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Voronoi Diagram Applications Towards New Sustainable Architectural Language

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Abstract: **This paper is concerned with the study of how to generate irregular geometric shapes that simulate their counterparts in nature, based on mathematical rules, specifically through Voronoi diagram, which already has been used in a group of contemporary buildings and urban design projects. The paper deals with this diagram through a theoretical study that explains the characteristics and applications of this diagram, with a review of examples of engineering formations that exist in nature and to which the applications of the Voronoi diagram apply. The paper aims to how to achieve a balance between form and function through this diagram, by studying and analyzing a group of contemporary buildings whose design was based on this diagram, whether in shaping the facades, forms and the structural systems.**

Keywords: Voronoi diagram, Biomimetic Pattern, parametric design, contemporary architecture.

1.INTRODUCTION

The nature of processes and principles of biological structure self-organization, as well as their representation using mathematical models that may be applicable in technology, including architecture, are becoming increasingly important in modern design methods. As a result, bionic design components influence modern architecture and urban design in ways that are more significant. The advancement of computer technology has made it possible to design more intricate surfaces and structures that modelled after organic shapes. More and more often, the elevation of modern buildings shaped by the discretization of the surface using the Voronoi diagram, as seen in the honeycomb structure or the dragonfly wing. The concept of the voronoi diagram appeared in the last century as a mathematical theory concerned with the characteristics of natural shapes. It received great interest from architectural designers, as it enabled them to simulate natural shapes in their designs of facades and building forms, as well as landscaping and urban design.

Bionic design plays a significant role in the advancement of the field of architecture design because it can act as a link between design and other related sciences. It also gives wide range of innovation for architects to produce new contemporary forms of buildings that are in line with the contemporary technological revolution.

2. RESEARCH PROBLEM

In the recent period, a group of contemporary buildings were constructed, whose facades were designed using a set of advanced computer programs such as grasshopper and rhino which producing non-stereotypical architectural shapes and forms. Therefore, the research question is:

How to using Voronoi diagram to producing non-stereotypical facades elements that simulate nature and achieve sustainability.

3. RESEARCH GOALS

- Reviewing the idea of voronoi diagram, how to create it, and its mathematical rules.
- Running comparative philosophical study to review the different effects of this diagram on a group of various contemporary buildings.

4. METHODOLOGY

- The theoretical part dealt with the characteristics of the Voronoi diagram, and its applications in architecture.
- The applied part is a comparative study of a group of contemporary buildings that used this diagram in its design in order to develop a design methodology that can be used to create buildings that strike a balance between contemporary form and sustainability.

5. VORONOI DIAGRAM

The Voronoi diagram is an engineering mathematical system based on dividing a specific area into a group of adjacent and close cells. each cell is connected to the other through a center point located inside it, which is a special type of decomposition of the metric space that is determined by a separate group of points that can Divide multidimensional space into subspaces.

Voronoi diagram can be done in a few simple steps to generate a variety of irregular geometric shapes, which give unlimited scope of creativity to the architectural designer whether in building forms, facade formations, or other areas such as landscaping and urban design.

The diagram was named Voronoi diagram relative to the Russian scientist *georgy voronoi*, who laid down the foundations and principles of this diagram. He worked hard to investigate the influence of computational approaches in architectural design. [1]

Architects are using Voronoi diagram so often because it produces very organic looking patterns. It is also useful for urban planners for example for comparing areas covered by different hospitals, or shops, etc. With Voronoi diagram one can easily determine where is the nearest services zones or hospital.

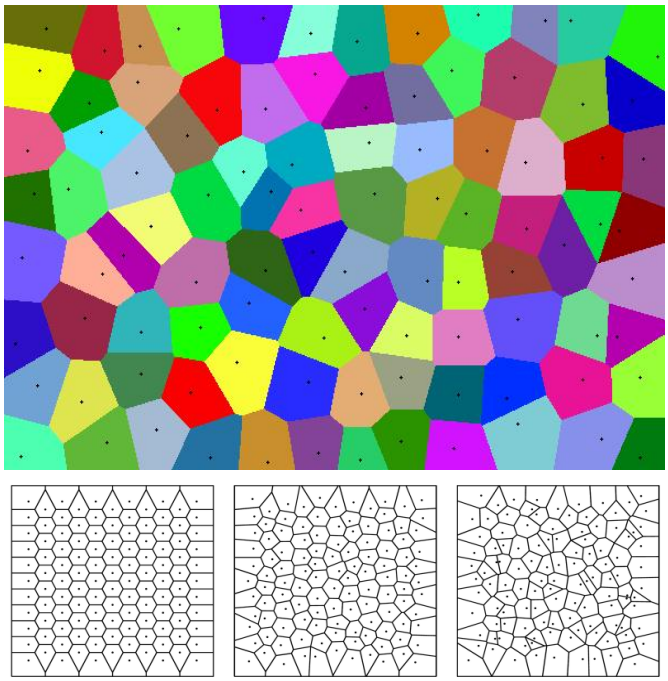

Figure 1. Voronoi diagram.
source: (https://www.codeproject.com/)

Figure 2. Voronoi diagram in nature.
source: (https://iq.opengenus.org/voronoi-diagram/

Urban planners can study if certain area needs more new services zones or hospitals etc. Voronoi diagram's commonly used boundary-based representations, store groups of sites, cells, edges, and vertices. These representations are complex because they must support adjacency relationships between elements of various types of representations, in addition to the data sets.

