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Voronoi Geometry for Building Facade to Manage Direct Sunbeams

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Abstract

Nowadays, ultra-advanced facades have made great strides, and parametric simulation software has made a significant contribution to this advancement. Voronoi shells, based on their irregular nature, are one of the most advanced facades that are being used in modern building facades. In this paper, the main focus is on the behavior of these facades against incident light from the sun. The method presented in this research is based on Ladybug Tool's plug-in capabilities. Using the analysis of weather information and the desired geometry, direct rays as a vector in each time step is prepared, and the amount of direct sunbeam hours by considering the contexts (Facade) calculated. To estimate the comprehensive method, the same workflow evaluated winter (P2) and summer (P1) solstice as a cross-sectional study (Max & Min solar altitude). The results indicate that the type of geometry Voronoi and the thickness of the facade frame have a great effect on the direction of the rays inwards and also the type of geometry should be controlled at latitudes appropriate to the solar altitude; because of the geometric intricacies of the Voronoi facade have a great deal to do with the solar altitude.

Keywords: voronoi façade, advanced façade, daylighting, compu-lyzer architecture, high-performance architecture, ladybug tools plugin.

Introduction

Daylight and advanced facade

Natural light for humans, in addition to providing visual conditions, is very important in terms of psychological effects and mental (Hosseini et al., 2019). Daylight is known as a source of renewable energy, and it's more use can reduce the consumption of artificial energy and generally save on non-renewable energy (Javanroodi et al., 2018). The buildings are designed to repeat the feeling of being alive every day for human beings by flowing natural light during life (Saadatjoo et al., 2021). It is important to note that the overuse of daylight brings such as overheating spaces and increasing the risk of glare, but without a doubt, it has always been one of the most important criteria for architects and designers; as a result, trying to increase the amount of received natural light into spaces is perfectly justified (Krarti et al., 2005).

Due to its close relationship with environmental factors affecting the conditions of a building such as natural light, the form of the building has a very important role in the study of building physics today (Pisello et al., 2014). Building walls that are not surrounded by external contexts such as surrounding buildings, surrounding environment, and facades are usually most affected by sunlight and atmospheric factors (Srebric et al., 2015).

Considering the importance of facades in modern architecture in climatic and environmental issues, the promotion of building facades as a protective shell has been significantly developed (Talaei et al., 2022). Double skin facades are now known as a facade based entirely on the principles of environmental effect (Ahmadi et al., 2022), and many studies have been conducted on

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the title of environmental factors in general and separately on such facades. Double skin facades have met many challenges and problems related to environmental factors [11] with the potential of smartening and moving their members (kinetic structure). In general, the advanced facades, in addition to meeting the designers-desired style, respond correctly to climatic challenges, and it can be explained that this type of facade is devising very locally oriented.

Reviewing the Voronoi model

For the first time in the 17th century, the advent of Voronoi diagrams was introduced to describe the formation of natural structures. In René Descartes ' Principles of Philosophy book in 1644, almost the first graphic representations of Voronoi diagrams occurred. According to the definition of this study (Polat and İlerisoy, 2020), the Voronoi diagram is a set of predetermined points, which are arranged based on the distance of points on a plane within the region, which can be called seed or generators. This diagram is known as tessellation Voronoi. From a mathematical point of view, the Voronoi diagram is a set of points divided within a plane, and each point has its boundaries based on the principle of triangulation. All points and boundaries of each concerned on their adjacent points. The vertices of each triangle are located in the center of the Voronoi cell, so that hypothetical extensions perpendicular pass through the middle of the Voronoi sides. In this study, which was conducted in 2018 by Giulia Angelucci and Fabrizio Mollaioli (Angelucci and Mollaioli, 2018), all the foundations and principles of the formation of the Voronoi diagram have been thoroughly and accurately investigated.

In this study (Agirbas, 2019), a Voronoi skin is compared to the WWR index (Troupa et al., 2019) to provide a better understanding of its performance. Due to few studies on the Voronoi diagram and in addition to a few studies on daylight efficiency, one of the most important gaps in the study of the penetration of direct sunlight is the complexity of Voronoi geometry; In fact, how much this structure prevents the passage of light into.

Aim and motivation

Nowadays, super-advanced facade design has developed a lot. To develop modeling software, especially software with parametrization capability (Bazazzadeh et al., 2021), the power and potential of designers in creating models with inherent parametric structure and non-conventional has been doubled (Shikunov et al., 2016). The variety of super-facades is enormous due to the many capabilities of the grasshopper plugin and algorithms derived from genetics scientific. Increasing this diversity and consequently their formal complexity, in the field of architecture is an advantage, but in terms of performance of their behavior in response to environmental factors, it can be a weakness in some situations; because high complexity leads to many variables. In this paper, the main goal is on investigating the penetration of direct sunlight in such facades. In other words, evaluate the reaction of a parametric Voronoi shell on the building façade (Mele et al., 2019) with advanced variables. To cover the study among the multiplicity of parametric forms, we choose an advanced Voronoi model so that an almost comprehensive study can be obtained in the light penetration field. Architects are also very encouraged to be inspired by natural phenomena (Ali et al., 2019) to create their forms; Natural forms such as fly wings or giraffe body skin; for example, Beijing National Aquatics Center (Zhang et al., 2012) designed and built-in 2010 (Fig. 1).

Fig. 1

Beijing National Aquatics Center; based on the Voronoi pattern (Zhang et al., 2012)

This research can give an understanding of whether this pattern as a facade, in addition to the aesthetic of architecture, has a good performance against sunbeams or in general daylight, which is one of the most important factors in human comfort. Finally, it is important to mention that in this paper we have tried to use the parametric ability of the Grasshopper plugin to create a model of Voronoi with maximum variability so that the research in the discussion of the penetration of direct sunlight from any subject is not neglected.

Methodology

In the present methodology, considering that this paper is inherently in the form of research-analysis, the hierarchy in it must be fully observed. As Fig. 2 shows, the whole research method is summarized in the hierarchy.

