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A Geometric Method on Facade Form Design with Voronoi Diagram

Voronoi Diyagramı ile Mimari Cephe Tasarımı Üzerine Geometrik Bir Yöntem

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Abstract

Voronoi is a stochastic pattern that is the result of structural formation with the least material and least energy in nature. Therefore, Voronoi, which has become a biomimetic pattern, is a source of inspiration in architectural design and it has been increasingly used in this field. Modern design methods make it possible to adapt the process of self-organization of biological structures to architecture using mathematical models such as Voronoi. Especially on the facade, it is used on randomness and therefore irregularity as in nature and these irregular forms can be built thanks to the possibilities provided by technology. However, randomness limits the designer's ability to interfere with the form. In this study, a method was presented which including modeling process and material usage amount using Rhinoceros and Grasshopper software. With this method, it was aimed to make Voronoi a tool that the designer can control the process while producing patterns and to create a regular and systematic design principle by integrating it with the balance principle of geometry. The patterns whose impact areas were changed with symmetry, asymmetry and radial balance approaches were evaluated by comparing the amount of material used and their effect on the application process was evaluated. As a result, it was determined that similar increases occurred between the level of inclusion of direction and movement in the design and the level of randomness in the process of determining the most efficient one among alternative patterns in terms of material usage, as in nature.

Keywords: *Architectural Facade Design, Principle of Balance in Geometry, Voronoi Diagram, Computer-Based Design, Biomimetic Pattern.*

Özet

Voronoi doğada en az malzeme ve en az enerji ile yapısal biçimlenmenin bir sonucu olan stokastik bir desendir. Bu sebeple biyomimetik bir desen olma özelliği kazanan Voronoi, mimari tasarıma ilham kaynağı olmakta ve bu alandaki kullanımı giderek artmaktadır. Modern tasarım yöntemleri, matematiksel modeller kullanarak Voronoi gibi biyolojik yapıların özörgütlenme sürecinin mimariye uyarlanmasını mümkün kılmaktadır. Özellikle cephedeki kullanımı doğada olduğu gibi rastgelelik ve dolayısıyla düzensizlik üzerine kurulu olmakta ve teknolojinin verdiği imkânlar sayesinde bu düzensiz biçimler inşa edilebilmektedir. Ancak rastgelelik, tasarımcının biçime müdahale etme durumunu kısıtlamaktadır. Çalışmada Rhinoceros ve Grasshopper yazılımları kullanılarak modelleme süreci ve malzeme kullanım miktarı bilgisini içeren bir yöntem sunulmaktadır. Bu yöntem ile Voronoi'yi, tasarımcının desen üretirken süreci kontrol edebildiği bir araç haline getirmek ve geometrinin denge ilkesi ile bütünleştirerek düzenli ve sistematik bir tasarım prensibi oluşturmak amaçlanmaktadır. Simetri, asimetri ve radyal denge yaklaşımları ile etki alanları değiştirilen desenler, kullanılan malzeme miktarına yönelik karşılaştırma ile ele alınmış ve uygulama sürecine etkisi değerlendirilmiştir. Sonuç olarak, alternatif desenler arasından malzeme kullanımı bakımından, doğada olduğu gibi, en verimli olanı tespit etme sürecinde yön ve hareketin tasarıma dahil edilme düzeyi ile rastgelelik düzeyi arasında benzer artışların oluştuğu tespit edilmiştir.

Anahtar Kelimeler: *Cephe Tasarımı, Geometride Denge İlkesi, Voronoi Diyagramları, Bilgisayar Destekli Tasarım, Biyomimetik Desen.*

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1. Introduction

The Voronoi diagram can be found in many places in nature. From cell division to patterns in animal skin, from the structure of the fly wing to the leaf structure; it can be seen in many examples in various scales. Formal formations in nature such as Voronoi are integrated into man-made objects to create more efficient and sustainable structures. Being inspired by nature today; It investigates not only the direct transfer of form but also the formation process of the form in nature. In this case, it is possible to define complex forms and systems of biological structures by using appropriate mathematical models (Nowak & Rokicki, 2016).

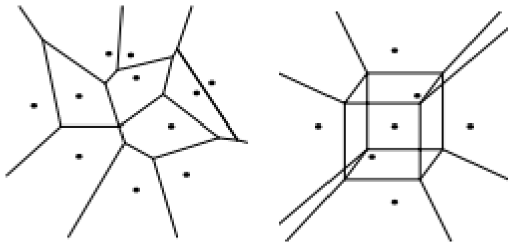
Voronoi Diagrams, which are formed with a set of points and have a polygonal cell structure, are becoming widespread in architecture today. Many architects use Voronoi Diagrams, a method of space discretization, to shape structural forms, create patterns for the facades of buildings, and design spatial forms. Architectural facades created using Voronoi are designed as an irregular shape, just like in nature. In this case, the design is created automatically by the computer, and the decision-making authority of the designer is constrained. Thanks to the method presented in this study, the designer can use the Voronoi diagram to produce pattern alternatives in line with the own rules through the balance principle and can determine the most efficient one among these patterns in terms of material used.