For instance, an edge must store at least one link to the cell that the boundary of the edge encloses, as well as links to the previous and subsequent edges in the boundary.
These representations are helpful for computing Voronoi cell parameters like area and perimeter as well as for efficiently traversing a Voronoi diagram. [4]

5-1 VORONOI DIAGRAM IN NATURAL SHAPES

The Voronoi diagram describes many structures found in nature such as dragonfly wings, turtle shells, plants' leaves beeswax structures, and others. The nearest neighbor, shortest path, and tightest fit are indicators of nature's propensity to favor efficiency provided by the Voronoi pattern. A Voronoi pattern's cells each have a seed point. A cell is the closest thing to everything else inside than any other seed.

In nature, Voronoi diagrams can be found everywhere. Although we have encountered them countless times, we may not have described them in this manner. [12] We did not realize that these amazing formations could be translated into geometric mathematical relations, which we can simulated in innovative contemporary designs. Despite being clear and straightforward, Voronoi diagrams have amazing characteristics.

The design formations resulting from the Voronoi diagram are similar to those resulting from the parametric design in terms of their simulation of forms that already exist in nature. However, the Voronoi diagram can obtain natural shapes consisting of straight lines, while the parametric design is mainly depended on curved lines.

5-2 HOW TO GENERATE VORONOI DIAGRAM

It is easy to create a simple Voronoi diagram, just throw a random scattering of points across a plane, connect these points with lines (linking each point to those, which are closest to it and then divide each of these lines with a perpendicular line. [24]

Therefore, we can generate that diagram within the following steps:

A. Determine the main generated points for the Voronoi diagram.
B. Drawing lines connecting the main points.
C. Drawing perpendicular lines from the middle of the previous lines.
D. Connecting the lines drawn in the previous step then we will have a complete network, which consist of many cells.

Through this diagram, we can get an infinite number of shapes by simply changing the center points, as the shapes of the network change accordingly. Figure 4 shows how to change the shapes generated from a Voronoi diagram

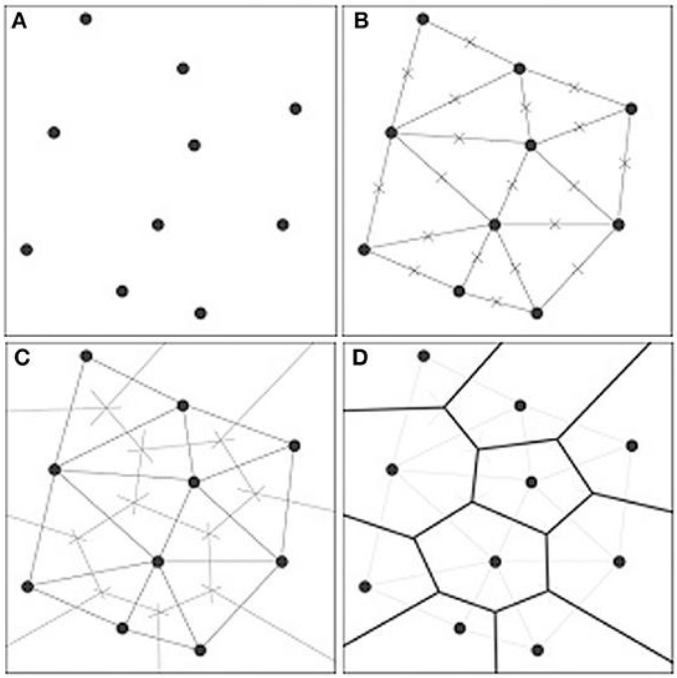

Figure 3. Voronoi diagram steps.
source: (https:// www.frontiersin.org/)

6. VORONOI DIAGRAM APPLICATIONS IN ARCHITECTURE

While mathematics searches for hidden facts, architecture applies these facts and highlights them in the form of buildings that fulfill functional and aesthetic requirements.

Digital design programs that rely directly on mathematical sciences such as Rhino, Grasshopper have become an active role in the development of architectural design in general, which led to the development of initial ideas in the early stages of design, the multiplicity of proposals submitted to the design, and the multiplicity of possible solutions to solve the problems that designers face during design, in addition to accuracy in solutions and speed of production.

6-1 THE IMPORTANCE OF USING VORONOI DIAGRAM IN ARCHITECTURE DESIGN

Voronoi diagram is an important tool in changing the used traditional methods in solving many of design problems that were hindering architects to simulating nature and designing non-stereotypical shapes such as follows:

- Difficulty in forming complex shapes or organic shapes due to complex structural system calculations.
- Difficulty dividing surfaces into curvature forms and making cutting lists for surfaces of different materials.
- Accurate environmental calculations that determine the degrees of sunlight spreading inside the building.

Wasting a lot of time in producing proposals that translate the proposed nature shapes into real shapes to choose the best-proposed design solutions.