Software and metrics

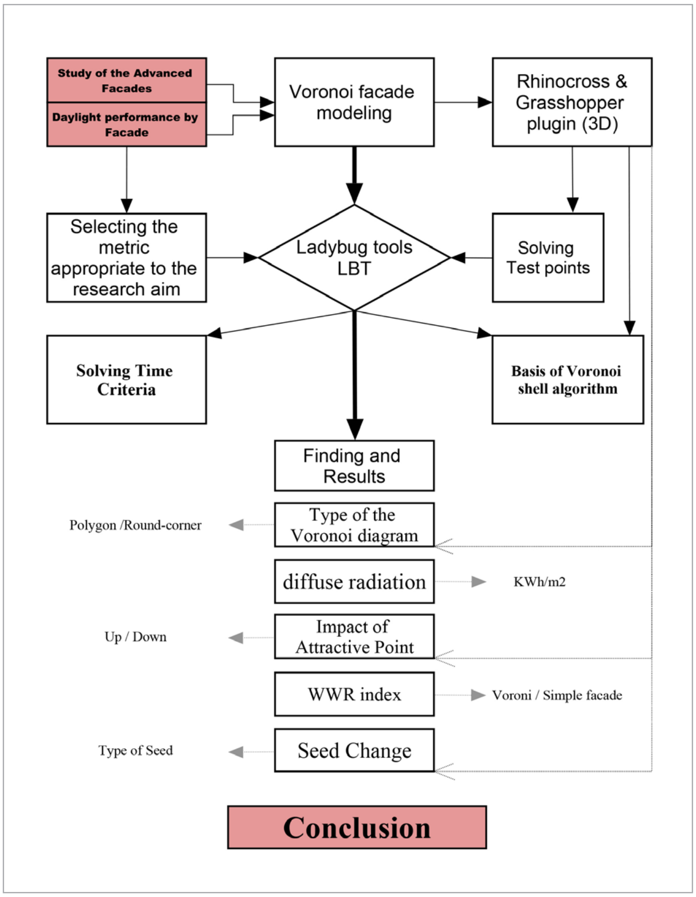


Fig. 2

The methodology in brief; the whole research method is summarized in the hierarchy

The three-dimensional design of this case study has been algorithmically written in the Grasshopper plug-in, which is available pre-installed in Rhinoceros software from version 6 onwards (Fallahtafti and Mahdavinejad, 2021). Ladybug Tools are plugins that can be added to the Grasshopper plug-in environment (Pilechiha et al., 2020) to simulate a variety of building physics (Goharian et al., 2022), and under parametric simulation capabilities (Toutou et al., 2018), all environmental simulations can be done quickly and in a short time (Goharian and Mahdavinejad, 2019). Unlike all environmental simulation software, these plugins have free coding and all code elements are visible including materials, geometries, and constructions (Motamedi and Liedl, 2019).

Simulations such as shading objects and buildings and any context directly apply to Ladybug (Valitabar et al., 2021). The simulation process in Ladybug, first after analyzing the geometry and coordinating its location in the coordinates, based on the involvement of the sky matrix, sends the direct rays of the sun that correspond to the time-step divisions to the test points (Roudsari et al., 2013). The input geometry is placed in front of the beams as a barrier, and the ladybug dynamically records the number of hours the beams reach the sensors directly, averaging those hours per square meter H/m^2 (Eltaweel and Su, 2017). As a result, sunlight hour analysis engine (SHA), the hours of direct sunbeams in each test point are calculated separately and their average is hours per square meter, which is the main metric in the analysis of the passage of direct light rays through the shell in this paper.

To investigate the diffusion beams separately, in this study, Radiation simulation has been used, which the output unit of that is the kWh/m² (Talaei et al., 2021). However, it should be noted that the main purpose of this study is to direct beams investigation.

Work plane and test points

Our case study in terms of latitude and location is middle of the northern hemisphere, with the following geographical specification; 35º_ north latitude. So that the lowest-altitude angle represents high latitude and the highest-altitude angle represents low latitude. All-weather information used in this study is taken from the Energy Plus database which is available on its website (Ghasri et al., 2016). The study model selected in this paper, based on the style of such a facade, is considered a floorless volume with dimensions of 4*6*9 meters (Fig. 3). Since the purpose of this study was only to investigate the passage and penetration of light through the parametric lattice shells, there was no need to determine the architectural functions. In other words, the common productivity indicators in evaluating daylight, such as DA, and sDA, have not been used, and only the required metrics have been selected for the main purposes of research. For this model, a Voronoi facade with a width of 4 meters and a height of 9 meters is considered. The thickness of the Voronoi facade varies from 0 cm to 60 cm based on the predetermined domain.

The work-plane for calculating this shell due to very geometric variables and parametrical configuration has been set in three levels so that the result of these work-planes can by a three-dimensional understanding give to the audience, how the performance of facade in allowing the rays. Finally, at a distance of every 3 meters, these test points are divided by the total height of the space; Height of 1 meter, 4 meters, and 7 meters.

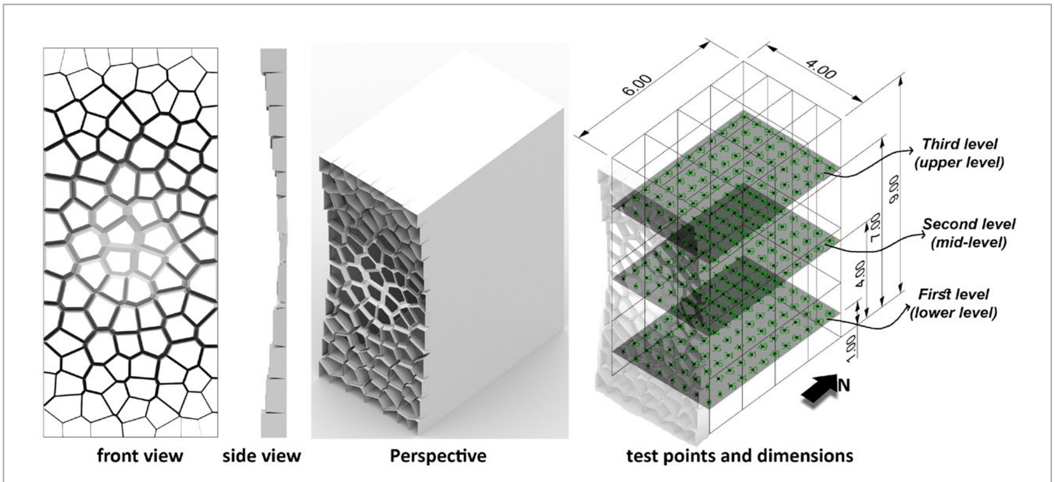


Fig. 3

Illustrating three-dimensional model of case study, with dimensions of 4 * 6 * 9; In this model, no floor is considered due to a detailed analysis of the facade. The first, second, and actually, third levels show the test points

Voronoi shell parametric algorithm and the basis of its cell creation

To make a Voronoi diagram in the Grasshopper plug-in (Vantyghem et al., 2021), two-dimensional and three-dimensional methods can be used to produce a Voronoi pattern. The 3D Voronoi component creates diagrams in a three-dimensional boundary by points, and the 2D Voronoi component does the same act in a two-dimensional boundary (Ying et al., 2015). According to Table 1, the inputs of this component include the items that can be used to control the diagrams generated by them.