Within this study to create a pattern for the architectural facade, firstly, square, and circular shaped basic grids were created using Voronoi with periodically arranged point clusters. The patterns are obtained by changing the positions of the points on these grids. Grid boundaries and point numbers were kept constant. In order to increase the visual perception on the facade, it was aimed to have a geometric order of the patterns, and in this direction, the points are moved as a group on the grid. This grouping was called the "impact area" in the study. Geometric order was obtained through the principle of balance. On the grids arranged with three different balance principles as symmetric, asymmetric, and radial, the affected areas that give points rotation and translation capabilities are determined. Points outside the impact area have not been interfered by the designer. This affects the size of the Voronoi cells and thus the shape of the pattern. The line lengths of the new patterns were obtained to determine the amount of rod material to be used for facade production. Within the study, the relationship between the amount of displacement of the points in different types and the total length of the rod to be used was investigated.

2. Voronoi Diagram

The emergence of the Voronoi diagram, which is a graphical explanation of structure formation in nature, dates back to the 17th century. It is seen that Descartes used similar diagrams in his book of principles of philosophy in 1644 to explain that the solar system consists of vortices. The first comprehensive presentations were featured in the work of Gustav Dirichlet and Georgy Voronoi. Voronoi still maintains its importance since its emergence and continues to be developed with new technology in diversified fields. Today, it is used in many different fields that are involved in science and technology such as astrophysics, ecology, geometry, hydrology, meteorology, computer graphics, and statistics (Okabe et al., 2000).

The mathematical definition of the Voronoi diagram can be briefly expressed as the process by which a specified set of points divides the entire area into parts. Each point determines the boundaries of its sub-area within the whole area concerning the location of neighboring points (Coates et al., 2005). All locations within the boundaries of a Voronoi cell are closer to the point in the center of the cell than other points (Aurenhammer, 1991). The diagram, which can be created in both two and three dimensions (Figure 1), is convex polygons consisting of centers (points), cell edges and cell vertices in two dimensions; They are polyhedrons consisting of points, vertices and surfaces in three dimensions (Nowak & Rokicki, 2016).



(a) (b)

Figure 1. (a) Voronoi diagram in 2D (b) and in 3D (Fortune, 2017).

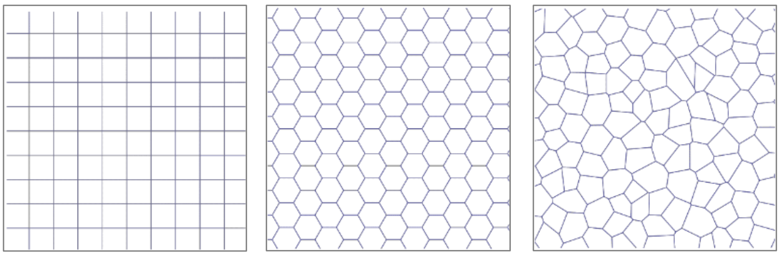
The diagram, which is shaped according to the relationship of each point with its neighboring points, reorganizes itself when the positions of the points are changed or when point extraction and addition processes are applied. Thus, it is a complex system configured by the relationships between points (Coates et al., 2005).

3. The Voronoi Diagram Within the Context of Geometry

Voronoi diagrams created with a random set of points are a product of computational mathematics. In the field of architectural design, it is a widespread view that uncertainty and randomness are an integral part of Voronoi. Thereby, it is believed that patterns similar to the formations in nature are obtained (Wu & Zhang, 2016). However, Voronoi diagrams do not have to be created only with random points in structural layout. Any set of points can be used as input to create grids in the plane. In Voronoi diagrams where the positions of the points are determined by the designer, geometric cells are obtained by placing the points periodically in the plane. For example, square cells are formed in the layout where the distance between points is fixed and the points are in the center of the squares (Figure 2a). Similarly, hexagonal grids are a result of triangular point placement (Figure 2b). Voronoi diagrams created with randomly placed points (Figure 2c), on the other hand, have a very soft composition in many respects and are more variable, asymmetric, scalable, and irregular compared to hard grids such as square and rectangular.

Grids such as square and hexagon are particular cases of the Voronoi diagram. In addition to having the ability to imitate other grids, it also can change and transform.

This feature of manageability allows the designer to switch from one grid to another during the design process (Kardasis, 2011).



(a) (b) (c)

Figure 2. a and b are patterns created from periodically placed points; (a) Square grids, (b) Hexagonal grids, (c) Voronoi diagram created from randomly placed points (Kardasis, 2011).

4. Principle of Balance

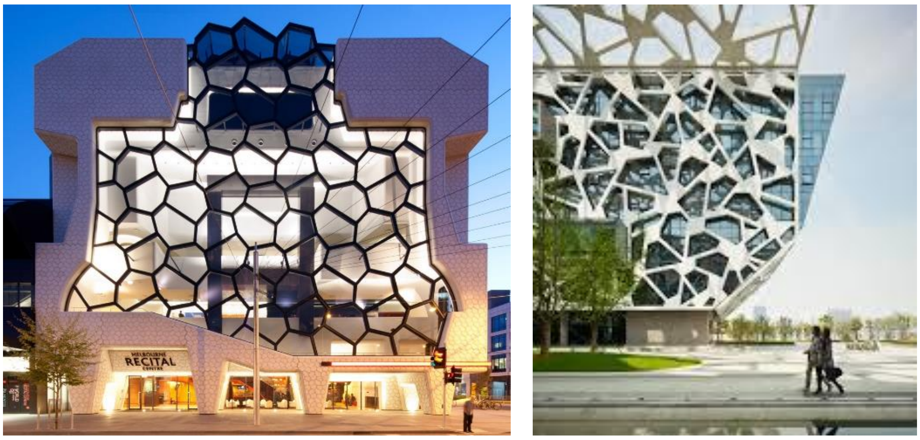
The physical-mental existence of human and all organic life tend to achieve balance. An imbalanced composition appears accidental, discontinuous and, therefore useless. The elements involved in the structure tend to change shape and location at all times to achieve a state that is better in harmony with the whole. On the contrary, in a balanced composition, there is a distribution in which all the actions included in the system, in both physical and visual balance, are stopped. It creates a sense of stability and robustness against the building in those who observe the building (Arnheim, 1974). Besides that one, the shapes arranged with the principle of balance have the feature of being perceived to a great extent by the observer at first sight.

