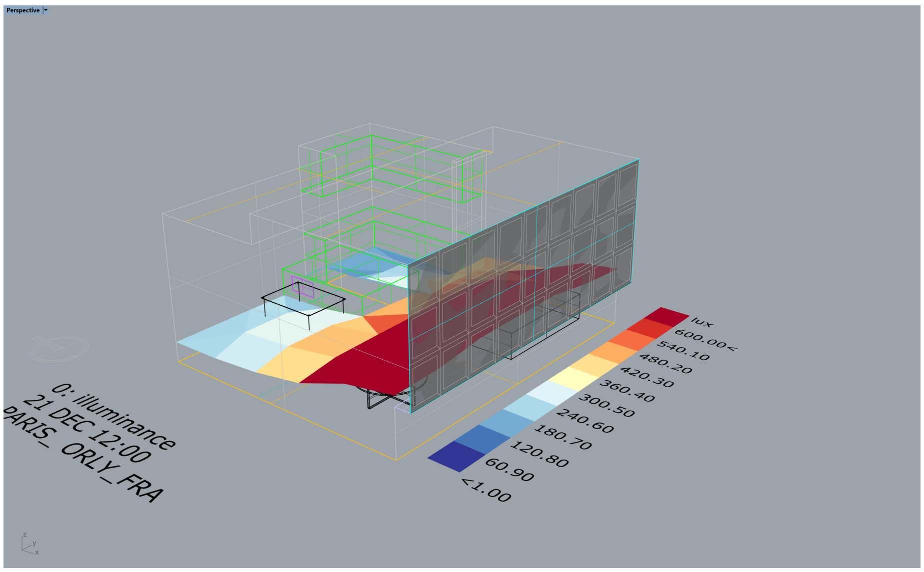

Figure 2: In this figure the windows are large, which allows for much of the sunlight to transmit through.

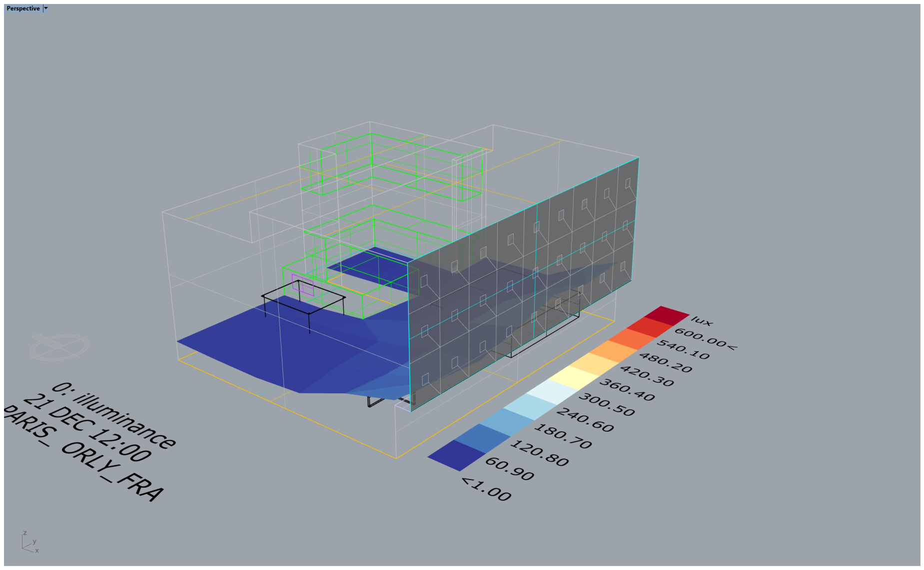

Figure 3: In this figure the windows are small, which allows for only little sunlight to transmit through.

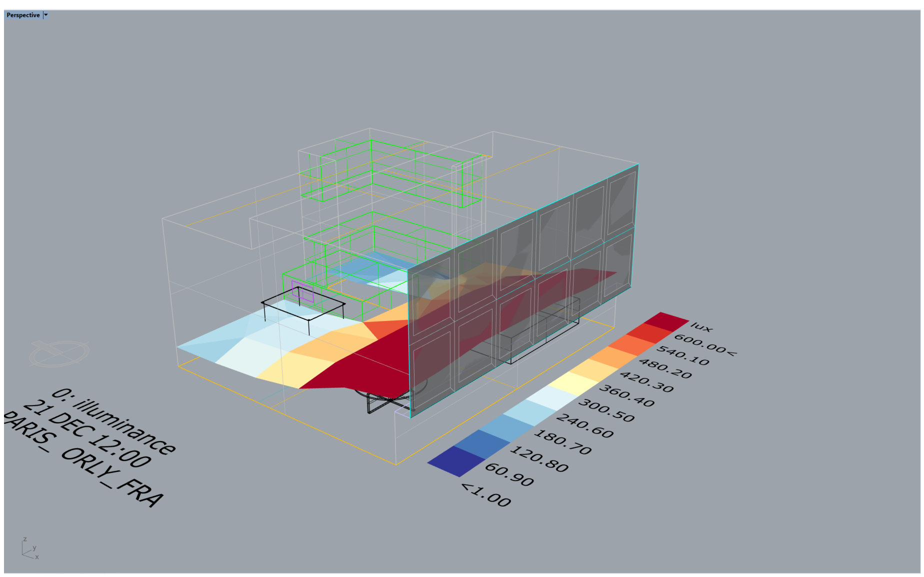

Figure 4: In this figure the windows are larger but there are fewer windows compared to Figure 2, which has an influence on the distribution of the sunlight transmitting through.

This parametric design is very straightforward and limiting and it does not allow for many design choices in regards to the aesthetic of the building's exterior. Reviewing the ascetics of a building might be highly subjective and research shows that architects and public have different opinion when it comes to architecture [33, 34, 35] . However, it has been found that certain visual features can be linked to certain affective responses [36]. In his article J.L. Nasar [37] analysis two kinds of aesthetic variables on building design: *formal aesthetics* and *symbolic aesthetics*. Formal aesthetics has to with the shape, proportion and in general relates to the physical appearance of a building. Symbolic aesthetics has to do with the human experience interpretation of a building and their associations. Both are interesting to investigate, but for this project the formal aesthetics of the building of these are perceived is in focus. J.L. Nasar [37] provides an overview in his analysis of the elements in formal aesthetics:

- Enclosure: The openness and spaciness of space.
- Complexity: The diversity of a space.
- Order: A degree to which a scene hangs together as hangs together

J.L. Nasar [37] found that building with the design goal of evoking pleasantness should have high order and a moderate complexity while design review seeking excitement should have low order and high complexity. These design goals might be different depending whether the point of view is inside or outside the building. The design goals inside a building might be to create a diffuse and bright lighting scenario with little or none glare that is visually pleasing. The design goals from outside a building might be related to the visual appearance of the building and how it is perceived in terms of either pleasantness, excitement or calmness. In this project the proposed parametric design will be driven from lux measurements inside the building. However, the parametric design should still be able to create a diverse series of outcomes, such that both considerations are taken into account.

The parametric developed in this project are inspired from tutorials made by parametric house and has been modified to fit this project. One of the important things to determine is range of the parametric properties such that it allows for the creation interesting yet somewhat realistic results, as for example the minimum and maximum size and number of windows. In total 3 different parametric facade designs were implemented.

Parametric Design 1 - Triangles In the first parametric design a series of triangle shaped windows surrounded by a frame is formed a flat surface. The number of windows is controlled by the UV scaling factor, and the size is controlled by a parameter set between 0.1 and 0.9, since 1 would remove the frame of the window and 0 would remove the window. The size of the windows is offset by an attractor point, which creates a bit of variation in the design. The attractor point works as a gradient that sets a minimum windows size at point's position and then lerps to a maximum value based the distance from that point. This can also be used the other way around going from maximum to minimum. All the parameters are listed below:

- The x-coordinate of the attractor point
- The y-coordinate of the attractor point
- The UV scale factor
- The base scale of the of frames
- The minimum scale of the frames based on the distance to the attractor point
- The maximum scale of the frames based on the distance to the attractor point

This design has high order as described by J. L. Nasar [37] and the pattern is repetitive. It gives a very straightforward control of the incoming light, as the size of the frames dictates the amount of sun light allowed to transmit as in the conventional design described earlier. The attractor point builds on top of that and gives the design a little complexity and the potential to block out the light in some areas. Adding even more attractor points gives the designer even more control over the window properties and gives the option of creating many different light settings.