Table 1

The 2D Voronoi component

Input parameters	P	R	B	Pl
genus	Point	Number	Rectangle	Plane
description	Points for Voronoi diagram	Optional cell radius	Optional containment boundary for diagram	Optional base plane

The most important part of this component is the input of points, which can consist of one or multipoint. Due to the random nature of Voronoi diagrams (Ali et al., 2019), these points are best chosen stochastically. The Populate 2D component can arrange the desired number of points at a certain boundary randomly. The inputs of this component are as follows (Table 2).

Table 2

The Populate 2D component

Input parameters	R	N	S	P
genus	*Rectangle*	*Integer*	*Integer*	*Point*
description	The rectangle that defines the 2D region for point insertion	Number of points to add	Random seed for insertion	Optional pre-existing population

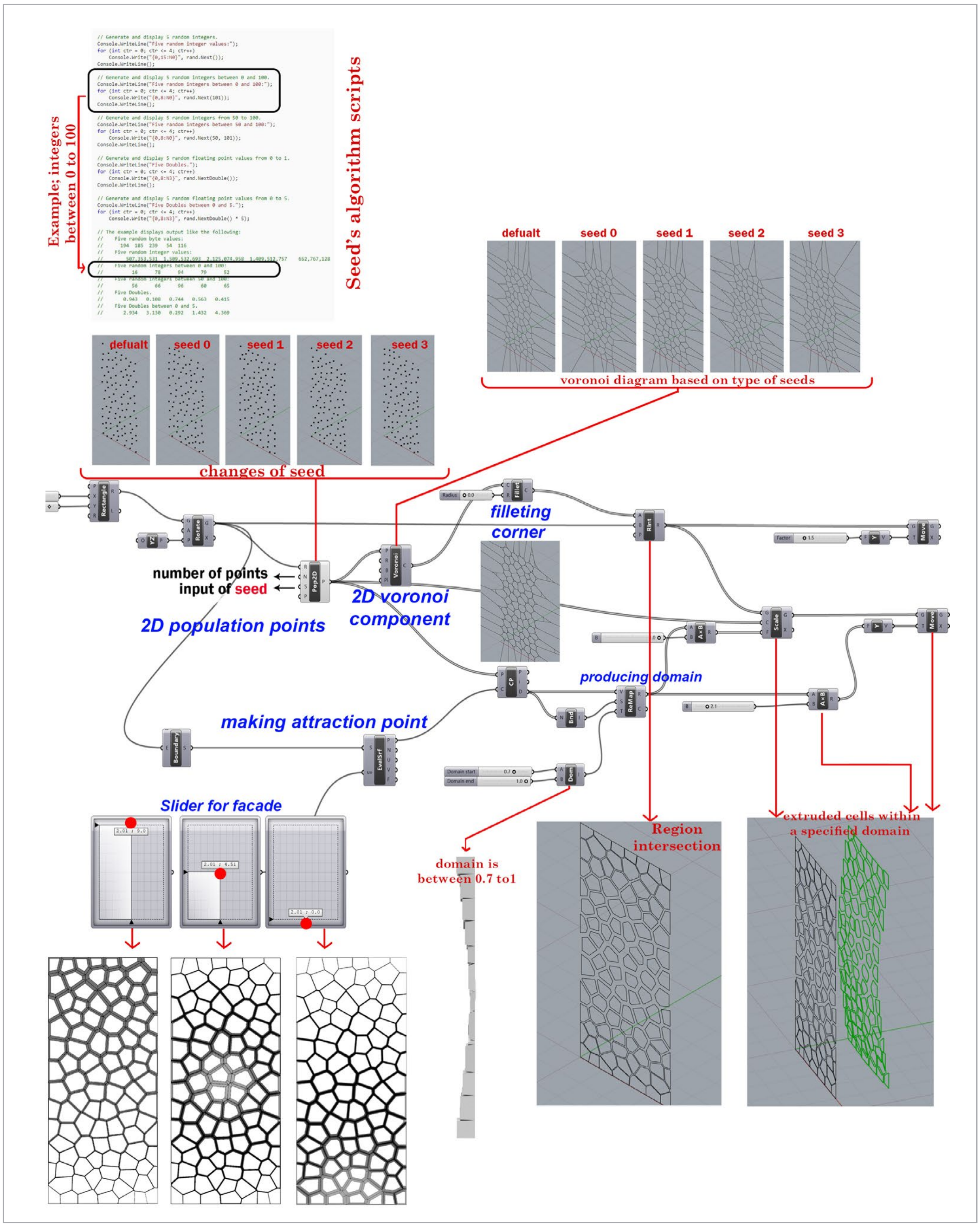


Fig. 4

Definition of Voronoi pattern simulation algorithm and the effect of algorithms on research's scenario. The major variables in the figure include seeds, the type of Voronoi pattern, the intensity of the pattern by the absorption point, and the domain of the side-curvature

Fig.4, illustrates a complete description of the Voronoi shell parametric algorithm and the basis of its cell creation. The most important input of this component is Seed, which as is clear from its algorithm's script, randomly (Hao and Hoshi, 1977) creates points in a certain region. With this variable, the external facade can be analyzed from different aspects in terms of issues of environment according to its accidental nature. Moreover, the production of different locations of points at the specified boundary is the 2D Populate component, and then entering the Voronoi component produces a variety of diagrams with a variety of Sides.

With the ability to alternation-absorb all the elements of the facade in one place in three dimensions and focus the structure of the facade at a specific point, it can produce a very complex example of Voronoi. It should be noted that in this paper, our goal was to study a Voronoi facade that covers all the intricacies of a Voronoi in three dimensions. With an MD slider, it determines the position of the attraction point in the 2D dimensions of the facade to the Evaluate Surface component, and the Closest Point component takes the points from the Populate 2D component and takes the center from the Evaluate Surface, and finally producing new points according to the attraction point.

Argument for time-section

For a general study, but a period in which high- and low-angle beams can be examined separately, it is necessary to determine the time cut from the whole year. The two 3-month periods which in the middle of each period coincide with the winter solstice (low -altitude) and the summer solstice (high altitude) (Ge et al., 2017). In general, by investigating the earth's annual motion and also the motion of the earth around itself, it can be concluded that in terms of solar altitudes, two points in the orbit of annual motion, namely the autumnal equinox and the vernal equinox, are exactly symmetrical and their altitudes are identical (Dendrinos, 2017).

As shown in Fig. 5, the two selected periods in the desired location are analyzed in terms of radiation. The period with high solar altitude lasts from May 5 to August 5. In this period (P1), the average solar altitude that it has for three months at noon is about 70 degrees, and the amount of radiation in the 70-degree-edge of the skydome is generally at its maximum. Also in the middle of this period is the 171st day of the year, when the maximum amount of sunlight in this period is concentrated almost in the center of the skydome, and by this time criteria can investigate facades, devices, and any context, when the rays are at a sharp angle.