The architect wants to take visual decisions more systematically while designing. In this case, the balance becomes an important factor in determining the dynamics of the composition (Arnheim, 1974). There are three types of balance elements: symmetrical, asymmetrical, and radial. Symmetry occurs with the presence of a center or an axis. The symmetry axis consisting of two points provides a balanced distribution of the elements included in the plane (Ching, 2007). In geometry, symmetry is created by rotation, reflection, and translation. Symmetrical balance is achieved by having the same or very similar elements on both sides of the area divided by horizontal, vertical, or an axis located at any angle on the plane. Radial balance provides a visual focal point where elements are positioned circularly around a center. Unlike symmetry and circular balance, asymmetry is not arranged around a certain axis. Asymmetry creates a complex design structure where the elements balance each other and, therefore it is the most dynamic balance (Zhao et al., 2014).

5. Use of Voronoi in Architectural Applications

The skills such as manual dexterity, mastery, memorization, and rapid calculation required for traditional construction techniques are no longer sought in today's design techniques. Digital design tools replace these abilities and require intellectual skills such as intelligence, thinking and decision making (Terzidis, 2009). However, traditional techniques are being gradually abandoned in order to pave the way for new design challenges and to build more efficient structures (Angelucci & Mollaioli, 2018). Digital design is based on algorithmic designs that have the ability to generate code. It is possible to generate the structure of a cellular grid system by changing the values of its components (Oxman & Oxman, 2010). In this way, the architect can create individual tools and produce the most appropriate architectural forms using the scripting language. Creating a structural surface using rod elements based on topological information provides in terms of architecture interesting designs (Gawell & Nowak, 2015).

Facade applications in architecture such as determining the shape of the panels, tessellation of the double-sided facade, and structural shaping of the building skin are observed (Nowak & Rokicki, 2016). Especially with the latest developments in technology, tall buildings with a diagrid system are shaped with nature-inspired cellular patterns. These biomimetic patterns, what the degree of irregularity can be adjusted arbitrarily, are preferred to obtain aesthetically attractive facades (Angelucci & Mollaioli, 2018). Besides its aesthetic feature, it provides a form with the least material and least energy, just like in nature (Dimcic, 2011). Melbourne Recital Center in Melbourne and Alibaba Headquarters in Hangzhou are sample buildings with a facade shaped by Voronoi (Figure 3) (Nowak, 2015).



(a) (b)

Figure 3. (a)Melbourne Recital Center, (b)Alibaba Headquarters (Url-1, Url-2)

The load transfer of mosaic facades with such complex cell structure is generally as follows: Some nodes of the structural grid used in the facade are installed at the points where they intersect with the the load-bearing points of the building. In this case, the loads on the non-intersecting facade nodes are indirectly transferred to the structural system of the building (Brzezicki, 2018).

When the literature is examined, experimental studies have been reached including analysis and research on the shell, structural system, and space design formed with Voronoi. For example, Tonelli et al (2016) used the Voronoi diagram to design grid shell structures. The tensor area obtained in the result of the stress analysis on the initial surface was used as a metric. Voronoi tessellation was performed on this metric, and then aesthetics were improved by using symmetry and ensuring the regularity of the cells. Thus, in the study, a method was presented on shell design with strong static performance and aesthetically pleasing appearance with Voronoi (Tonelli et al., 2016). Herr and Fischer (2013) researched to find a modern alternative for the triangular and rectangular beam layout using Voronoi diagrams. The patterns were dynamically generated by defining algorithms. The patterns generated for the beam and column layouts are discussed in terms of density, the capacity of load carrying, and aesthetic appearance (Herr & Fischer, 2013). Friedrich (2008) researched the static performance of the 3D Voronoi diagram as a framed structural system. The edges of polyhedrons generated with Voronoi are considered structural members of a static system. Different techniques were investigated to optimize the cell structure in terms of its structural features (Friedrich, 2008). A study was carried out by Harwiansyah (2016), which includes using 3D Voronoi diagrams for a house design in which trees act as carriers in a forest area. In the study, trees were taken as a point set. Thus, the settlement of trees became the factor determining the formal features of the spaces that make up the house (Harwiansyah, 2016).

Some studies focus on facade design using Voronoi diagrams and analyze grid structures generated in this way (Torghabehi & Buelow, 2014; Gawell & Nowak, 2015; Gawell & Rokicki, 2016; Mele et al., 2016). Torghabehi and Buelow (2014) presented a study proposing to create a Voronoi patterned building skin for a mid-rise building. For the outer skin, the desired data were introduced to the system such as the complexity of the Voronoi pattern and then, material efficiency and resistance to environmental effects and alternatives were produced using the genetic algorithm. Then, the algorithm presented the best possible results for the designer (Torghabehi & Von Buelow, 2014). Gawell and Nowak (2015) performed analytical tests on the efficiency of planar rod structures generated using the Voronoi diagram. The horizontal, vertical, and cross axes that prevailing in the construction industry became the determining elements in shaping the patterns. It has been determined that the patterns created in the metric with the same number of points produce different results in terms of efficiency. As a result of the study, it was emphasized that different patterns can be produced according to the needs of the user using Voronoi tessellation (Gawell & Nowak, 2015). In the study of Rokicki and Gawell (2016), the efficiency of various grid systems developed in the digital environment in terms of material consumption was discussed. Three different metric dispositions were created, regular geometry, Voronoi, and Delaunay, and each layout were analyzed within itself. According to the results obtained from the study, it revealed that the array of points was a factor affecting the total length of the material used (Rokicki & Gawell, 2016). In the study conducted by Mele et al., (2016) Productivity analyzes were carried out for the building skin created using the Voronoi diagram in high-rise buildings, according to the density and irregularity of the pattern. Efficiency was obtained by dividing the total weight of the structural steel used for the model by the total floor area of the building, and it was found that as the irregularity increased, the structural weight generally decreased (Mele et al., 2016).