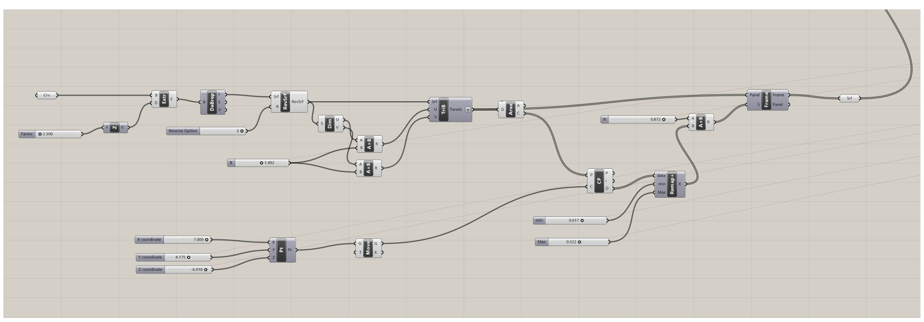

Figure 5: This figure shows the Triangle parametric design in grasshopper

Parametric Design 2 - Voronoi This design is based on Voronoi tessellation which is a type of noise pattern that creates a series of random points and regions are created around those points based on the distance. In this case the created regions are used as windows. With this design the window sizes and placement are controlled like the previous design, but in a more organic and less structured way. The parameters controlled in this design is amount of points to be distributed in the Voronoi tessellation, and the size of the areas created. In addition to that 2 attractor points are used to create areas with denser Voronoi tessellation. The position and radius of these attractor points are controlled in the parameters. All the parameters are listed below:

- The x-coordinate of the 1st attractor point

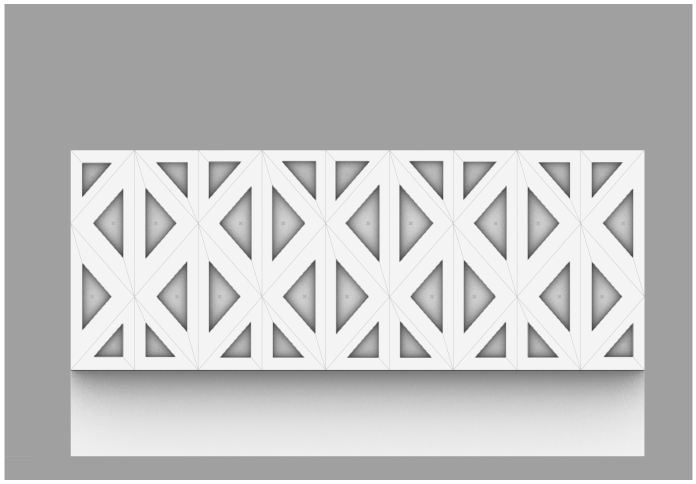

Figure 6: This figure shows the Triangle parametric design in Rhino

- The y-coordinate of the 1st attractor point
- The x-coordinate of the 2nd attractor point
- The y-coordinate of the 2nd attractor point
- The radius of the the circles surrounding each attractor point
- The amount of Voronoi points in placed on the surface
- The amount of Voronoi points in placed in the attractor point
- The area sizes of the each Voronoi point

This design creates a more organic window patterns that might be more visual pleasing that the previous design yet still gives a high order. The attractor points allow for complexity in the design and creates visually interesting results.

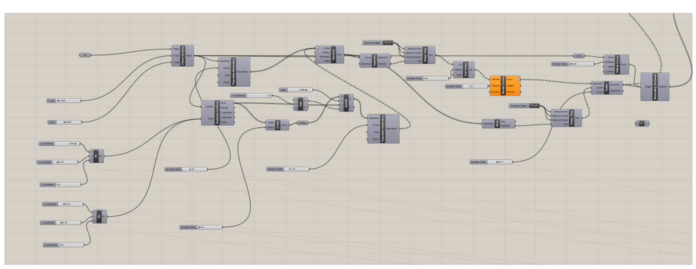

Figure 7: This figure shows the Voronoi parametric design in Rhino

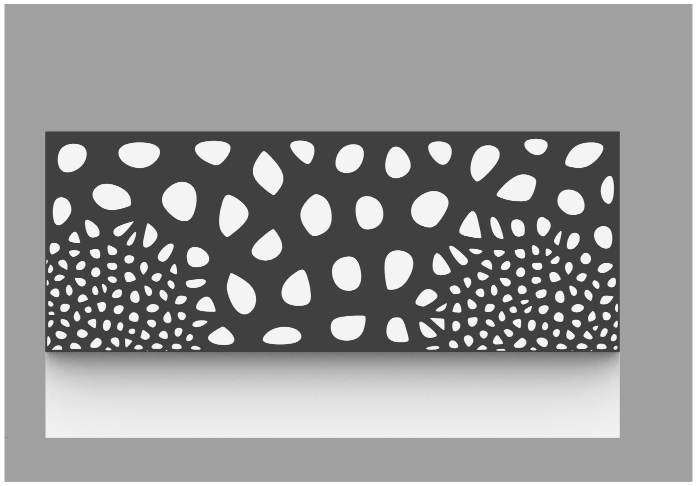

Figure 8: This figure shows the Voronoi parametric design in Rhino

Parametric Design 3 - Louvre In this design a curved surface is defined by 2 attractor points which is used to displace the surface based on a graphic mapping such as: linear, curved, Perlin noise or sinus summation. The position of the attractor points, the amount of displacement, and the type of graph can be controlled in the parameters. The windows are then created by slicing this bend surface and dividing into a series horizontal lines and the space in between allows light to transmit through. Behind this facade is a glass surface instead of windows. The number of horizontal lines and the maximum and minimum size of these lines can be controlled by the parameters. The latter allows for a skewed representation of the lines in either direction which allows for the blocking of light in either the left or right side of the room. All the parameters are listed below:

- The x-coordinate of the 1st attractor point
- The y-coordinate of the 1st attractor point
- The x-coordinate of the 2nd attractor point
- The y-coordinate of the 2nd attractor point
- The amount of displacement
- The amount horizontal lines
- The x-coordinate of the point used to rotate the horizontal lines
- The y-coordinate of the point used to rotate the horizontal lines
- The minimum scale-value of the horizontal lines

- The maximum scale-value of the horizontal lines
- The selected type of graph mapping for the displacement

This building design provides a lot of more interesting design opportunities as it not only has the control over the window properties but also the bending of the facade. Combining this property with the sub-sectioning of the horizontal lines gives a lot of control in relation to the sun's angle of incidence. In gives a more diverse set of design situations that can have both high and low order and complexity which makes this design very powerful.

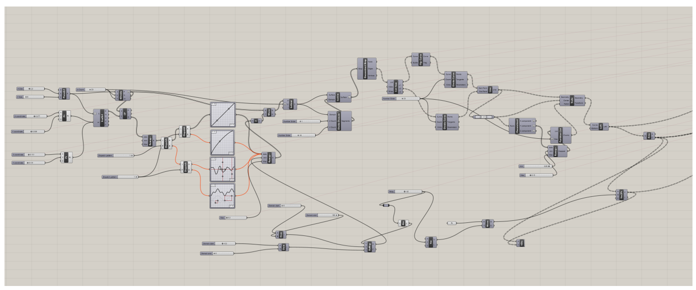

Figure 9: This figure shows the Louvre parametric design in Rhino

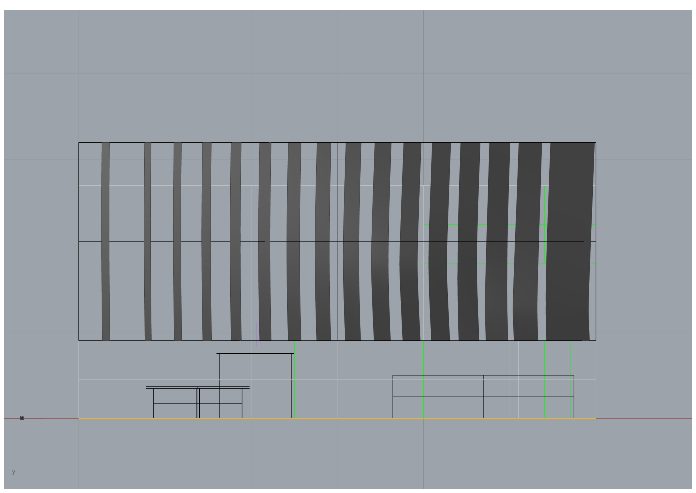

Figure 10: This figure shows the Louvre parametric design in Rhino

4 Implementation

4.1 Generative design

4.2 Daylight analysis

The daylight analysis in this project is achieved using Ladybug and Honeybee which are both add-ons for Grasshopper. The project file in grasshopper is based on a template gathered from HYDRA, which is a community with project example files for Ladybug and Honeybee. In this project the floor of the geometry is measured in lux with a grid-based daylight analysis simulation, which is executed with DAYSIM and Radiance. The measurements in this project is therefore based on horizontal illuminance values alone in order to keep things simple in the calculations. In architectural lighting design it is usually the desk space that is taken into consideration when measuring lux, as the motivation is optimize the work environment by minimizing the daylight glare probability (DGP) while still providing a certain amount of lux. However, in this project it is the atmospheric quality that is important and thus the practicalities concerning optimized workspace is not important. In this project the floor geometry is divided into several points where the respected amount of lux is stored. In the project the desired amount of lux for a specific region of the floor is defined, and then the difference between the measured and desired lux value is calculated. In addition to this, the (DGP) is also measured from a viewpoint placed in back top right corner of the room as seen in Figure 11. This gives a full viewpoint of the building facade and the room itself.