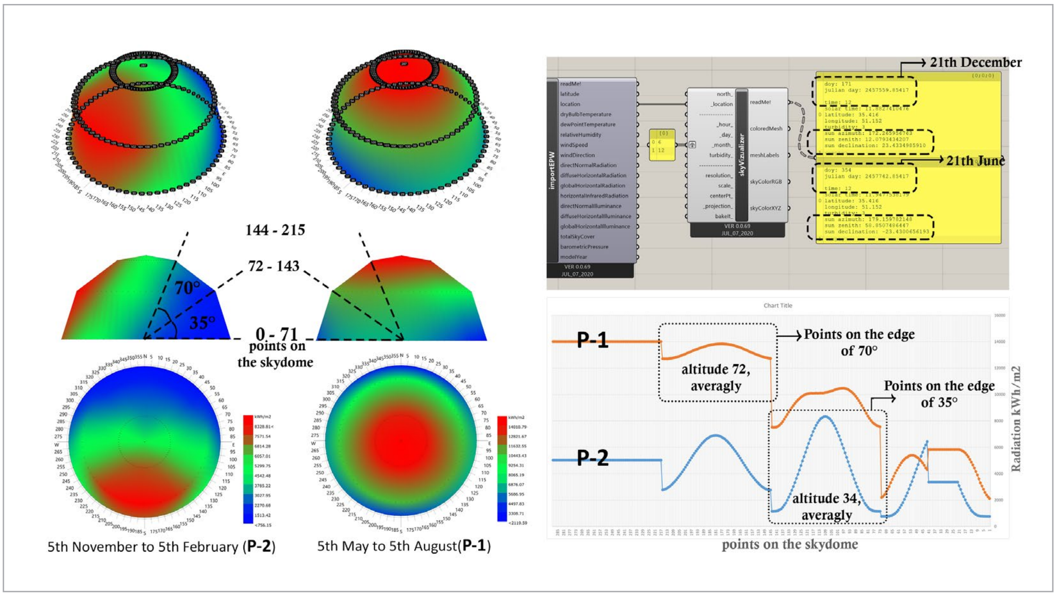


Fig. 5

Radiation information; 5th November to 5th February (P1) and 5th May to 5th August (P2). According to ethe arth's annual motion and also the motion of the earth around itself, two points in the orbit of annual motion, namely the autumnal equinox and the vernal equinox, are exactly symmetrical and their altitudes are identical

The second period, or P2, is the period that starts on November 5 and ends on February 5. As it is known in this period, the radiation is concentrated in the 35-degree-edge of the skydome during all the hours that the sun is present in the sky, the average solar altitudes of this period, and also the altitude on December 21 are about 34 degrees. Also, December 21 coincides with the 254th day of the year. This period (P2) can be representative to investigate the performance of a facade, building, or any context when the sun is emitting at a low angle.

Findings and Discussions

According to **Table 3**, many variables can be used to investigate the Voronoi shell according to each location. Investigating and concluding each section separately can be tailored to the unique characteristics of a Voronoi shell, but in general, the main variables are geometries and configurations. Investigating at a low-altitude angle is suitable for high latitudes and also high -altitude angles are suitable for low latitudes, also the result of both can be suitable for medium latitudes. The type of Voronoi diagram mounted on the shell can be selected according to a cross-sectional study with a better efficiency approach based on latitude; In other words, a cross-comparison.

Table 3

Variations

	Parameter varied		Variations		Category
Goals	Ray's angle	Sun Altitude Angle	Low-altitude	High-altitude	Time
			30 - 40	60 - 80	
		Sun Azimuth Angle	110 - 250	75 - 280	
	Voronoi diagram	Side's angle	Polygon / Round-corner		Configuration or geometry
	ambient bounce	Radiation analysis (kWh/m2)	Direct / Diffuse		
	The performance or architectural Aesthetic	WWR index	Voronoi-opening / Simple-opening		
	Cover advanced variables	Attraction point	At top of the façade / At the middle of the façade / At bottom of the facade		
		Seed	Based on the grasshopper's component 0-1-2-3-4-5-6-7-8-9		

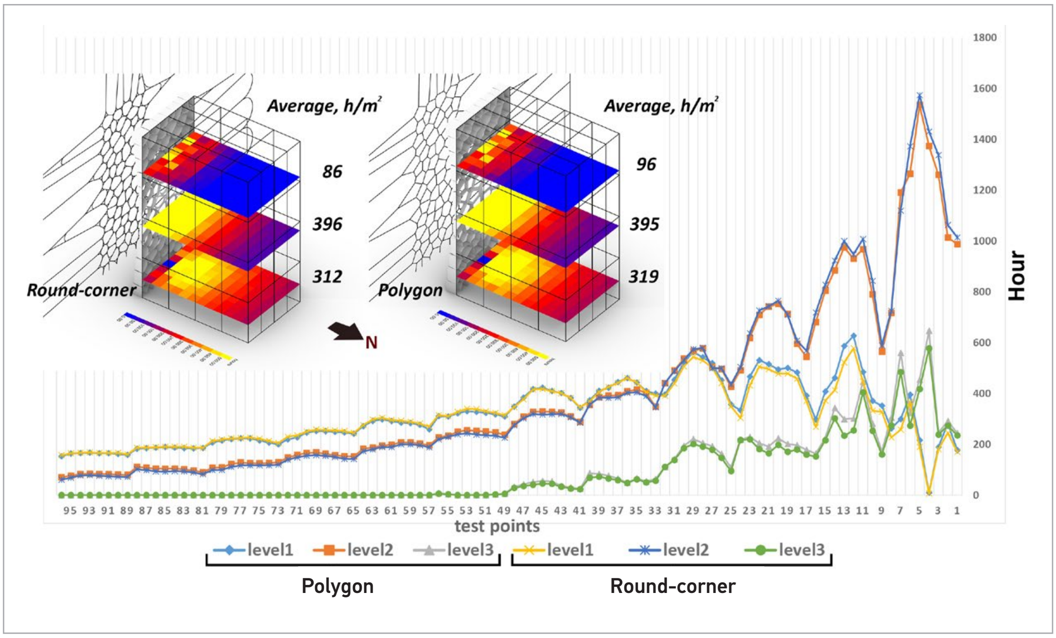
A radiation study can be a very reasonable and appropriate study, depending on the environment; For example, in places where there are many contexts around the building and the chaos-light are significant. In this study, the around-context ground is considered. The question of whether a Voronoi façade can be justified in terms of performance or simply be aesthetically pleasing can be proved by comparing the WWR index. Advanced variables in this shell due to the capabilities of parametric modeling can face the results with the wide domain of changes; this part in comparison with the performance can be adjusted to the latitude. In general, the variables in the super-advanced facade are so many that the choice of reviewing and comparing each of the variables with each other is at the discretion of the engineer and designer.