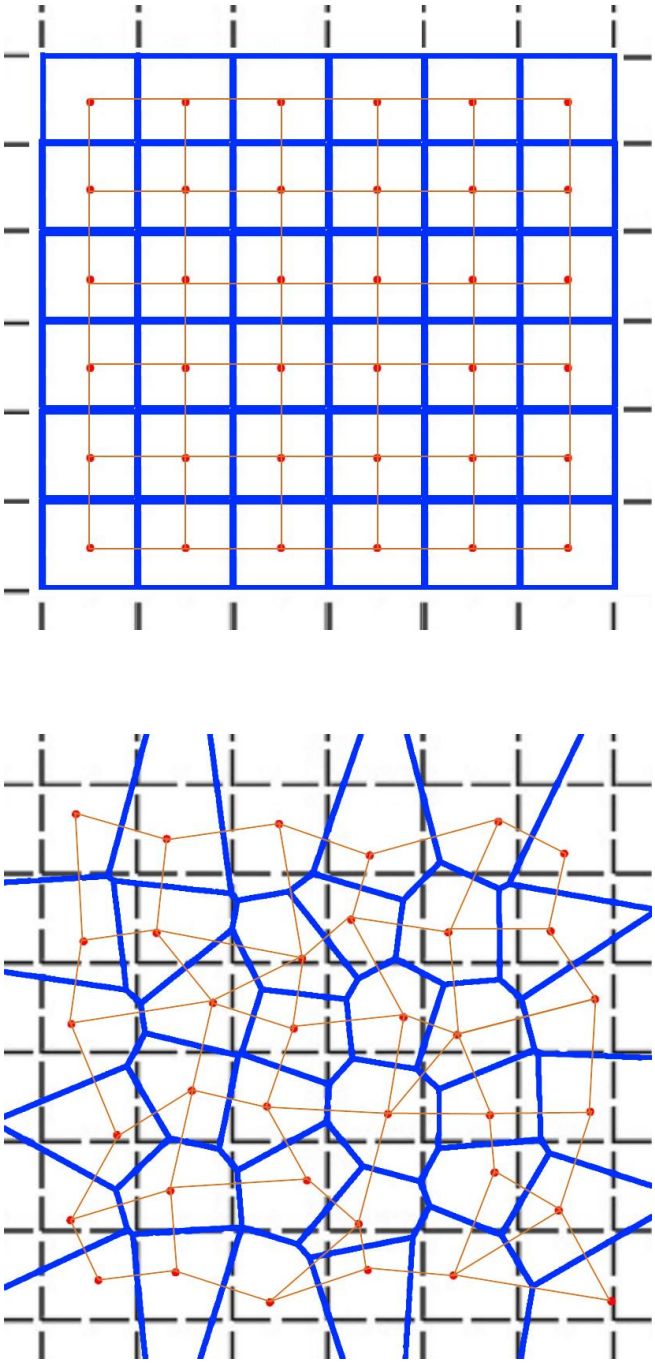

Figure 4. Changing in voronoi diagram shapes by changing the position of the center points, By Author

The Voronoi diagram plays an important role in the buildings design, whether at the level of forms or the shape of the facades. In addition, through facade formations in front of glass curtain walls, the concept of sustainability can be achieved by saving wasted energy by increasing the amount of day light inside the building, as well as reducing heat load by controlling the permeability of sunrays, in addition to making thermal isolation for the building's outer envelope.

In landscaping design works, walkways and green areas can be made with irregular geometric shapes that simulate

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natural shapes. Amazing contemporary shapes of hardscape fixtures and furniture can be designed.

7. The Applied Study

The applied study relied on selecting a group of different international contemporary buildings, in which the Voronoi diagram had a clear implantation in its design, and by analyzing these buildings in terms of form and function. We can recognize the importance effect of this diagram in the development of the contemporary architecture. Figure 6 shows Voronoi diagram applications in architecture.

7-1 Alibaba Headquarters, Hangzhou, China - 2001

The total area of the new international Headquarters for Alibaba Company is about 150,000 square m2. The plans consist of large open office space and the layout looks like a campus (Figure 5). The project accommodates approximately 9,000 employees and the buildings are arranged around a central open space with vary in height from four to seven stories.

Buildings elevations has been designed to maximize access to natural light and airflow to all workstations and distinguished with sun shading screens that represent Chinese ice-pattern window screens, which are prominent throughout the city's renowned historical gardens. These elements were designed based on the applications of the Voronoi diagram, as they came in the form of irregular geometric shapes simulated nature clearly. [18]

Figure 7 shows a study of the distribution of multi points from Voronoi diagram on a part of one of Alibaba company buildings, and shows how the points are randomly spread, which led to the appearance of the elements as close to nature shapes as possible.

Also, from the elements that were designed by using Voronoi diagram the upper sheds that connect the different buildings to each other, so that their shape, which is identical to the shape of the sun shading units in the facades, contributes to shading the courtyards while providing the necessary natural lighting.