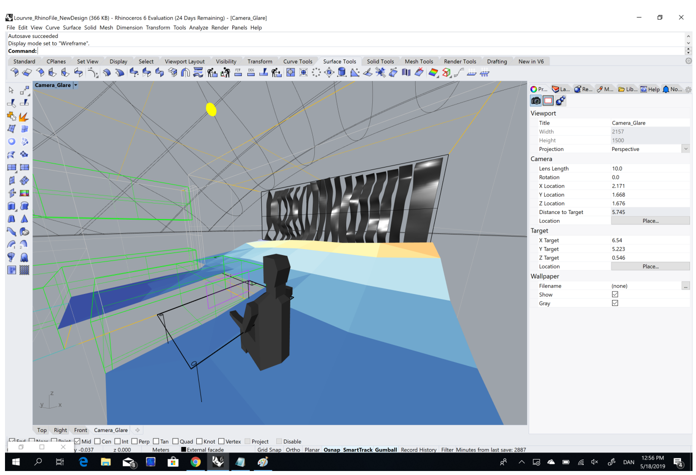

Figure 11: The viewpoint used for the DGP measurements

4.3 Optimization

Measuring the daylight analysis is a time consuming process, which becomes a problem when combined with genetic algorithms. Taking the default settings of Galapagos has a population of 50 in each generation and the daylight analysis in this project with default settings takes about 1 minute, which in the end means that I take around 1 hour to perform one generation. In this project the bottleneck is the time it takes to perform the daylight analysis.

Z.Su and W.Yan [38] used a GA for multiple-design objectives: maximizing daylight performances in patient rooms and minimizing the nurses travel distance to each patient room. In their research they tried to apply offline simulation to each building simulation, as for example all the rooms with windows facing the same direction will have the same daylight illuminance results in any GA generation and across the generations. This meant that only the building position and not room configuration was used in the GA. Unfortunately, this is not possible in this project as the window configuration is of interest and thus this cannot be pre-computed. Therefore other measures was needed to optimize the usage of this. First of all, the size of each cell in the grid-based simulation was increased to make a less dense grid. This means that some detail information is lost in the calculations, yet in the effort to optimize the process it is necessary. Second, the size of the population is set to only 30. With a low population there is an increased risk of reaching a local maximum rather than an optimal solution. To counter this potential issue, the evaluations will be run several times to ensure that the GA finds an optimal solution. At last the GA will only run for a short amount of generations (20). The results described by S.L.Torres and Y.Sakamoto [24] shows that after a few generations the main characteristic of the building is found and afterwards only smaller changes is found. For this project is it enough that the GA learns the main characteristic, as the purpose of this project is to achieve artistic expression rather than accurate measurements. The optimization choices reduce the time of resources spent generating the building facades while still achieving the required precision in the measurements.

5 Evaluation

5.1 Scenario A

The purpose of this test is to evaluate the 3 different parametric design's ability to produce the desired outcome in different scenarios which in this case is a contrast light scenario and a more balanced scenario. In the end it will be decided which of these parametric designs is most fitted for the purpose of making different atmospheres. This test will be a single-objective optimization as it will focus on the lux measurements and not the DGP in order to keep things simple at this point. The different test scenarios are:

- Scenario A.1 A room with an average of 350 lux in both left and right side

- Scenario A.2 A room with an average of 50 lux in both left and right side
- Scenario A.3 A room with an average of 300 lux in the left side and 150 in the right side

The rooms are split into two sections (left and right) of 17 points each, and the average lux value of the 17 points on either side is measured. The fitness criterion in these tests are based on the difference between target lux value and the measured lux value for each room. This is measured by taking the absolute value between the measured and the target lux value. Thus, the fitness score can be written as:

$$Fitness = abs(target_{\text{Left}} - (\frac{\sum_{n=1}^{17} measured_{\text{Left}}}{N}) + abs(target_{\text{Right}} - (\frac{\sum_{n=1}^{17} measured_{\text{Right}}}{N})$$

The goal of the GA is to minimize this number, since this would mean that the difference between the target lux and the measured lux is low. The GA will run for 20 generations and the best solution at that point will be considered as the final solution.

5.2 Scenario B

In the previous evaluation the conclusion was that the Louvre design provided the most versatile design opportunities. This evaluation is an expanded version of the 1st evaluation and the goal is to create even more test scenarios to see how this parametric design can be used to create different lightning scenarios. The Voronoi and triangle design are still a part of 1 test scenario each in this test to compare them to the Louvre design. The test scenarios of this evaluation are:

Contrast – High and low This test scenario is like the test scenario in the 1st evaluation. However, instead of using specific lux values as the fitness criteria, the GA will instead either maximize the aspect ratio between the left side and the right side of the floor. The goal of this is to see which effect a high and low contrast in the measured lux value has on the perceived atmosphere.

$$Fitness = \frac{\sum_{n=1}^{17} lux_{\text{Right}}}{\sum_{n=1}^{17} lux_{\text{Left}}}$$

Average illumination(50, 200 and 350) This test scenarios is similar to first scenario in the 1st evaluation, as the goal in this test is to create average illuminance values of respected 50, 200 and 350 lux. The goal of this division is to see what effect the average illuminance has on the perceived atmosphere.

$$Fitness = abs(lux_{\text{target}} - \frac{\sum_{n=1}^{17} lux_{\text{measured}}}{N})$$

Different parametric designs The goal of this part of the test is to see what effect the different parametric designs has on the perceived atmosphere.

The two parametric design designs will create an average illumination of 200 lux and be compared with the corresponding version of the Louvre design. The fitness function is the same as in the previous scenario.

Min/max and DGP The goal of this part is to create high and low contrast as in the first part. However, in here the goal is not to create high/low contrast between darkest parts of the scene and the brightest parts on the floor, which in this case corresponds to the front and back of the geometry. In addition to that the DGP is also taken into account. This DGP is multiplied by a value of 10 in order to give it more influence in the fitness function.

$$Fitness = \frac{lux_{\text{Front}}}{lux_{\text{Back}}} + DGP$$

All scenarios are performed with the same weather condition and the same light settings, which is set to Paris at 12:00 pm at the 21st of December. and the north direction of the light is set to 90 degrees. In total of 9 test scenarios is used in this evaluation. A full overview is provided in the list below:

- Scenario B.1 A high contrast between the right and left side of the room
- Scenario B.2 A low contrast between the right and left side of the room
- Scenario B.3 An average of 50 for both the right and left side of the room
- Scenario B.4 An average of 200 for both the right and left side of the room
- Scenario B.5 An average of 350 for both the right and left side of the room
- Scenario B.6 An average of 200 for both the right and left side of the room with the Voronoi Parametric Design
- Scenario B.7 An average of 200 for both the right and left side of the room with the Triangle Parametric Design
- Scenario B.8 A high contrast between the minimum and maximum measured value of the lux and a high DGP
- Scenario B.9 A low contrast between the minimum and maximum measured value of the lux and a low DGP

5.3 Scenario C

In the previous evaluation the same weather condition was used in all 9 scenarios, in the effort of isolating the influence of the parametric design on the lightning . In this evaluation the fitness criteria is kept constant while the properties of the daylight becomes the variable. The motivation behind this evaluation is to see how the daylight will influence the appearance of the parametric design but also the daylight measurements. In this scenario a total of 7 different scenarios is chosen and compared to the first scenario in the previous evaluation where the fitness criteria is high contrast between the left and the right side of the room.