Which Voronoi diagram

The comparison of the penetration of direct rays in two Voronoi skins with the same seed and the same attractive point but with different diagrams in all altitudes and azimuths throughout the year is done in **Fig. 6.** Considering the seed and the absorption point Voronoi pattern are the same, they act almost identically in the penetration of direct rays, but investigating minor discrepancies can give designers useful design keys. In the first and third levels, the model with the polygon diagram has slightly increased the average hours compared to the model with the round-corner diagram, and this issue correctly proves that rounding the corners of the diagram slightly reduces the area of the openings in the Voronoi tessellation, thus blocking the passage

Fig. 6

Comparison of Sunlight Hour Analysis between two models with round-corner diagram and polygon diagram (annual simulation). In the first and third levels, the model with the polygon diagram has slightly increased the average hours (direct beams) compared to the model with the round-corner diagram



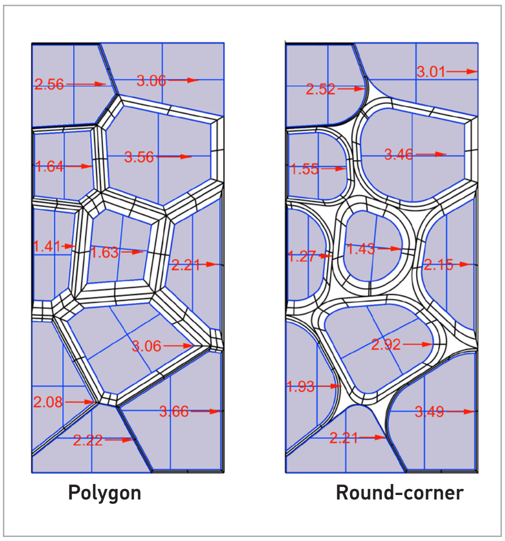
some of the beams. Also in the value of recorded hours on the test points, you can see changes in the depth of space, which is almost the same in both models, and a slight increase is observed near the facade of the polygon pattern.

As can be seen in Fig .7, the round-corner model reduces the area compared to the polygon model by keeping constant the seed and the population of points; therefore, the light transmission channel becomes a bit narrower and the corners are somewhat obstructed by bypassing rays.

Fig. 8, illustrates a scrutiny investigation of the inner surfaces of cells. As it turns out, the main difference between a flat-inner cell and a curved-inner cell is the path of extension of the rays after the collision. According to the conventional law of reflection (the angle of incident ray equal to the angle of reflection), the cell inside is flat and emits the rays in parallel with the same angle of incidence; but a curved cell acts as a concave mirror and concentrating the rays at a focal or propagates beams widely. This issue is the greatest difference in the behavior of the facades against incident light. The angle of reflection after the collision varies in both cells according to the altitude's angle and azimuth's angle. The curved-inner cell spreads the beams in parallel, but the curved cell depending on the distance the beams hit the object after bounces, is completely variable and unpredictable along the path. As shown in the graphs at the bottom of Figure 6, in a polygon cell, all the rays that reach the cell are reflected in proportion to the specified angle of each flat surface of the cell; in other words, the angle of the incident light is equal to the reflected light, and the total area of each flat surface of the cell, reflected the rays predictably. But in a round cell, due to the curvature of the cell surface, each point has a different perpendicular extension; as a result, the reflections change direction from each other differently.

Fig. 7

The ratio of the reduction of the area of the round model to the olygon model



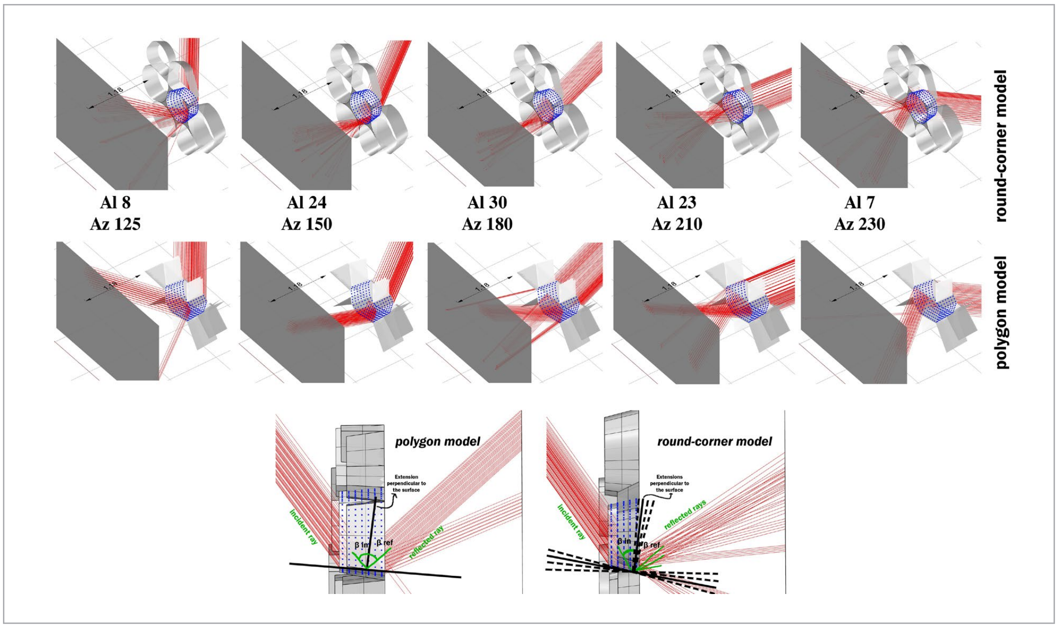


Fig. 8

Scrutiny of bounces after the incidence, in flat-inner cell and curved-inner cell

Investigating diffuse radiation

In the discussion of radiation simulation, diffusion rays can be investigated by removing direct rays. According to Fig. 9, when direct rays are removed; in the middle level, the round-corner model has increased radiation relatively, but in the first and third levels, the polygon facade has a better performance. In the round-corner facade, in the middle of the skin, due to the attractive point, the thickness of the skin has been reduced, and this reduction in thickness has increased the efficiency in the middle level. When diffuse beams are removed and direct beams are taken into account alone, the result mentioned in the previous sentence can be seen. In other words, the round-corner model allows more beams to pass through the skin only when the thickness has decreased. Nonetheless, in the annual simulation it can be seen that, as a whole, the polygon model still behaves better in allowing light to pass through, and especially when the thickness of the facade is high, the Voronoi polygon model works justifiably.