It is understood that there is an orientation towards the interpretation of the new shapes formed by changing the point positions on the diagram according to material efficiency in the limited studies specific to the facade (Table 1). However, when considered with the basic design principles, its change in both visual and quantitative aspects will be important for its evaluation in the design process. It will contribute to the literature on creating an answer to this question: “Can the Voronoi diagram be designed with the balance principle, which is one of the basic design principles of geometry?”.

Table 1. An Evaluation on Voronoi Diagrams Used in Facade Design

	Authors	Purpose	Constants	Variables	Outcome
1	Torghabehi and Buelow, 2014	It was aimed to find the most efficient patterns produced using the Voronoi diagram for building skin design with the help of genetic algorithm (GA).	-The dimension of the exterior surface of the building - Environmental factors - Aesthetic value (complexity level of the Voronoi pattern)	The width of the tubular system and the formal differences of the Voronoi pattern	The algorithm has found the most effective patterns in line with the determined criteria.
2	Gawell and Nowak, 2015	Different dispositions of Voronoi patterns were compared.	- Metric system - Voronoi points and number of cell - Axis direction of the rods (must be horizontal or orthogonal)	The locations of Voronoi points on the metric	It was determined that the efficiency values of different Voronoi patterns obtained by simply changing the positions of the points are different.
3	Rokicki and Gawell, 2016	Voronoi diagram and other grid structures are compared separately on efficiency.	- Metric system - Voronoi points and number of cell	The locations of Voronoi points on the metric	It was concluded that the layout for the Voronoi patterned structure affects the system weight.
4	Mele et al.,2019	The efficiency of the Voronoi pattern for tubular system design in high-rise buildings was optimized according to the disposition and density.	-The dimension of the exterior surface of the building	The regularity and density of the Voronoi diagram	It was determined that as the irregularity of the Voronoi diagram increases, the structural weight generally decreases.

6. Method and Case Study

The method that enables the designers who create facades using Voronoi to systematically transform the mathematical principle into form was presented. It was accepted that the facade created by this method was a self-supporting system created with structural rods in the vertical plane. The production of the facade was considered to be done by induction method, in the simplest terms. The cells are formed by combining the rods, then the cells are combined to complete the form of the facade.

The graphs showing the data of the patterns produced represent the total structural rod length and the longest rod length to be used on the facade. Thanks to the total structural rod length data, the designer can determine the optimum during pattern generation. The longest rod length data will assist in determining the length of the material in parallel with the strength of the material in the structural analysis process, which will then be carried out independently. In addition, if more structural rods of the same length were to be used for the facade, the physical production of the designed facades would be easier and faster.

Based on the aforementioned reasons (Section 4), 3 different layouts were created with the balance principle, which is one of the design principles of geometry. The 3 layouts were designed with symmetry, asymmetry, and circular balance, respectively. Based upon the feature of the Voronoi diagram that can be repositioned and transformed by means of points, the design was carried out through the "Grasshopper" plugin of the Rhinoceros program.

First, points were placed at equal distances on the rhinoceros x-z plane to form the pattern. The point (pt) component has been added to the Grasshopper canvas (Figure 4) and the points set to this component. The points were moved by the designer in separate directions for each balance principle. Since the distance between the points was arranged as 6m, the frame enclosing the points was determined 3 m away from the outermost points. This was because each point in the Voronoi diagram was considered to be the center of the cell. This limit was set for the boundary input of the Voronoi component. Then the point input of the Voronoi component was connected to the pt component to create Voronoi from the points.