- Scenario C.1 The north direction with an angle changed from 90 degrees to 45 degrees
- Scenario C.2 The north direction with an angle changed from 90 degrees to 0 degrees
- Scenario C.3 The time of day changed from 12 pm to 10 am
- Scenario C.4 The time of day changed from 12 pm to 2 pm
- Scenario C.5 The month of the year changed from December to March
- Scenario C.6 The month of the year changed from December to June
- Scenario C.7 The month of the year changed from December to September
- Scenario C.8 The month of the year changed from December to June and he time of day changed from 12 pm to 6 am
- Scenario C.9 The month of the year changed from December to June and he time of day changed from 12 pm to 6 pm

5.4 Results

5.4.1 Scenario A

In this scenario the capabilities of each of the parametric designs was evaluated by applying different fitness criteria: a balanced light with an average of 350 lux and a contrast lightning result of 300 in the left side and 150 lux in the right side. The fitness score was computed based on the difference between the target measured lux and the target lux. The results from this scenario is seen in Figure 12 and each scenario is visualized in figure 13-21.

Scenario	Fitness Score
Triangle A1	7.05
Triangle A2	4.70
Triangle A3	35.51
Voronoi A1	18
Voronoi A2	39.09
Voronoi A3	130.46
Louvre A1	26.69
Louvre A2	52.94
Louvre A3	15.06

Figure 12: This table shows the results from scenario A

The Voronoi did not manage to optimize the its results in Scenario A.3 and was only useful when making more balanced light setting in Scenario A.1 and A.2. After going through 20 generations the fitness score had only been minimized slightly, even after running several trials of the test. The attractor points did not contribute as ways to either block or increase the transmittance of light.

The Louvre and triangle parametric design was usable in all three scenarios, even though the Louvre design had a relatively high fitness score in Scenario A2. This indicates that the Louvre design might not be as useful to create very dark lighting scenarios. However, this is a different case than with the Louvre design i Scenario A.3, and it is not a concern.

Both the triangles and the Louvre design were able to create contrast light settings as dictated by the second part of the evaluation. However, in the end the Louvre design provides more design opportunities and it is in general more versatile. The parameters in the Louvre design provide the ability to adapt to the the sun's angle of incidence in a way the triangles don't. Because of this the next evaluation will focus more on the Louvre parametric design rather than the other two.

This test scenario gave insight in how types different parametric design should be developed if the desire is to be able to create many different results both in terms of daylight measurements but also for visual appearance. This was important to find out before proceeding with Scenario B.

Figure 13: Scenario A.1 A room with an average of 350 lux in both left and right side with the triangle design

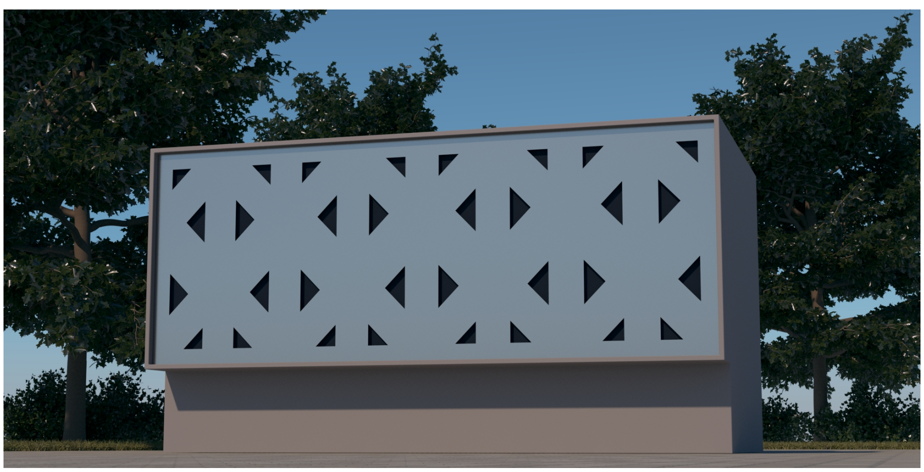

Figure 14: Scenario A.2 A room with an average of 50 lux in both left and right side with the triangle design

Figure 15: Scenario A.3 A room with an average of 300 lux in the left side and 150 in the right side with the triangle design

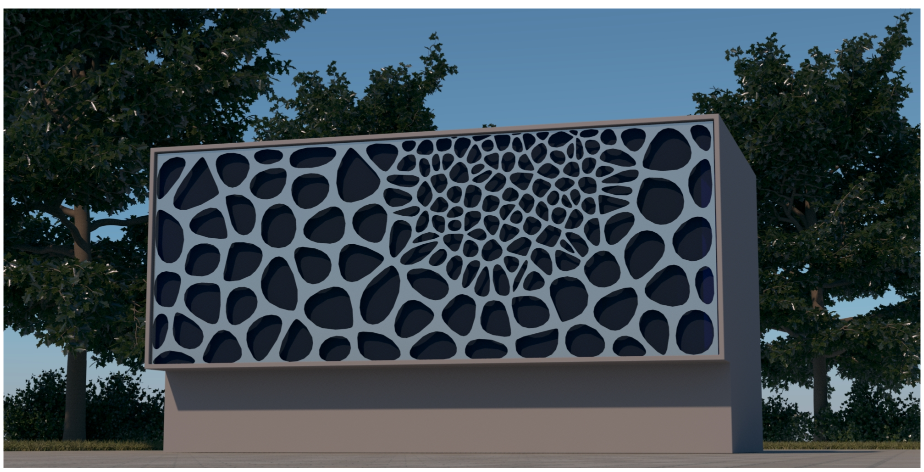

Figure 16: Scenario A.1 A room with an average of 350 lux in both left and right side with the Voronoi design

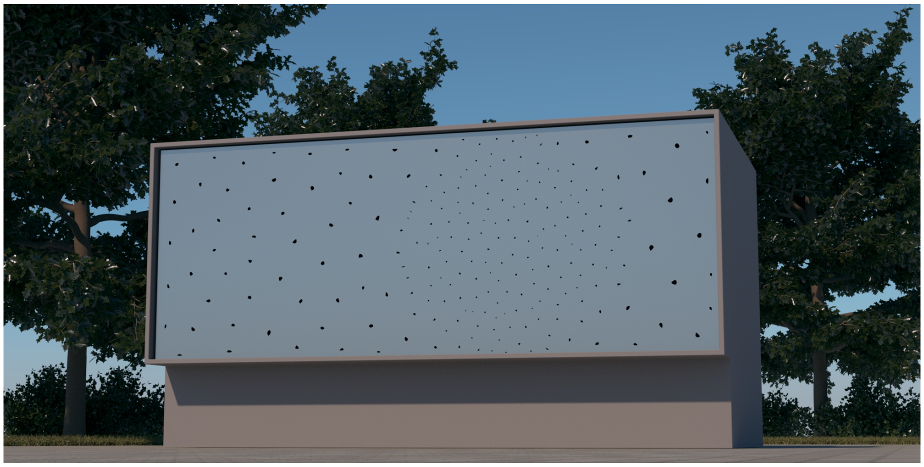

Figure 17: Scenario A.2 A room with an average of 50 lux in both left and right side with the Voronoi design

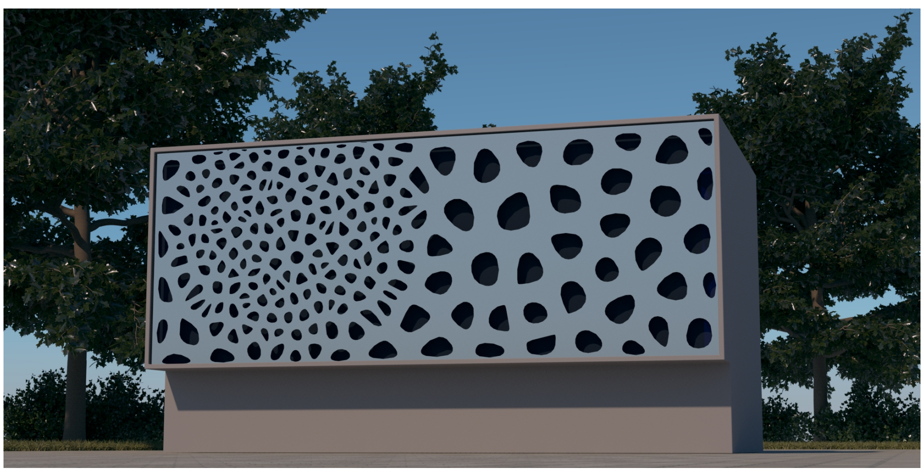

Figure 18: Scenario A.3 A room with an average of 300 lux in the left side and 150 in the right side with the Voronoi design