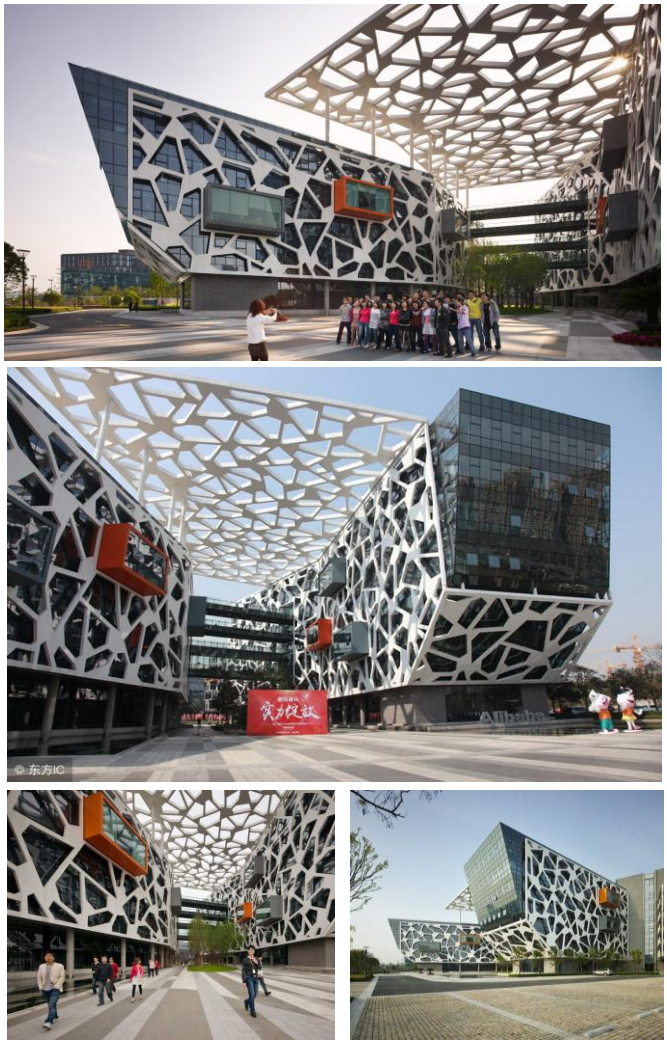

Figure 5. Alibaba headquarters
source: (https://www.e-architect.com/china/)

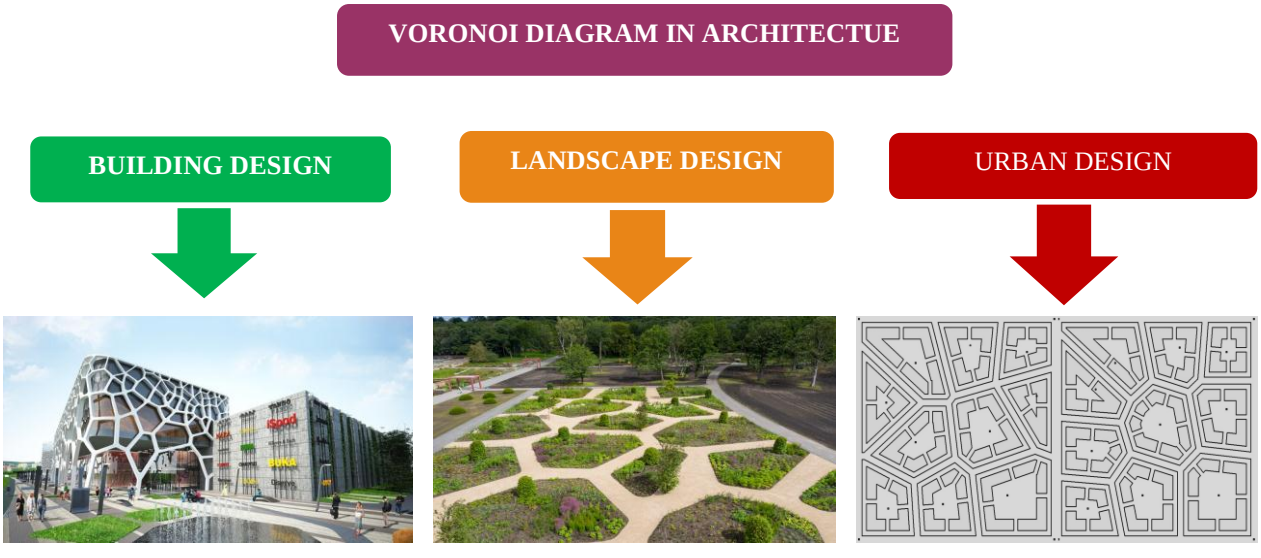

Figure 6. Voronoi diagram applications in architecture, By author

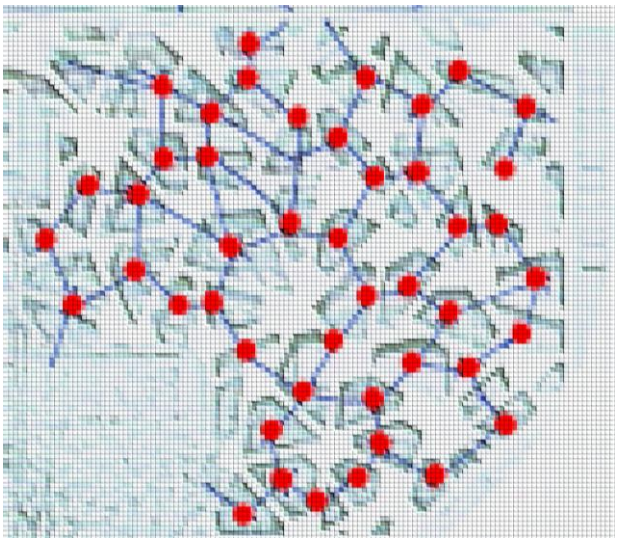

Figure 7. points generated with Voronoi diagram on part of elevation, By author

Figure 8. Alibaba headquarters layout
source: (https://www.e-architect.com/china/)

7-2 AIRSPACE BUILDING, TOKYO, JAPAN - 2007

The airspace building is located in a green area in the middle of a residential neighborhood containing traditional buildings. The owner wanted a unique shape for his building while preserving the outer green area to establish a buffer zone around the building and achieve the concept of organic architecture by linking the building with the surrounding natural environment.