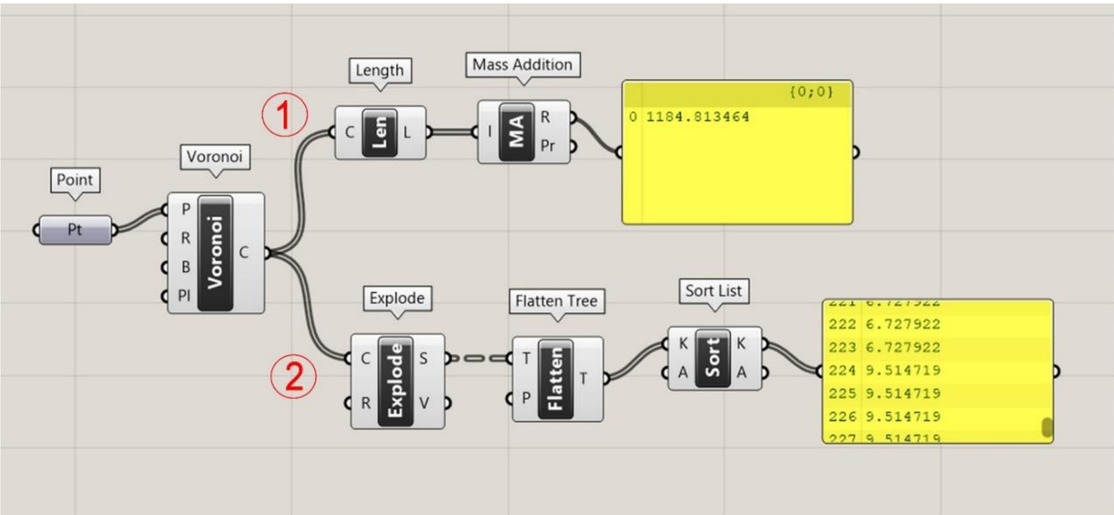


Figure 4. Grasshopper script to create and analyze patterns

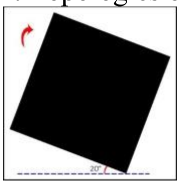
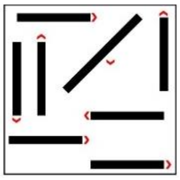
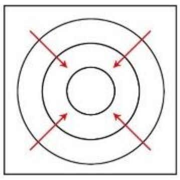
It was necessary to follow the marked path 1 in Figure 4 to determine the total rod length. The Voronoi component was connected to the Lenght (Len) component to determine the length of each line that generates the Voronoi diagram. Then Len was connected to the Mass Addition (MA) component to determine the total length of the bar. So the lengths of the rods obtained with the Len were summed. The result of the calculation was reflected in the panel component.

In order to find the longest bar length, it was necessary to use path 2. Voronoi was connected to the Explode component after it was connected to the Pt component. Because the Voronoi component gives the total length of the cells. It was necessary to use the explode component to detect the lines each cell had separately. It was then linked to the flatten tree component. Because the line lengths obtained after explode were in the form of groups. Each Voronoi cell represents a group. However, the group was not suitable because it was wanted to determine the longest one among all the lines.

The sort list component was used to create this list and detect the longest line. The result was reflected in the panel component.

Two different grids were created on the vertical plane. One reference grid was created for the patterns obtained through symmetry and asymmetric balance, and a different reference grid was created for patterns based on radial balance. Different impact areas were determined on these reference grids created with different balance principles (Table 2). Rotation for symmetrical balance, movement in the determined direction for asymmetric balance, and translational movements towards the center for radial balance was applied to the impact area. The amount of displacement has been gradually increased for each balance principle. The positions of the points included in the impact area on the grid have changed, and new patterns have been formed at each stage. The amount of material required for the structure was determined by calculating the total line length of the patterns obtained.

Table 2. Topologies of İmpact Areas and their Constants and Variables.

Balance Principle	 **Symmetry**	 **Asymmetry**	 **Radial**
Constants	The number of points, plane boundaries, the axis of symmetry, material properties used	The number of points, plane boundaries, material properties used	The number of points, plane boundaries, location of the center on the plane, material properties used
Variables	The position of points on the plane at each step relative to the angle of rotation of the impact area.	The position of points on the plane at each step relative to the direction of movement of the impact area.	The position of the points on the plane at each step relative to the distance of the impact area to the center.

6.1. Voronoi Diagram Generated with Symmetrical Balance

After the symmetry axes required for symmetrical balance were determined on the plane, the shape and size of the impact area were defined. Two symmetry axes intersecting each other at right angles and 4 square-shaped impact areas, each affecting 9 points, were shown schematically in Figure 5.

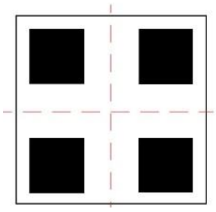


Figure 5. The positions of the impact areas on the grid were positioned in accordance with the symmetrical disposition

The reference grid determined as the starting pattern (Figure 6a) was created from 49 points and had a square Cartesian feature. Rod length was determined as 6 m, total rod length was 1176 m. These figures were used as a reference for comparison with the patterns created. The impact area determined on this grid is positioned to be symmetrical to each other. In each step, the rotation angle of the impact areas on the plane was increased by 15 degrees and rotated in 3 different angles namely 20, 45 and 60 degrees, respectively (Figure 6).

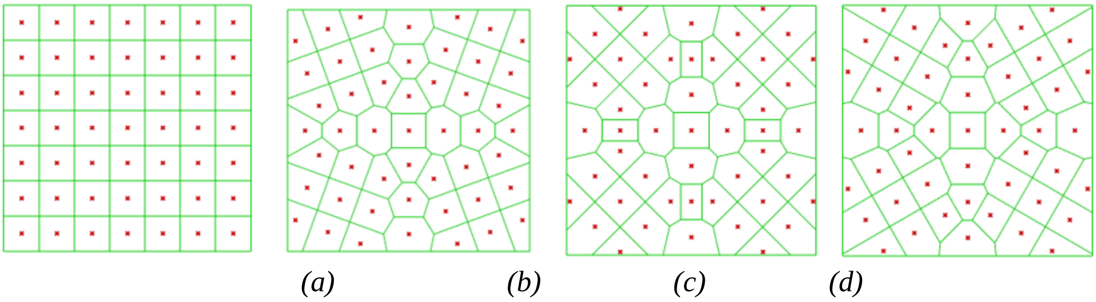


Figure 6. Topological Voronoi structure variants generated by rotating at different angles; (a) Reference Grid(X), (b) A1 grid, (c) A2 grid, (d) A3 grid