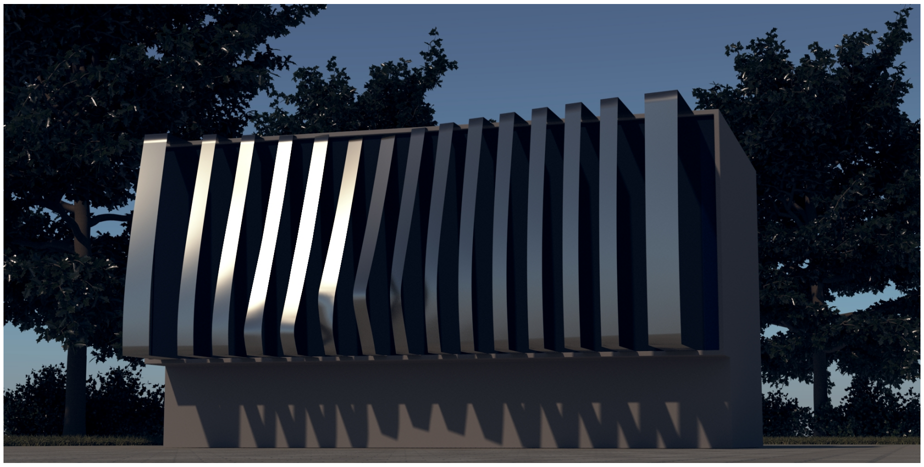

Figure 19: Scenario A.1 A room with an average of 350 lux in both left and right side with the Louvre design

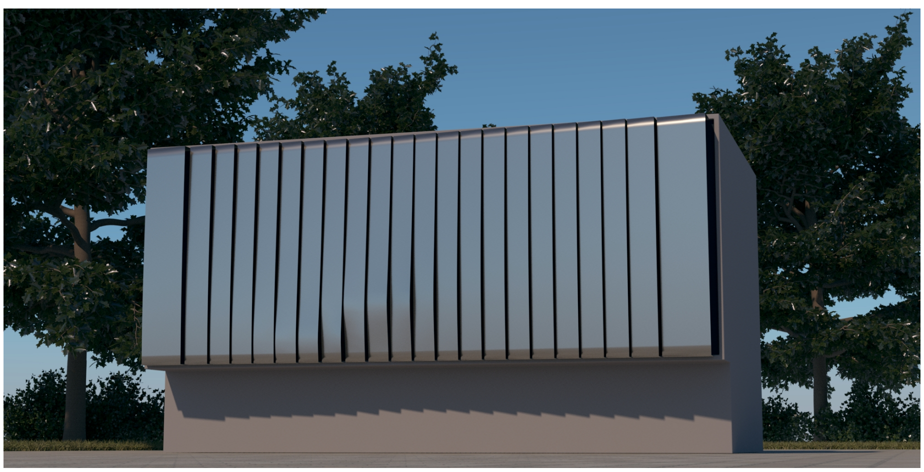

Figure 20: Scenario A.2 A room with an average of 50 lux in both left and right side with the Louvre design

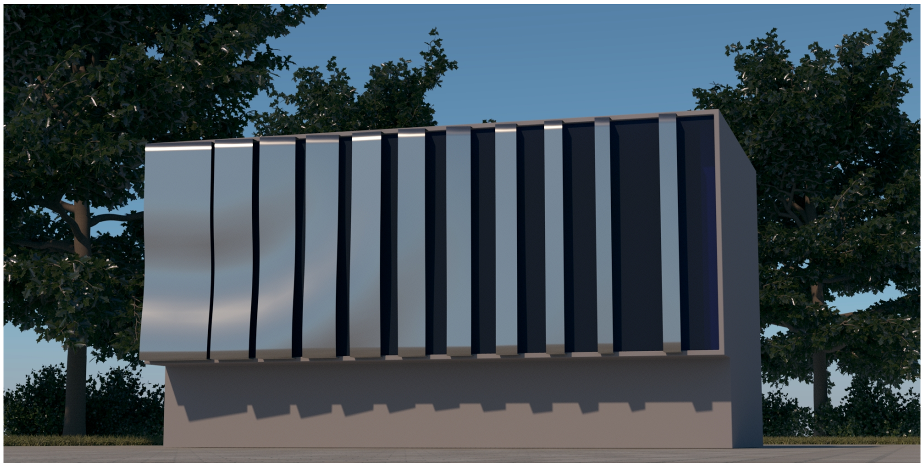

Figure 21: Scenario A.3 A room with an average of 300 lux in the left side and 150 in the right side with the Louvre design

5.4.2 Scenario B

In the second test scenario the Louvre design was tested in 7 different scenarios: An average of 50, 200 and 300 lux, a high/low contrast scenario in terms of the right side and left side of the room and a high/low contrast in terms of the minimum and maximum measured lux. The Voronoi and triangle design was also tested in the scenarios with an average of 200 lux. While the impression of the space is different between the 3 parametric design, the results also shows that the Louvre design was able to produce many different results that gives different impressions. This demonstrates the versatility of this parametric design as it can produce many different lighting condition. In this evaluation the light condition was the same, in order to isolate the parametric as the only variable. Images of the results are provided below in Figure 22-30.

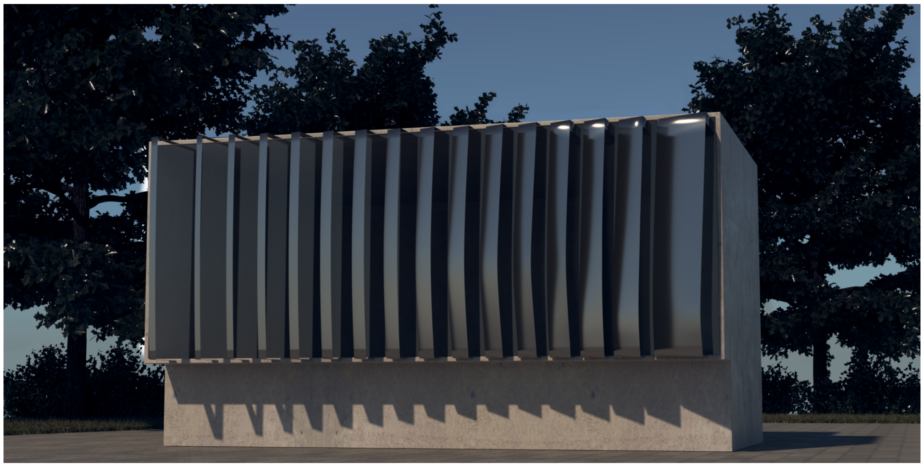

Figure 22: Scenario B.1 A high contrast between the right and left side of the room

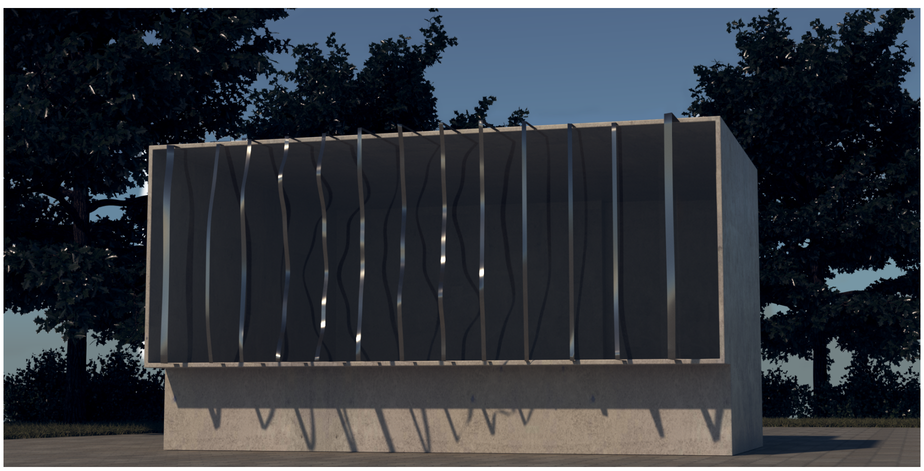

Figure 23: Scenario B.2 A low contrast between the right and left side of the room

In scenario B.1 and B.2 the fitness criteria was to respectively minimize and maximize the ratio between lux measurements in the right side and the left side of the room. This gives two very different outcomes where B.1 has a more complex look with a lot of contrast which is needed to maximize the ratio. In scenario B.2 the building design has high order and low complexity which is needed since it will even out the light transmittance and thus minimize the ratio. This could possibly have been achieved with a more dense distribution of the horizontal lines and with more thickness in each of them. This would lower the average illuminance in the room, but would still achieve a balanced light scenario with low contrast.