The building is a mixed residential and commercial use. The building consists of four floors, with an area of 300m2 / floor and contains four residential units and a car maintenance center, in addition to two large studios for photography. The building distinguished by its unique façade designed by faulders studio, which is simulate tree leaves.

The façade is composed of two separate layers of metal sheets to achieve the Voronoi diagram in a three-dimensional image. This solution provides the necessary privacy for the occupants of the building while protecting the interior spaces from direct sunlight, in addition to reflecting the excess light away from the building, which makes it appear as if it is floating in space. Through the Voronoi scheme, cells of various shapes and sizes were created and distributed according to the function of the internal space. [16]

Figure 9. Airspace building
source: (https://faulders-studio.com)

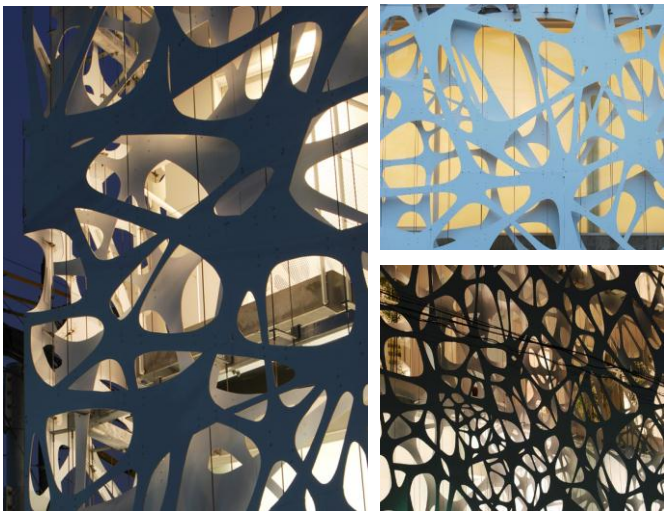

Figure 10. Double Metal Sheets In Facades
source: (https://www.arch2o.com/airspace)

7-3 SPANISH PAVILION - 2005

The pavilion represented Spain in the Aichi International Exhibition in Japan in 2005; the outer envelope pavilion was

designed by using a Voronoi diagram, so that the cells are of irregular hexagonal shape, also the centers of the cells not uniformly distributed.

The colors of the cells varied in a symbolic image of a group of distinctive things in Spanish culture. Hexagonal shapes are derived from the geometric Islamic patterns in an abstract image. [4] These patterns of cells provide indirect lighting inside the spaces, similar to that provided by the Islamic mashrabiyas.

Figure 11. Airspace building
source: (https://www.arch2o.com/airspace)

7-4 The Water Cube, (National Swimming Center), Beijing, China - 2008

In 2008, PTW Architects won the international competition for the design of the water cube building in the Olympic games court. The building combines architectural symbolism and the unique water bubble structure, to construct an appropriate complement to the National Stadium.

The main challenge that the architects had encountered was to create unique structure that fill the space between the natural and built environment [23]. The designer was aiming to create a natural shape by using triangulated space frame in the external cladding, which simulated bubbles with a variety of cells with different proportion, and shape. The designer tackled this challenge by creating a division system based on Voronoi diagrams to fills the facades with this bubble cells, these shapes symbolize the water in the swimming pools inside the building, which means that by using the Voronoi diagram the principle of "*form follows function"* can be achieved.

Figure 12. The Water Cube
source:(https://arquitecturaviva.com)

The total volume of the Water Cube is 177 x 177 x 31m^3 so the breathtaking architecture here is match by engineering innovations in fabrication, materials, and environmental management. The blue bubble cells made by tough, durable plastic material called ETFE (ethylene tetrafluoroethylene) which acts as a greenhouse, it transmits more UV light than glass and cleans itself every time it rains, its translucent nature allows natural daylight to penetrate the interior of the building and acts as an insulator to passively heat the building and pool water.

This environmentally friendly concept reduced energy consumption by 30%, which is equivalent to covering the entire roof with photovoltaic panels. [19] The outer cladding of the Water Cube consists of 4,000 (ETFE) bubble cells in about 50 different shapes, while the roof cladding contains seven different shapes of bubbles, which repeated throughout; therefore, the appearance of the building seems as a cube of water molecules.

Bubble cells fixed to space frame structure consist of 22,000 steel members in which each member must be made as small as possible to reduce the load of the steel.

Figure 13. The Water Cube under construction
source:(https://arquitecturaviva.com)

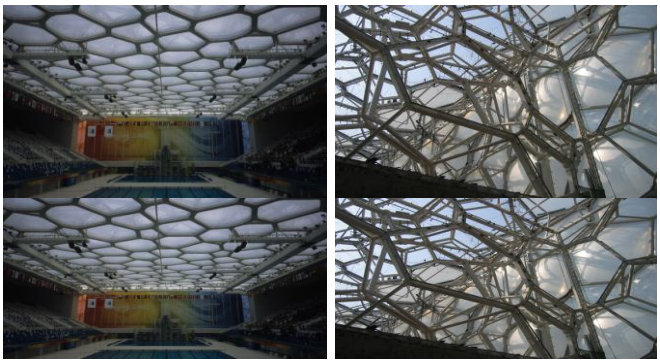

Figure 14. The blue bubble cells source:(https://arquitecturaviva.com)

Figure 15. National Performing Arts Center source:(https://google.com)

Figure 16. Site Plan of National Performing Arts Center source:(https://google.com)d