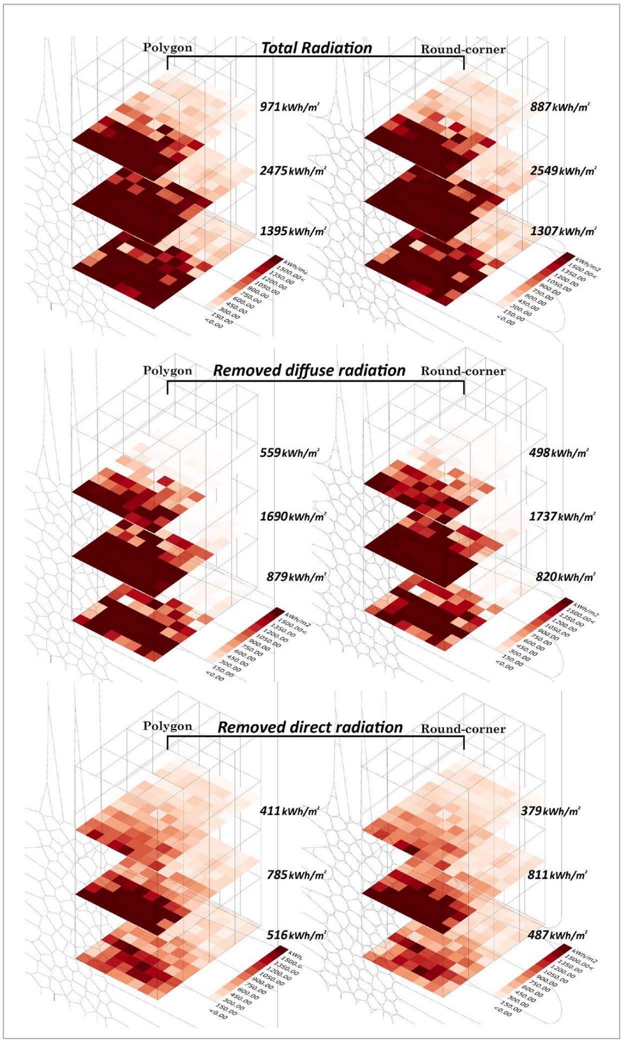


Fig. 9

Radiation analysis between the round model and the polygon model; for separate investigation of direct beams and diffusion beams (annual simulation). The round-corner model allows more beams to pass through the skin only when the thickness has decreased

Cross-sectional study

As shown in Fig.10, during the period when the altitudes are high (P1) and the incident beams are emitted to the facade at the maximum angle; in the model where the corners are broken (are not round), there is less obstruction, and this can be seen from the values recorded by the test points located in front of the facade. Although in this period (P1) the direct rays are very small due to the high altitude, but also at the beginning and the end of the day a considerable amount of direct rays radiate on the facade's building which is important. And as can be seen from the graph, this small amount of beams can be seen in the mid-level due to the smaller skin thickness. In general, in the P1 period, direct rays, especially at low latitudes, are less important and it can be concluded that at high latitudes and subsequently cold climates, the Voronoi patterns on sunbeams-facing walls are appropriate.

In the P2 period, although the sun is present in the sky for a few hours compared to the P1 period, the amount of the penetration of direct rays is much higher because the rays emit at a low angle in this period. In the first level, the round-corner model has a better performance in this period, especially in testing points near the skin, but in the middle level, the performance of the poly-

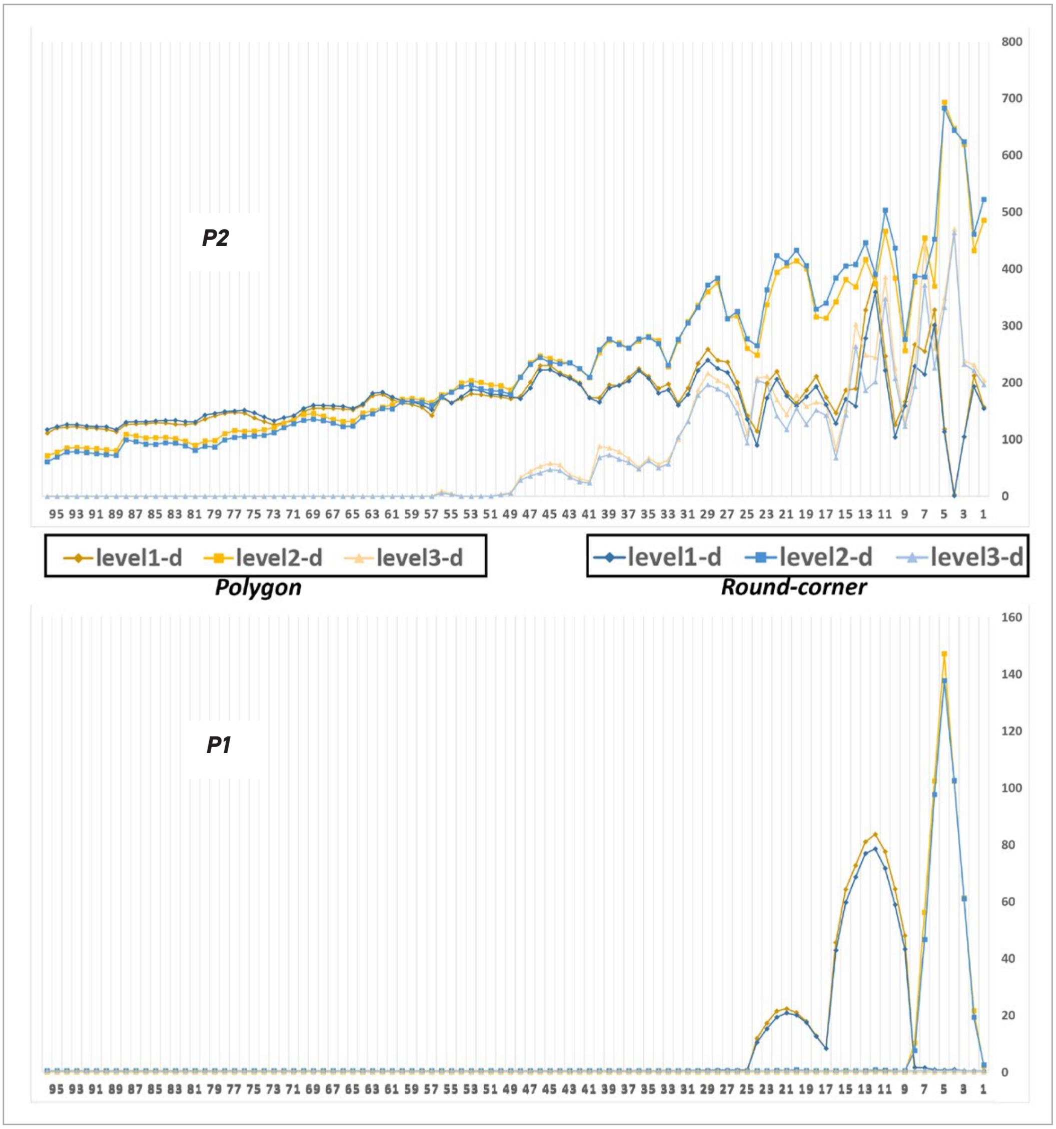


Fig. 10

The cross-sectional study between the polygon model and round-corner model (Sunlight Hour Analysis) gon-Voronoi model is better, and this can be seen in all test points located in this level. Also, in the third level, the round-corner Voronoi model has received almost more direct rays. In general, it can be concluded that this period (P2) has the greatest impact on the passage of direct rays, and the Voronoi facades in terms of blocking sunlight, should be more evaluated in this period.