Figure 24: Scenario B.3 An average of 50 for both the right and left side of the room

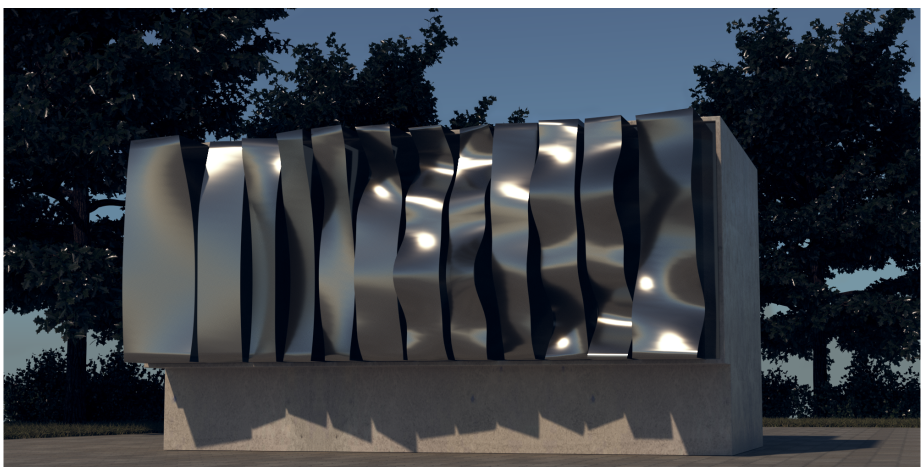

Figure 25: Scenario B.4 An average of 200 for both the right and left side of the room

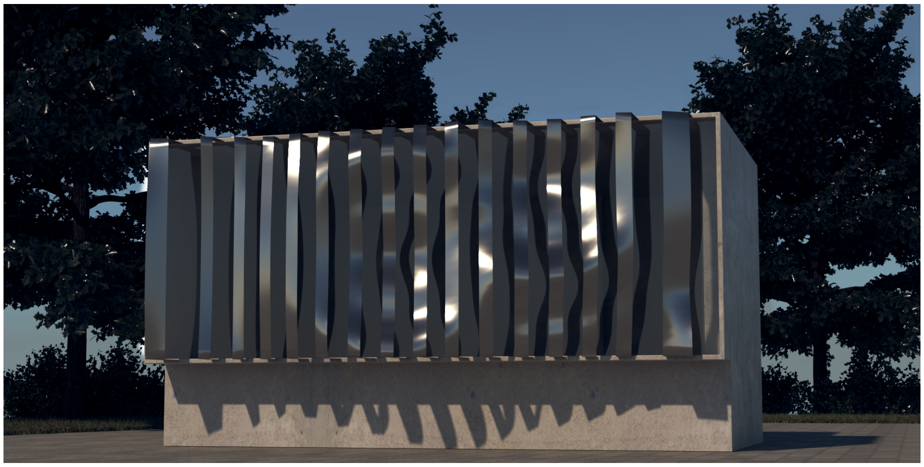

Figure 26: Scenario B.5 An average of 350 for both the right and left side of the room

The most noticeable thing when comparing scenario B.3, B.4 and B.5 is the openness in the building facades. Scenario B.3 has a much more dense and less open look compared to both B.4 and B.5, which was expected to happen since this have the lowest target average illumination level. What is interesting to see in both scenario B.3 and B.4 is how the the displacement has been used to allow only a small amount of sunlight to transmit. This gives a visually complex look with little order as compared to scenario B.5.

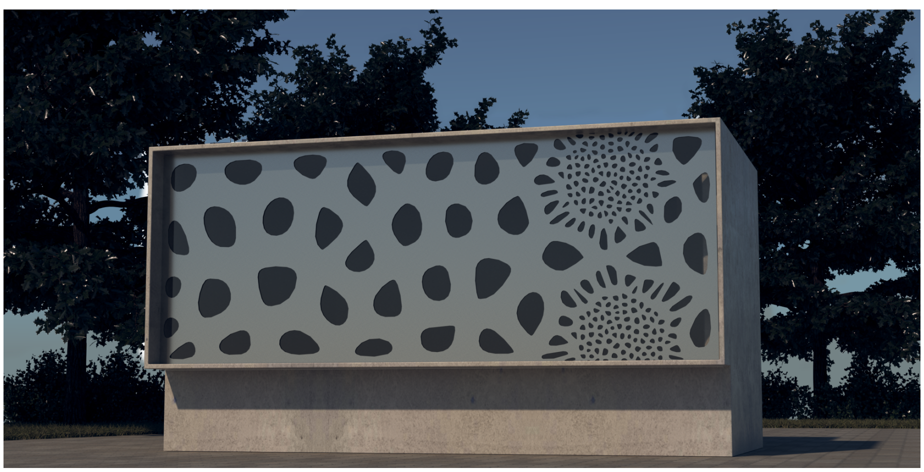

Figure 27: Scenario B.6 An average of 200 for both the right and left side of the room with the Voronoi Parametric Design

Figure 28: Scenario B.7 An average of 200 for both the right and left side of the room with the Triangle Parametric Design

Comparing scenario B.6 and B.7 to scenario B.4 there are significant differences in visual output. In B.6 and B.7 the building facade has high order, low complexity and a partly openness whereas B.4 has low order, high complexity and less openness. This shows that achieving a balanced light scenario with an average of 200 lux can be achieved different ways with different trade-offs, depending on the parametric design.

Figure 29: Scenario B.8 A high contrast between the minimum and maximum measured value of the lux and a high DGP

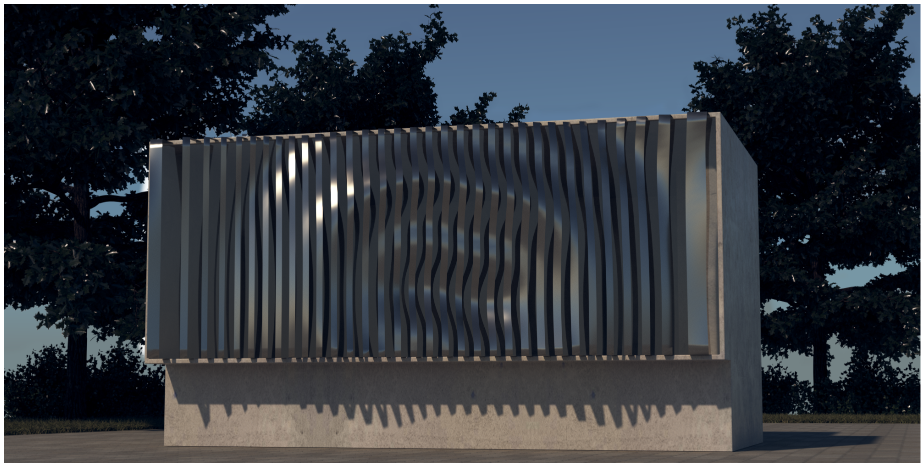

Figure 30: Scenario B.9 A low contrast between the minimum and maximum measured value of the lux and a low DGP

In scenario B.8 and B.9 the fitness criteria was to respectively minimize and maximize glare probability and the ratio between lux measurements in the front and the back of the room. The result in B.8 is similar to B.4 where the displacement of the building facade is used to create small entrances for the light to transmit through, which increases the glare probability. Maximizing the ratio between lux measurements in the front and the back of the room has been achieved with a more dense and less open result. The result in B.9 has been achieved with a more balanced look that still has a bit of complexity caused by the surface displacement.

The GA was able to optimize the fitness score in all 9 scenarios. Even within the first few generations the GA was able to learn the main characteristics of the building and in the later generations only smaller configurations was changed, which resembles the findings by by S.L.Torres and Y.Sakamoto [24]. It is possible that if the population was larger and the GA ran for more generations a more optimized results would have been found, which also might have changed visual outcome a bit. However, the results of this test shows the that GAs has the ability to generate different visual results and achieve different artistic expressions, and thus learning the main characteristics of a building is sufficient in this case.

5.4.3 Scenario C

In scenario C the fitness criterion was kept constant and the lighting properties such as north angle, time of day and month of the year was the variable. The motivation behind this was to investigate how the lightning properties influenced the outcome of the parametric design. The fitness criteria in all of these scenarios was the same as in scenario B.1 and thus these results are compared directly to this scenario on 3 parameters: the visual appearance of the buildings, the fitness score and the average illumination level. An overview of the fitness score and the average illumination level is shown in figure 31. In the visualization in scenario B the light settings were set to create a balanced and diffuse lightning in the visualization. An image of Scenario B1 in more accurate light properties can be seen in Figure 32.