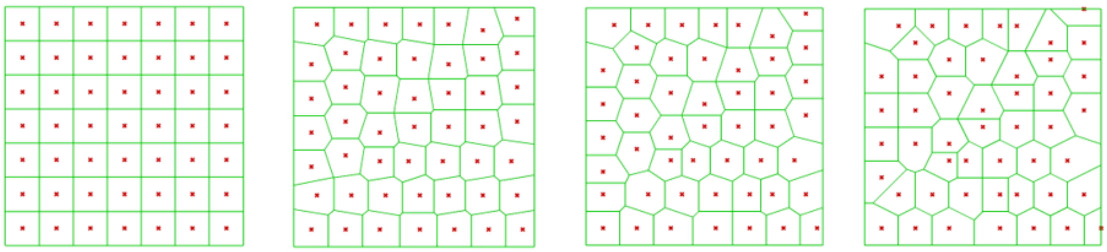
The total length of the rod and the longest rod length of each of the 3 different patterns (Figure 7) obtained were compared. As a result of the analysis, it was determined that with the increase in the angle value, the total length of the rod to be used to generate the pattern increased. In addition, as the angle of the 6 m long bars forming the reference grid increased, the distances between each other changed in relation to the new positions of the points. And accordingly, it was observed that the length value of the longest rod in the pattern gradually decreased. It was determined that A1 was the most efficient pattern in terms of material usage among the patterns obtained with symmetrical balance layout (Figure 7).

Figure 7. Analysis of properties that change as the angle of rotation of the domain increases in the radial balance disposition

6.2. Voronoi diagram generated with asymmetrical balance

In the asymmetric balance disposition where there was no specific axis, the location of the impact areas according to the visual weight was determined. 3 different patterns were obtained by providing vectorial displacement of the domains placed at different angles in different directions. In the comparisons, the reference grid created with the symmetrical balance was taken as the starting pattern with the same properties (Figure 8a).

B1, B2, and B3 patterns were created by moving 1, 2, and 3 units, respectively, in the directions expressed in Table 1. Voronoi patterns obtained were shown in Figure 8.



(a) *(b)* *(c)* *(d)*

Figure 8. Topological Voronoi structure variants with asymmetrical balance disposition; (a) Reference Grid(X), (b) B1 grid, (c) B2 grid, (d) B3 grid

When the total rod lengths were compared, no steady increase or decrease was found on the values as a result of the change in the amount of displacement (Figure 9). The reason for this was the irregularity of the impact areas located asymmetrically and the points that were moved in more than one different direction. On the other hand, the lengths of the 6 m long bars that make up the reference grid changed as the amount of displacement increased, it was observed that the length gradually increased. Among the patterns obtained with the asymmetrical balance layout, B2 was found to be the most efficient pattern in terms of material usage.

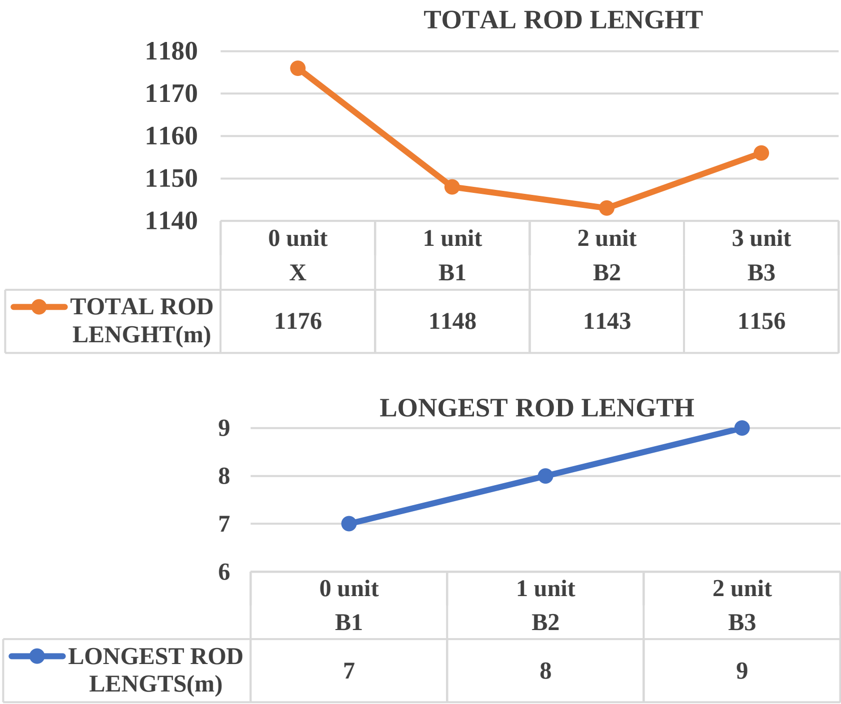
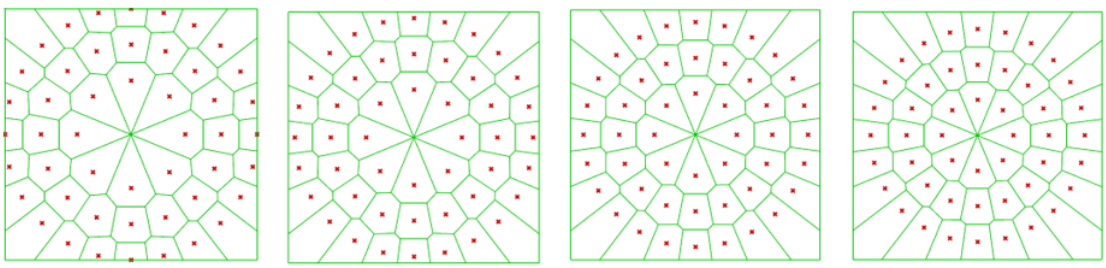


Figure 9. Analysis of structural properties that change as the amount of displacement of the points increases in the asymmetrical balance disposition

6.3. Voronoi Diagram Created with Circular Balance

For the radial balance in which the elements were circularly positioned around a center, a different grid was taken as reference from the reference grid used in other layouts. The value of points of the reference grid that supports radial balance (Figure 10a) and the reference grid used for symmetry and asymmetric balance were close to each other. The grid consists of 48 points, the total bar length was 1154 m, the longest bar length was 9.4 m. These figures were taken as reference for comparisons to be made.