Adapting the WWR index

As can be seen in Fig .11, in the P1 period, due to the change in the shell thickness of the Voronoi facade, both on the first and the middle level, the test points near the facade receive approximately 100 hours of direct beams. While the simple model does not receive any direct beams during the P1 period. In general, the frequency and the changes of Voronoi shells (thickness) have the advantage that in some situations the highest-angle-beams allow penetrating. Finally, at times and places where the sun is at high altitudes, the penetration of the sun's rays into the inside can be controlled by changing the attractive point in the Voronoi shells.

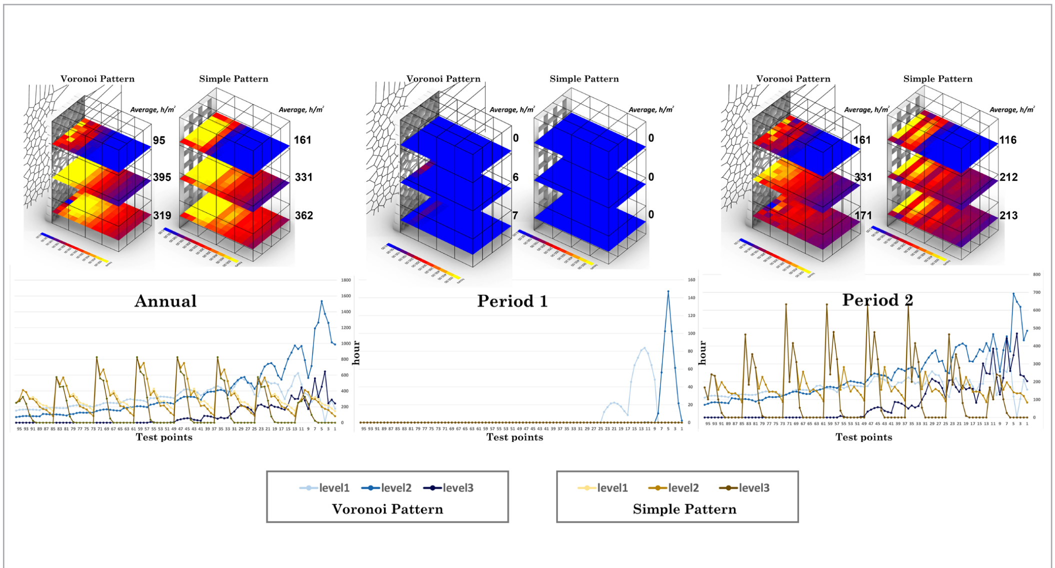


Fig. 11

Comparison of Sunlight Hour Analysis between Voronoi pattern and simple openings with equal WWR index (annual simulation). In the P1 period, the Voronoi facade, both on the first and the middle level, the test points near the facade receive approximately 100 hours of direct beams. The Voronoi model, receives direct beams uniformly to the depth of space, while the simple model has received hours of direct beams sporadically

In the P2 period, according to the recorded values on the test points, the Voronoi model, receives direct beams uniformly to the depth of space, while the simple model has received hours of direct beams sporadically. According to the record of the average in each level, in the P2 when the angle is low, it can be seen that the Voronoi facade due to its irregular and stochastic geometry has significantly increased the penetration of beams into space. This difference can be seen in all levels, especially in the middle level, which is almost 1.5 times higher. As a result, the excellent performance of the Voronoi pattern can be seen at times when the titanium is low. In the study of the whole year, i.e. in all angles, the Voronoi pattern model generally has lower average sunbeams than the simple pattern at low and high levels where the wall thickness has increased.

Impact of attractive point displacement

By shifting the attractive point, or in other words, shifting the alteration of the thickness of the skin, many changes are very important in design decisions from all aspects. As shown in Fig .12, when the absorption point transfers from the center of the model upwards, in the period when the altitude's angle is high i.e. P1, its performance improves because the wall inclines to the sky, and the rays they face fewer obstacles. However, only an area of the space in this period benefits from direct beams located in front of the wall (near the facade). On the other hand, when the attractive point is pulled down, the thickness at the bottom of the wall naturally decreases, and the slope of