Scenario	Fitness Score	Average illumination Right	Average illumination Left
B1	2.00	372.97 lux	186.03 lux
C1	2.25	295.02 lux	132.74 lux
C2	2.04	334.26 lux	162.49 lux
C3	2.02	63.02 lux	31.17 lux
C4	2.00	429.27 lux	214.45 lux
C5	2.23	5372.37 lux	2409.45 lux
C6	2.81	6843.78 lux	2422.41 lux
C7	1.62	9739.03 lux	6000.10 lux
C8	2.09	164.03 lux	78.61 lux
C9	1.91	1387.44 lux	727.62 lux

Figure 31: This table shows the results from scenario A

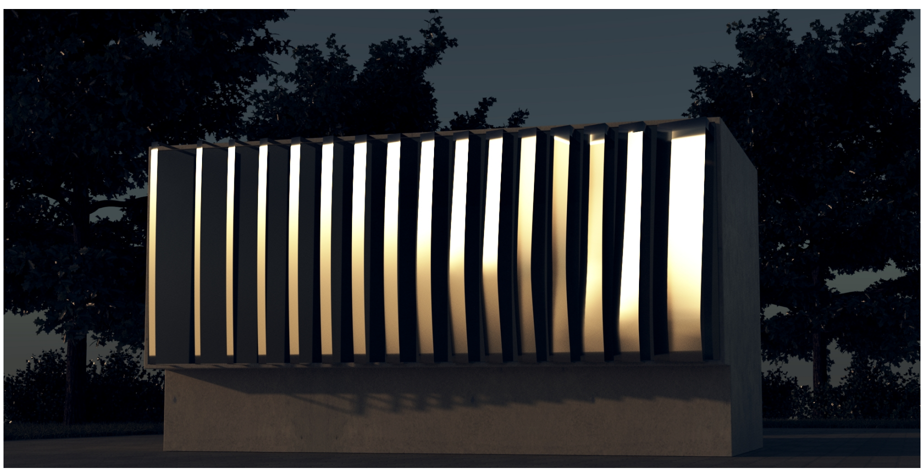

Figure 32: Scenario B1 With accurate light properties

In scenario C.1 and C.2 the sunlight direction was changed, which seemed to have a slight impact on the average illumination in both scenarios. Ladybug and honeybee uses a north direction to determine the direction of the daylight. In all cases for Scenario A and Scenario B this was set to 90, which means that the north direction points straight at the building. The results in scenario B.1 and C.1 are identical visually but the fitness score is higher in scenario C.1.

Comparing B.1 and C.2 the results are visually distinct, yet the fitness value are similar. In general this indicates the the sunlight direction has an influence on the impression of the room space in terms of the visual appearance of the facade but also the fitness score and the average illumination.

Figure 33: Scenario C.1 The north direction with an angle changed from 90 degrees to 45 degrees

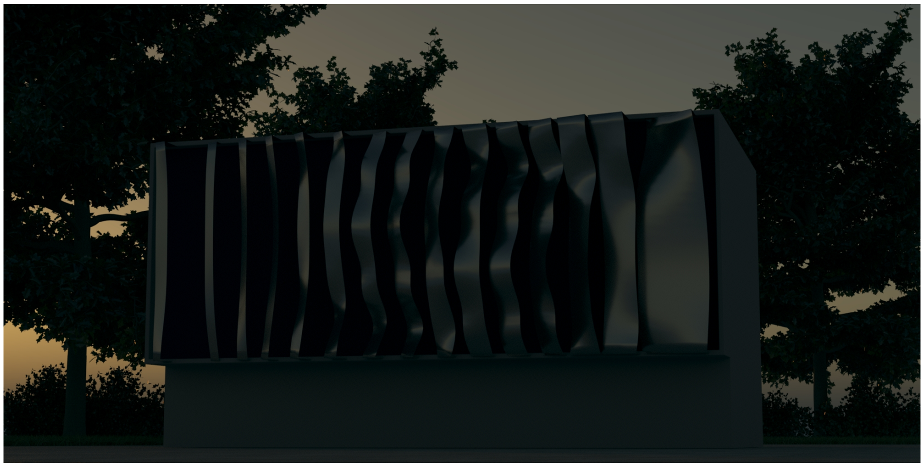

Figure 34: Scenario C.2 The north direction with an angle changed from 90 degrees to 0 degrees

Changing the time of day in scenario C.3 and C.4 did not have any significant influence, on either the visual or the fitness score. It change the average illuminance level which in the end would have an influence on the impression of the room. Scenario C.3 is much darker than scenario B.1. while scenario C.4 is brighter.

Figure 35: Scenario C.3 The time of day changed from 12 pm to 10 am

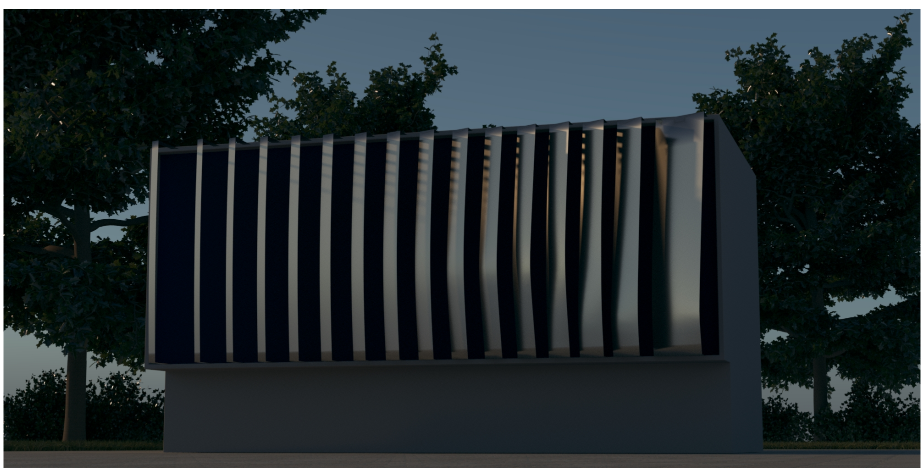

Figure 36: Scenario C.4 The time of day changed from 12 pm to 2 pm

Changing the season in scenario C.5, C.6 and C.7 changed the average illuminance and was much brighter in all scenarios compared to scenario B.1. The visual appearance was different in C.5 and C.7 and the fitness score was significantly different in C.6 and C.7. This goes to show that changing the season has a strong influence.

Figure 37: Scenario C.5 The month of the year changed from December to March DGP

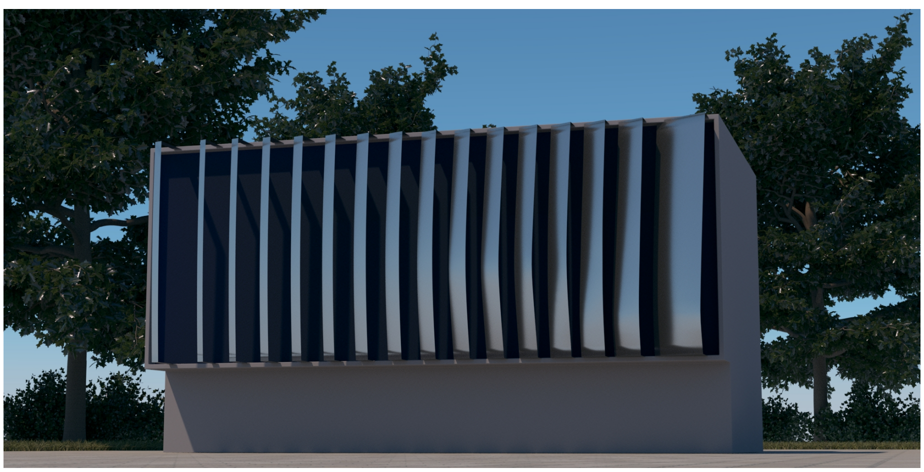

Figure 38: Scenario C.6 The month of the year changed from December to June

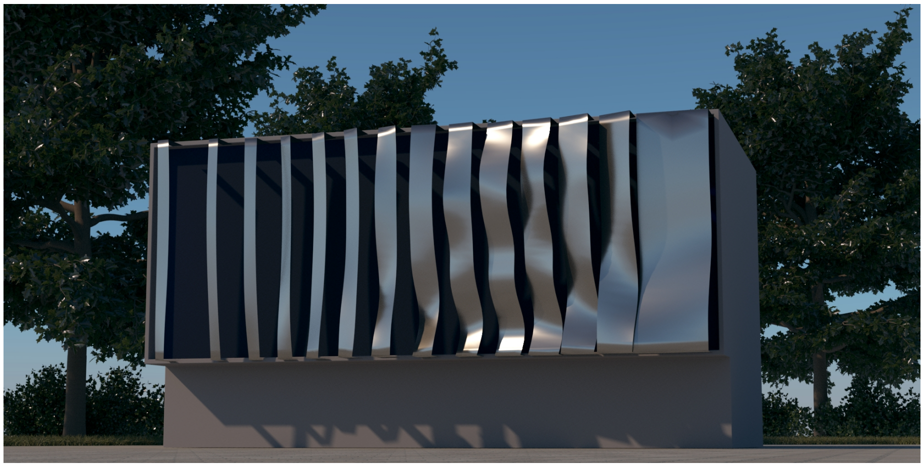

Figure 39: Scenario C.7 The month of the year changed from December to September

The last two scenarios C.8 and C.9 is a variation of scenario C.6 which means that the month is set to June but the time of day is changed to respectively 6Am and 6PM. The results from this test shows that the fitness score is only changed slight as seen in scenario C.3 and C.4, and the visual appearance is likewise identical. However, changing the time of day has a major influence on the average illumination.