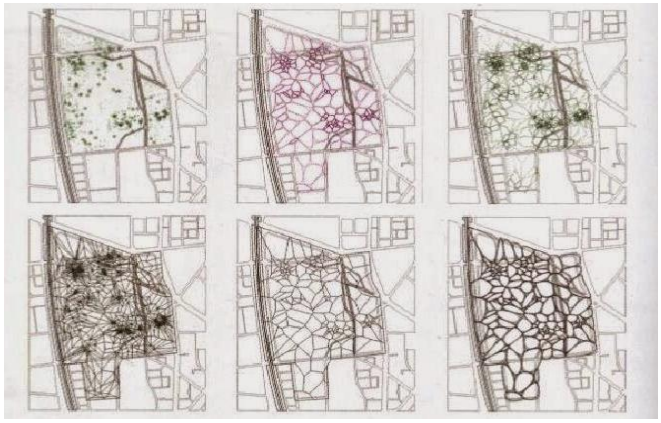

Figure 17. Design Steps through Voronoi Diagram. source:(www.archilovers.com)

7-5 National Performing Arts Center, Kaohsiung, Taiwan, Zaha HADID – 2008

In the design of Kaohsiung National Centre for the Performing Arts, Zaha Hadid used Voronoi diagram to analyzing the relationship between built and natural environment such as site trees and monuments In order to achieving an integrated unique design of the Spatial configuration, landscaping and visitors walkways, this pattern is similar to many self-organizing natural shapes.

In this project the using of Voronoi diagram generated a strong sense of organic coherence between indoor and outdoor, also the design depends on merging some cells to form a group of masses that shade the open spaces. [18]

7-6 Hourglass Corral House, Greece, 2020

The design of floor plan relied directly on the Voronoi diagram methodology, where each space was treated as a Voronoi cell, so that the shape of each cell differs according to the function and location of this space inside the building.

The cells were distributed in a positive way, represented in the closed spaces, and the other negatively represented in the open courtyards, so that create an integration between the built and natural environment, in addition to the natural form of spaces resulting from the application of the Voronoi diagram. [24]

Figure 18. Hourglass Corral House source:(https://www.archdaily.com/)

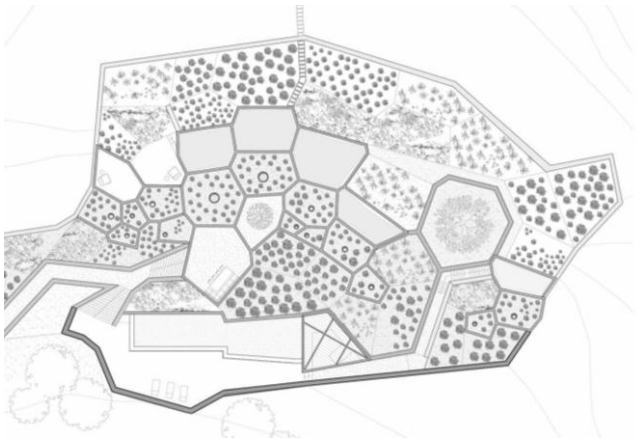

Figure 19. Voronoi Cells in Hourglass Corral House source:(https://www.archdaily.com/)

The ceiling of each cell folds upwards towards its center point where pierced by a circular skylight. The skylights are operable and along with the planted roofs, the outside shading, and the thick external walls they contribute to the reduction of the energy needs of the house.

8. TOWARDS NEW LANGUAGE IN ARCHITECTURE

The natural irregular forms which generated by Voronoi diagram represent a new architectural language in expressing the facades and forms of buildings. Since ancient times, architects have tried to design buildings in shapes that mimic nature, but it was very difficult at the level of design as well as implementation.

With the increasing development of computer graphic design software, parametric design emerged as a clear expression of the amazing technological revolution in the 21ST century. Parametric design characterized by curved surfaces that sometimes reach the point of exaggeration.

The difference between the design using Voronoi diagram and parametric design is that the latter gives a block with curved surfaces, while Voronoi cells have a natural geometric shapes characterized by their straight lines.

Despite the amazing capabilities of design programs, its users deal with it in a try and error manner until they reach a suitable shape for them, while Voronoi diagram characterized by the possibility of obtaining aesthetic and functional forms by studying the distribution of cells centers points according to functional and design requirements.

The importance of using the Voronoi diagram is that the concept of *"form follows function"* can applied realistically, as was done in a water cube building, where the shape of the building gives a strong indication of its association with water.

Similarly, it is possible to achieve the opposite of the previous concept so that *"the function follows shape"* by taking advantage of the irregular natural shapes of Voronoi cells in achieving functional gains that are directly reflected in the efficiency of the building's performance and its fulfillment of the requirements of its occupants.

Through the Voronoi diagram, it is possible to change the traditional shape of the glass curtains walls in the administrative buildings, for example, by adding different formations in the facades that distinguish each building from the other. Using of Voronoi cells in front of the curtain walls facades is better than traditional methods such as aluminum louvers.

The unique shape derived from nature, which provides natural lighting and prevents direct sunlight from penetrating, in addition to the privacy it achieves as it allows vision from the built environment to the natural environment while preventing the opposite. Figure 20 shows the effect of adding external lattice in front of the curtain walls and the extent of the change in the shape of the facades.

For example, Voronoi diagram can used in the design of the exhibition halls, museums halls. By studying the shape and arrangement of cells we can providing, a concentrated spots of natural light on the exhibits, figure (21) shows how to control the shedding of natural light spots on specific areas inside the space through the distribution of Voronoi cells in a well-studied manner.