The points that construct the diagram have been moved towards the center in the way shown in Table 2. C1, C2 and C3 grids were the resulting products of the displacement of the points in the reference grid towards the center by 1, 2 and 3 units, respectively (Figure 10).



(a) *(b)* *(c)* *(d)*

Figure 10. Topological Voronoi structure variants with radial balance disposition; (a) Reference Grid(Y), (b) C1 grid, (c) C2 grid, (d) C3 grid

According to the results, it was observed that as the amount of displacement towards the center increased, the total length of the rod used increased. In parallel with this, it was determined that the longest rod length increased with the increase in the distance between points (Figure 11). The movement of the points caused the patterns to scale proportionally, and accordingly, the material lengths gradually increased. It was determined that C1 was the most efficient pattern in terms of material usage among the patterns obtained with radial balance layout.

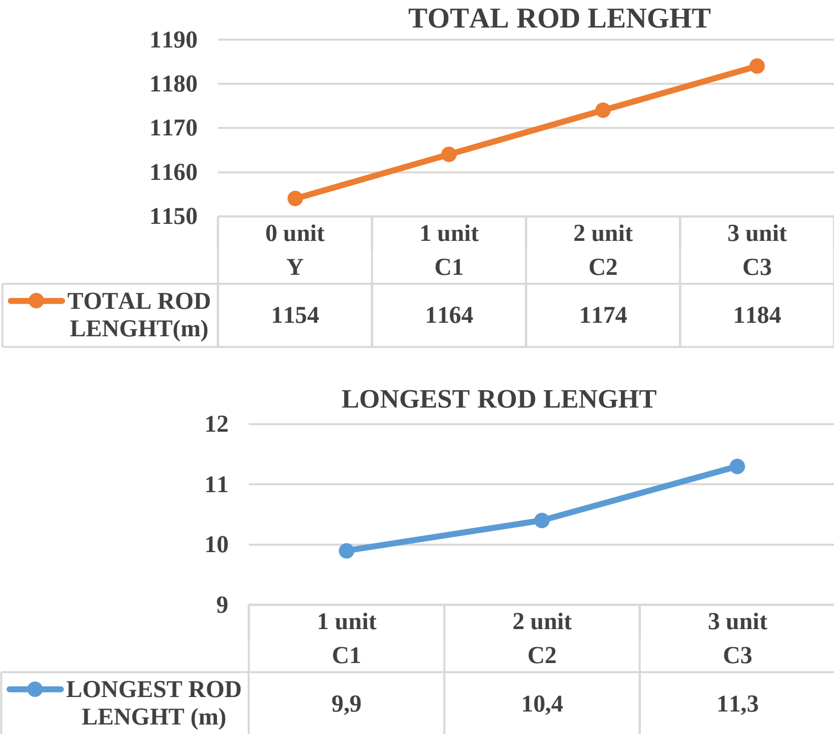


Figure 11. Analysis of the structural properties that change as the displacement of the points towards the center increases in the radial balanced disposition

7. Research results and discussion

Today, Voronoi tessellation is used as a space discretization tool to design roofs, facades, walls, and similar elements. Modern architectural understanding changes its modeling methods in parallel with technology and tends towards digital design. Voronoi diagrams, which can adapt and transform, provide flexibility to the designer in the architectural design process. In addition, with the help of the code created in the program, the design process can be improved by making selections thanks to the fact that all components of the design can be changed separately. Thus, the digital environment allows the designer to quickly change the properties of the final product at any time in the pattern generation process and to easily compare with previous data.

Within this research, the balance principle, one of the basic principles of design, was taken as a basis in order to shape Voronoi diagrams. Rotation, translation, and movement towards the center were carried out on three different orders created with the principles of symmetry, asymmetry, and radial balance. These applications, realized by changing the positions of the points, have been provided with a script produced in the Grasshopper. As a result, it was determined that the total rod lengths of the patterns obtained and the longest rod length to be used differ for each balance principle.

When the designer created patterns with symmetrical and radial balance, it was sufficient to set a single rule for the whole pattern, but he had to specify more than one direction and movement in asymmetrical balance. For this reason, in diagrams with symmetrical and radial balance, it was observed that as the displacement amount of points increases, the amount of material used increases. However, there was no clear result for asymmetrical balance. In addition, patterns in symmetry and radial balance had a more regular composition compared to asymmetrical balance. This layout contributes to the perception of the facade as a whole. On the other hand, if there are more cells of the same size that make up the pattern, it means that structural rods of the same length will be used. The manufacturing process is quite complex when there are many unique Voronoi cells in the pattern generated. For this reason, the physical production of the facades created with the symmetrical and radial principle would be easier than the production with the asymmetric principle.