Figure 40: Scenario C.8 The month of the year changed from December to June and he time of day changed from 12 pm to 6 am

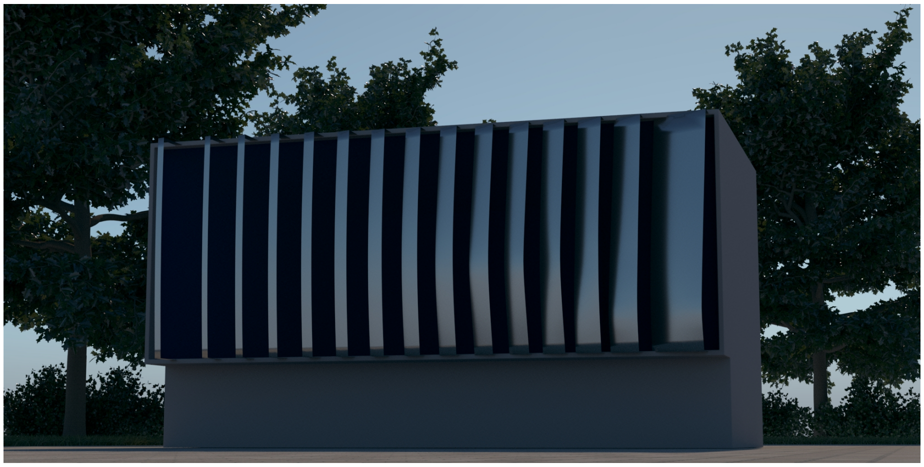

Figure 41: Scenario C.9 The month of the year changed from December to June and he time of day changed from 12 pm to 6 pm

In general this shows that changing the light properties can have influence on the parametric building design based on the visual appearance, the fitness score and the average illuminance level. This enables a new set of opportunities for future designs. This suggest that the lighting properties could be used as changeable parameters in a future parametric design.

6 Conclusion

This purpose of this project was to investigate how genetic algorithms in parametric building facade design to create different atmospheres in a room space based on the transmitted sunlight. The final problem statement of this project was:

> How can genetic algorithms be used to generate building facades that will radiate different atmospheres in a room space?

In this project 3 parametric building facades designs was implemented and put to test in 3 different test scenarios. In scenario A it was discovered which of the 3 parametric designs was the most versatile and was best suited for further testing in more complicated scenarios. The results from scenario A gave a good indication of what worked in when making a parametric design for this type of purpose. In the scenario B more complex and varying test fitness criteria was set up. In all 9 scenarios the GA was able to find an optimized result. This test scenario supported the findings of scenario A and proved the GA was able to produce the many different possibilities of the Louvre design even with few generations (20). In scenario C it was found that the daylight properties was able to influence the results in either visual appearance the fitness score or the average illumination, which opens for more design possibilities in the future.

In general this project demonstrates that this method of using GA in parametric building design is useful. Combining a versatile parametric design with GAs gives a lot of possibilities that can be used to create interesting designs for games or real time experiences. The results in this project shows that this method is capable of generating many different outcomes based on the given fitness criteria. The results in the different test scenario gives different lightning properties inside a room space and it is likely that the impression of each of these rooms are different. One thing that is important to investigate in future research is the user experience in regards to being present in these environments. This would firmly confirm the capabilities of this method in terms of being able to create different atmospheres.

7 Discussion

The combination of genetic algorithms and parametric building has previously been used for practical measures such as daylight systems [24, 25]. In this project the same method have been used in a more artistic way, and the results from the evaluation are promising. It shows that with the right type of parametric design GA are capable of generating visually different building facades based on a given criteria. The usage of this method extends that of traditional architectural design and can be used as a form of generative design for interior environments in video games or other real time experiences. The generated content from this method has the potential to create different atmospheres especially when combined with other parameters that goes into environmental design in games. As for example in the visualizations of the building facades in this project a metal material was used. This in itself impacts the perceived atmosphere as the glossiness of the metal gives a different visual appearance compared to a plastic material as seen in appendix A.

In this project the materials used in the simulation was kept the same in order to keep things simple. In real life scenarios the materials used has an impact on only perception of a room but also how the transmitted light is reflected across the room. Expanding the changeable parameters to also include materials properties would allow for a more complete simulation. This refers to both the material inside the room space and on the building facade.

While the results in this project are promising the ability to create different atmospheres was not fully documented and in order to do so more research is needed. Being able to prove this methods capability of creating different atmospheres would substantiate its usability. However, the results in this project shows that this method is capable of creating different lighting scenarios and diverse visual appearance which indicates its ability to create different atmospheres when considering the impact that light have on the impression of a room as research suggest [2, 3, 4].

8 Future Thoughts

8.1 User Experience

In the end the purpose of this project is to create different atmospheres based on light transmittance of the windows in the parametric building facades design. Interpreting an atmosphere is a highly subjective matter and difficult to measure with a fitness criterion. In this project the different fitness criteria stated might code for a light setup that has high or low contrast, but how that is perceived is depending on user evaluation. Therefore, it is important to take the user evaluation into account in this project in order to ensure that the generated building facade design produces different atmospheres.

In this project Genetic algorithms are used as a type of procedural generation, which is a great way to create content for video games. Procedural generation means that instead of content being created manually by a 3D artist the content is created though an algorithm where in some cases parameters set by the artist. This allows for a lot of content to be created in a much more time efficient matter. However, one thing to consider when making procedural generated content is to ensure that the content is not too similar, and too dull which has been one of the critique points of procedural generated content in the last few years.

G. N. Yannakakis and J. Togelius [39, 40] introduced a framework that connects user experience with procedural generation which they call Experience-Driven Procedural Content Generation (EDPCG). The EDPCG framework consist of 4 components, which is the Player experience model, Content quality, Content Representation and Content generator. Working with the user experience with procedural generation is an important aspect that ensures a higher quality of procedural generated content as it is updated based on user evaluation. This is something that is important to take into account in this project. Including user's in this project has an influence on the blueprint. Now the user becomes an isolated yet active part of this looping process as seen in Figure 42.

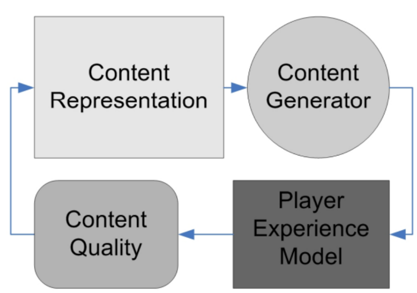

Figure 42: The main components of Experience-Driven Procedural Content Generation (EDPCG) as reported by G. N. Yannakakis and J. Togelius [39]

8.1.1 Virtual Reality

The user experience evaluation in this project will be conducted with VR. VR has the ability to place the viewer in a lifelike virtual environment, that provides a similar feeling of presence and emotional responses as in a physical environment [41, 42, 43]. VR provides a very immersive environment due to its mimicking of reality, and has been found to able to change mood states at participants [44, 45, 46]

VR has been found to be a valuable research tool for studies that includes human-environment interaction such as this project. S.F. Kuliga and C. Hölscher [41] made a project where they compared a physical office environment to a virtual representation of that office in two conditions: dark and bright light setting. Their results show that there was no significant difference between the physical and virtual environment in terms of both task performance and sense of presence. This shows that VR has a strong potential to be used in architectural research to get a sense of the how the virtual space influences the viewer in comparison to real life. Those reasons indicate why VR is a great tool for conducting the user evaluation in this project. In the end this evaluation can provide end end-user feedback to improve the design evaluation process that builds upon the GA optimization evaluation.

Another thing that would take this a step further would be to work with the symbolic aesthetics of a building as described by J. L. Nasar [37]. In this project things were kept simple and focused more on the formal aesthetics of the building but expanding this to also include symbolic aesthetics in the generative design. Controlling factors such as the naturalness and the style of a building would increase the usefulness of this method and make it even more powerful.

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