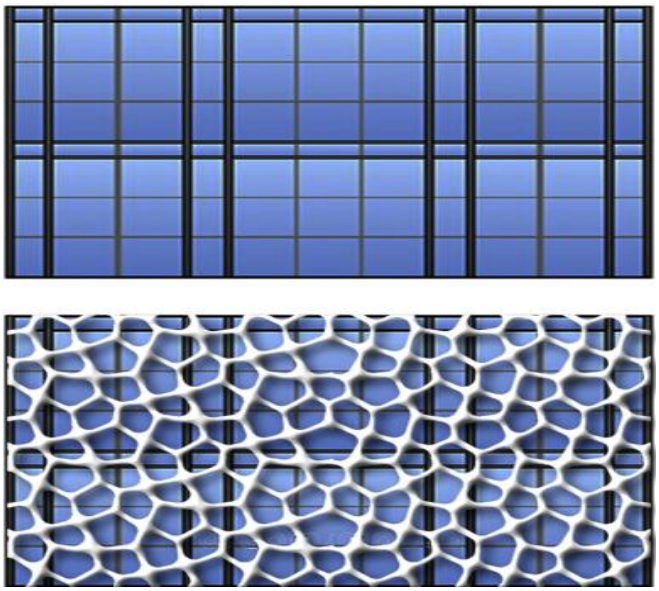

Figure 20. Effect of Voronoi cells on facades, By author

Figure 21. Concentrated spots of natural light, By author

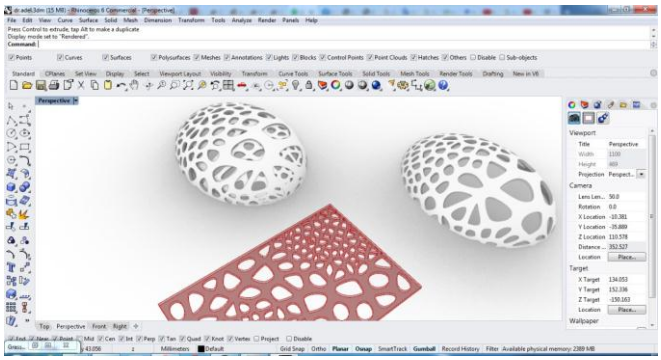

Figure 22. Using rhino software to creating voronoi cells, By author

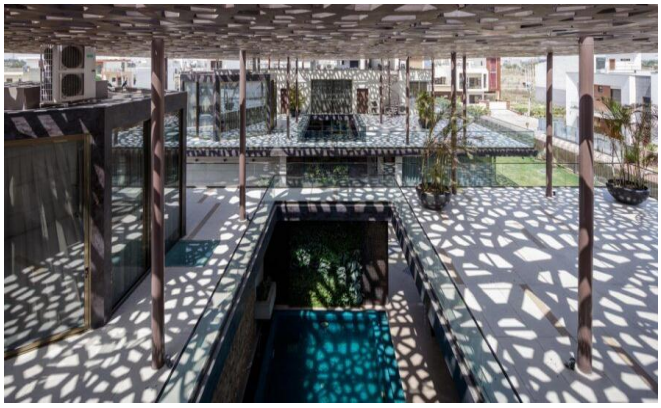

Figure 23. The shape of voronoi's shade source:(https://inhabitat.com/)

Voronoi cells can distributed by using RANIO software, after studying the cell centers in a way that achieves the permeability of natural light to specific areas according to the distribution of important elements inside the space.

The shapes of Voronoi cells is not only changing the shape of the facades or the building forms, but it can replace the traditional shapes of many of architectural elements such as louvers, colestra, skylights, handrails, internal screens and the horizontal pergolas used for shading.

With the movement of the sun and the change of the angle of light, the shapes of the shadows resulting from the Voronoi cells change, which gives a dynamic in the shape of the floors throughout the day.

9. VORONOI CELLS AND SUSTAINABILITY

The use of Voronoi diagram in architecture can contribute significantly to reducing carbon emissions. It is an effective way to achieve sustainability within buildings through the following points:

- *Achieving the concept of sustainability by using recycled materials in fabricating these elements.*
- *Reducing energy consumption by providing natural lighting and ventilation and making a heat-insulating layer to prevent heat transfer through the building's outer envelope.*

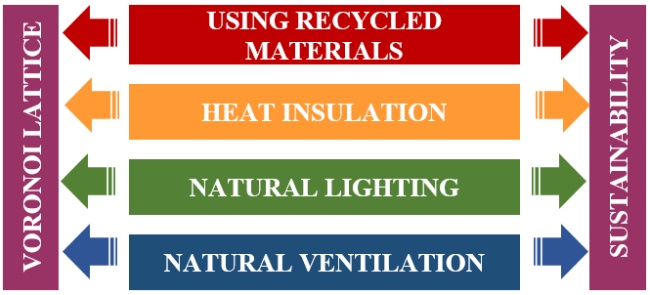

Figure 24. Impact of voronoi lattice in systainabilty, By author

9-1 VORONOI CELLS IN DOUBLE SKIN FAÇADES

Double skin façades consisting of two layers, usually glass and external lattice, wherein air flows through the intermediate cavity, this space acts as thermal and sound insulation to improving the building's thermal efficiency for both high and low temperatures. This system offers transparent façade, thermal and auditory comfort, reduced air conditioning costs.