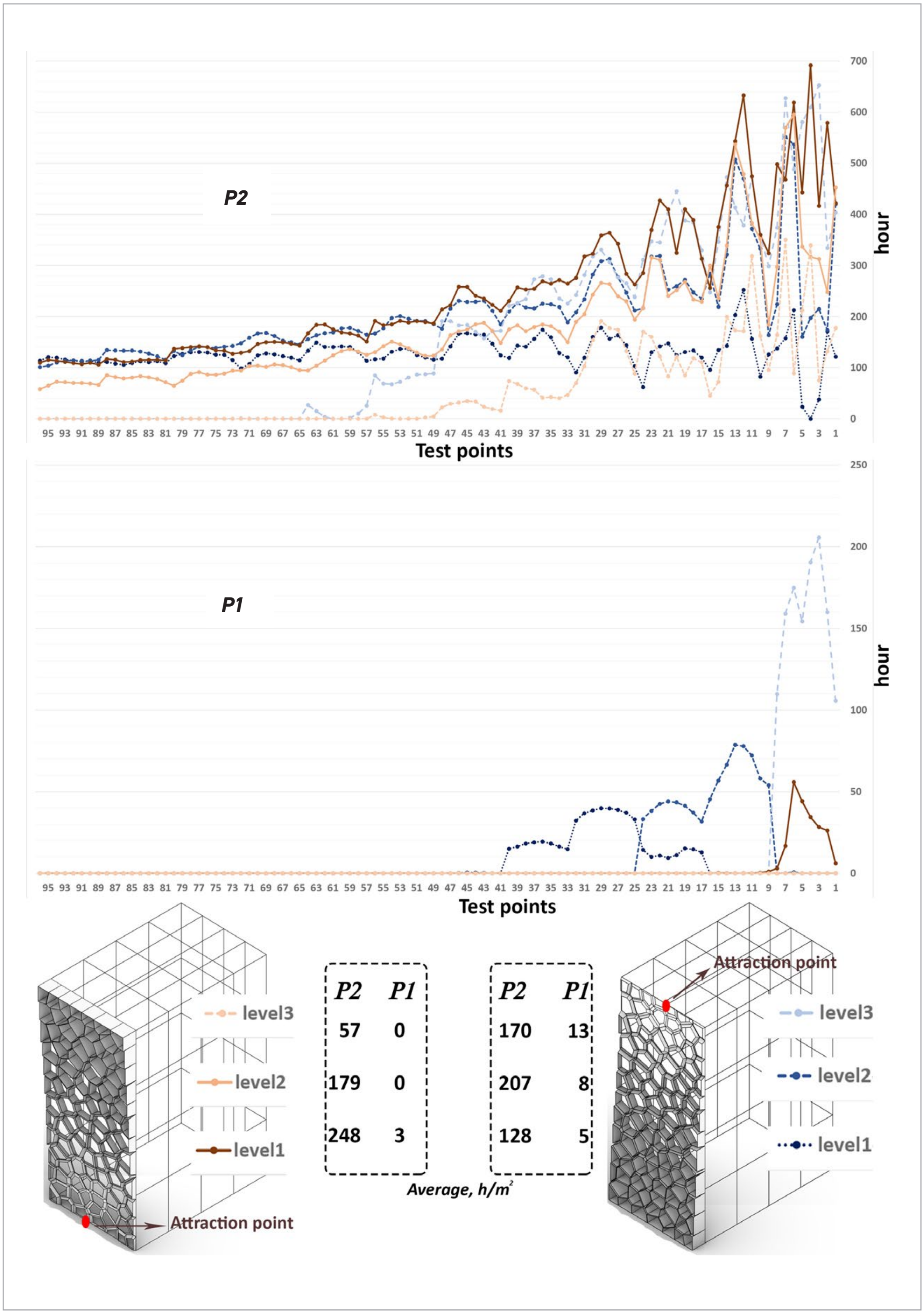


Fig. 12

Investigation of change and displacement of the attraction point in the Voronoi model (Sunlight Hour Analysis)

the wall is inclined downwards. As can be seen in the comparison in the P2 period, there is a great discrepancy in the recorded hours on the test points in the first level, compared to the upward absorption; especially in testing points close to the facade. This difference in value is observed in all levels in the P2 period, but relatively when the attractive point tends downwards, in the third level this difference is very large and it can be concluded that the upper level, the most impact accepts these changes. In the P1 and P2 periods, the lower level includes the least changes due to the displacement of the attractive point.

As a result, these outputs can be very useful in deciding the choice of internal functions in space, in other words, it is possible to control the direct beams in proportion to the internal functions by using the attractive point lever. From the results obtained in terms of average hours per square meter, it can be concluded that if the maximum amount of received rays are considered, the model with an attractive point upward has better performance. But if control of radiation has priority, an attractive point downward may be more useful; But in general, the attractive point should be in proportion to the internal functions so that the space is not affected by the risk of glare.

Impact of a seed change

Changing the seed with an equal number of points and its effect on the passage of light rays shows that changing the seed at any level, causes a change in the number of radiation hours, but the frequency of changes is in a certain range, which the interval of this alteration is important, which must be coordinate with the design goal. As can be seen from the simulation with the seed changes in Fig.13, there is an almost uniform alternation rhythm in the values at each level that these intervals of alternation are close to each other, in other words, there is not much difference (relate to latitude). The first level is almost the least affected by the change of side, and the middle and upper levels are more affected, and the range of these changes is the same concerning the sun's altitude angle at all latitudes. In general, changing the seed of Voronoi-pattern diagrams will have little effect on the passage of rays, unless there is a special sensitivity to architectural constraints.

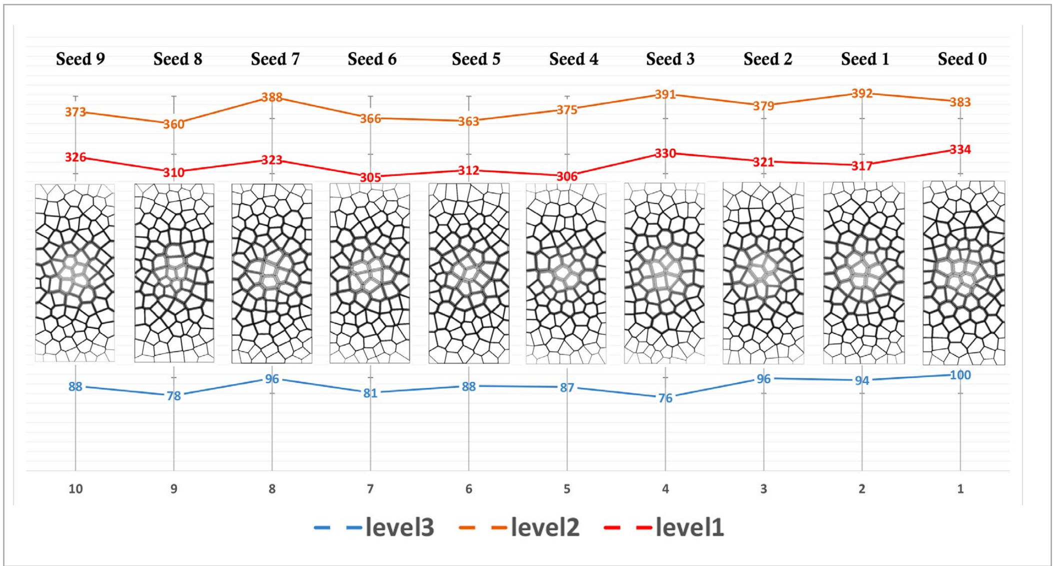


Fig. 13

Investigation of a seed change in Sunlight Hour Analysis (annual simulation)

Conclusions

Nowadays, parametric grid skins as the facade of modern buildings are undoubtedly an integral part of architectural ideas in modern cities. These types of facades are very attractive and their removal from modern architecture is inevitable. But from different environmental aspects, these shells should be examined and they have weaknesses, a careful study of them in different dimensions can develop both in their use as an architectural element and create a balance between the selected architectural idea and its weaknesses. This paper focuses specifically on the passage of direct rays of light when the Voronoi facade is facing the sun.

This study showed that while Voronoi patterns are inherently stochastic, controlling geometrical turbulence has a significant effect on daylight performance. In modern architecture today, an adaptation of nature and mathematical patterns in the appearance of the buildings is very common; if these implementations are based solely on architectural aesthetics, they are not only useful but also seriously impair the performance of the space. Scrutiny of advanced geometries in building facades is very difficult, but this method presented in this study showed that by separating the investigation fields, the complex prediction of these geometries can be overcome, and designed the geometry of these patterns according to the dynamic daylight issues and the desired location.

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