The impact area determination method specified in the study contributes to the designer to create complex patterns indirectly and to create this pattern in line with the boundaries determined by the balance principle, not randomly. The designer can obtain a large number of products with a small number of parameters and can use this method as a pattern exploration tool. Accessing at the same time, both of the images of the final product and the amount of material to be used speeds up the designer's decision-making process.

References

Angelucci, G., & Mollaioli, F. (2018). Voronoi-like grid systems for tall buildings. Frontiers in Built Environment, 4(December), 1–20. https://doi.org/10.3389/fbuil.2018.00078

Arnheim, R. (1974). Art and visual perception: A Psychology of the Creative Eye (The New Ve). The New Version, University of California Press.

Aurenhammer, F. (1991). Voronoi Diagrams - A Survey of a Fundamental Data Structure. ACM Computing Surveys (CSUR), 23(3), 345–405.

Brzezicki, M. (2018). Classification of oblique grids in curtain walls: A case-study of design strategies in modular edge-panels. Journal of Facade Design and Engineering, 6(1), 101–115. https://doi.org/10.7480/jfde.2018.1.1999

Ching, F. D. K. (2007). Architecture: Form, Space, and Order. John Wiley & Sons.

Coates, P., Derix, C., Krakhofer, I. S. P., & Karanouh, A. (2005). Generating architectural spatial configurations. Two approaches using Voronoi tessellations and particle systems. Proceedings of the VIII Generative Art International Conference (GA2005), 1–18. http://hdl.handle.net/10552/853

Dimcic, M. (2011). Structural optimization of grid shells based on genetic algorithms [University of Stuttgart]. http://elib.uni-stuttgart.de/handle/11682/98

Fortune, S. (2017). Voronoi Diagrams and Delaunay Triangulations. In J. E. Toth, C. D., O’Rourke, J., & Goodman (Ed.), Handbook of Discrete and Computational Geometry (3rd ed., pp. 705–721). CRC press.

Friedrich, E. (2008). The Voronoi diagram in structural optimisation [University College London]. http://eprints.ucl.ac.uk/14631/

Gawell, E., & Nowak, A. (2015). Voronoi tessellation in shaping the architectural form from flat rod structure. PhD Interdisciplinary Journal, 1, 47–55. https://doi.org/10.1039/C5CE01790D

Harwiansyah, F. D. (2016). Application of voronoi diagram as treehouse design tool. International Journal of Education and Research, 4(7), 63–78.

Herr, C. M., & Fischer, T. (2013). Generative column and beam layout for reinforced concrete structures in China. Communications in Computer and Information Science, 369 CCIS, 84–95. https://doi.org/10.1007/978-3-642-38974-0-8

Kardasis, A. (2011). The Soft Grid. Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/65438

Mele, E., Fraldi, M., Montuori, G. M., & Perrella, G. (2016). Non-conventional Structural Patterns for Tall Buildings : from Diagrid to Hexagrid and Beyond Non-conventional Structural Patterns for Tall Buildings : from Diagrid to Hexagrid and Beyond. Fifth International Workshop on Design in Civil and Environmental Engineering, October6-8, 2016, Sapienza University of Rome Representative, October.

Nowak, A. (2015). Application of Voronoi diagrams in contemporary architecture and town planning. Challenges of Modern Technology, 6(2), 30–35.

Nowak, A., & Rokicki, W. (2016). On Surface Geometry Inspired by Natural Systems in Current Architecture. Journal Biuletyn of Polish Society for Geometry and Engineering Graphics, 29, 41–51.

Okabe, A., Boots, B., Sugihara, K., & Chiu, S. N. (2000). Spatial tessellations: Concepts and applications of Voronoi diagrams (2nd ed.). John Wiley & Sons.

Oxman, R., & Oxman, R. (2010). New Structuralism: Design, Engineering and Architectural Technologies. Architectural Design, 80(4), 14–23. https://doi.org/10.1002 / ad.1101

Rokicki, W., & Gawell, E. (2016). Voronoi diagrams – architectural and structural rod structure research model optimization. MAZOWSZE Studia Regionalne, 19, 155–164. https://doi.org/10.21858/msr.19.10

Terzidis, K. (2009). Algorithms for visual design using the processing language. John Wiley & Sons.

Tonelli, D., Pietroni, N., Cignoni, P., & Scopigno, R. (2016). Design and fabrication of grid-shells mockups. Italian Chapter Conference 2016 - Smart Tools and Apps in Computer Graphics, STAG 2016, 21–27. https://doi.org/10.2312/stag.20161360

Torghabehi, O. O., & Von Buelow, P. (2014). Genetic based form exploration of mid-rise structures using cell morphologies. In D. Gerbe & R. Goldstein (Eds.), In Proceedings of the Symposium on Simulation for Architecture & Urban Design, Society for Computer Simulation International (pp. 85–90).

Wu, T., & Zhang, L. (2016). Image-Guided Voronoi Aesthetic Patterns with an Uncertainty Algorithm Based on Cloud Model. Mathematical Problems in Engineering, 1–18. https://doi.org/10.1155/2016/9837123

Zhao, S., Gao, Y., Jiang, X., Yao, H., Chua, T. S., & Sun, X. (2014). Exploring principles-of-art features for image emotion recognition. MM ’14: Proceedings of the 22nd ACM International Conference on Multimedia, 47–56. https://doi.org/10.1145/2647868.2654930

Url-1<https://johnmaddenphoto.com/portfolio/melbourne-recital-centre-mtc>. (Accessed: 25.10.2020).

Url-2<https://www.archdaily.com/118277/alibaba-headquarters-hassell>. (Accessed: 25.10.2020).