In hot climates, the cavity can vented outside the building to mitigate solar gain and decrease the cooling load. Excess heat drained through a process known as the chimney effect, where differences in air density create a circular motion that causes warmer air to escape. As the air temperature in the cavity rises, it is pushing out, bringing a slight breeze to the surroundings while isolating against heat gain. [18]

Through the Voronoi diagram, the shape of the external lattice can be designed in an aesthetic way that simulates nature, in addition to achieving the required function. It is also possible to vary the cell shapes according to the intensity of sunlight falling on the facade. Figure 25 is showing the idea of making double skin facades by using Voronoi lattice.

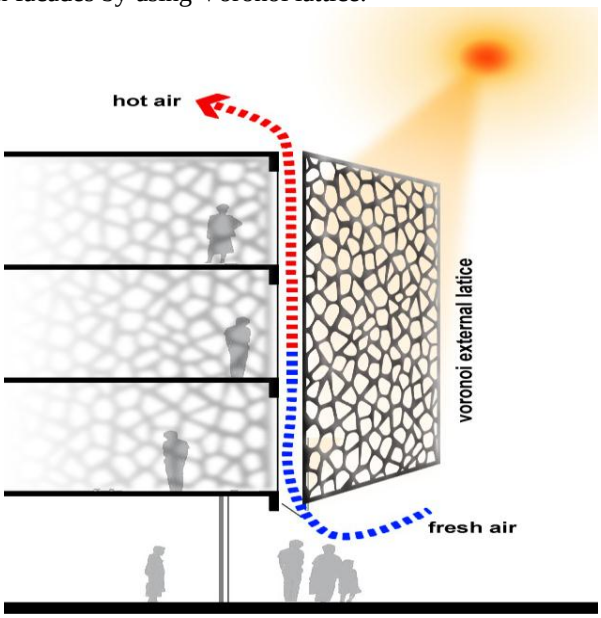

Figure 25. voronoi lattice in double skin facades, By author

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10. COMPARISON OF CASE STUDIES

The applied study showed that there is a positive effect of using the Voronoi diagram in the architectural design process in several respects, including those related to the shape of the buildings in terms of access to a new contemporary architectural language in expressing the facades.

Other than the many functional aspects for example giving more privacy to spaces that require it. In addition to achieving sustainability by providing natural lighting, reducing energy use, and using recycled materials.

After analyzing the study models, an analytical comparison running between them in terms of the nature of the shape of the Voronoi cells, and whether the diagram has been applied to the facades, the floor plans, or the mass of the building. As well as the type of Voronoi cells materials.

In addition, how to achieve the concept of sustainability by providing natural lighting and ventilation and using recycled materials. Table 1 shows a comparison study between the selective buildings.

11. CONCLUSIONS

i. Mathematics searches for hidden facts, but architecture applies these facts and highlights them in the form of buildings that fulfill functional and aesthetic requirements.

ii. Bionic design plays a significant role in the advancement of the field of architecture design because it can act as a link between design and other related sciences.

iii. The advanced computer softwares makes it possible to generating complicated geometrical surfaces inspired from nature.

iv. Modern design methodologies are placing more and more emphasis on the nature of biological structure self-organization processes and principles as well as their representation using mathematical models that may be applicable in architecture design.

v. Voronoi diagram can described many of natural forms, which can applied in architecture and urban design.

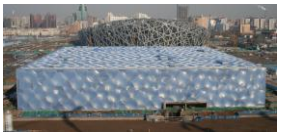
		Cell Shapes				Material					Sustainability								Style	
		Facades		Form							Daylight									
		Regular Cells	Irregular Cells	Building Mass	Floor Plan	Metal	GRP	Ceramic	ETFE	Brick Walls	Direct	Indirect	Skylight	Natural Venlation	Thermal Isulation	Recycled Material	Saving Energy	Contemporary	Parametric
1			•				•				•		•	•		•	•	•	
	ALIBABA HEADQUARTERS, HANGZHOU, CHINA - 2001																			
2			•			•					•			•	•		•	•	
	AIRSPACE BUILDING, TOKYO, JAPAN - 2007																			
3		•						•				•		•	•		•	•		
	SPANISH PAVILION - 2005																			
4			•						•		•		•		•	•	•	•		
	THE WATER CUBE, BEIJING, CHINA - 2008																			
5				•	•		•				•		•	•	•	•	•		•	
6					•					•	•		•	•	•		•	•		
	HOURGLASS CORRAL HOUSE, GREECE, 2020																			

Figure 26. Comparison of cases study, by author

vi. In nature, we can find voronoi diagrams in many examples everywhere. Although we have encountered them countless times, we may not have described them in this manner.

vii. Voronoi diagram is directly related to the concept of space filling, deriving structural properties; space organization based on neighborhood and closeness proximity

viii. Voronoi diagram gives wide range of innovation for architects to produce new contemporary forms of buildings that are in line with the contemporary technological revolution.

ix. With Voronoi diagram, we can achieving the concept of form follow function.

x. The facades of existing buildings can be simply upgraded by using voronoi diagram to redesign the outer screen through advanced computer programmers, and implementation by laser cutting machines.

xi. Voronoi diagram Applications in Architecture can create an intelligent product, which is matching with function, shapes and nature.

xii. Through Voronoi diagram, the concept of sustainability can be achieving by saving energy through providing natural lighting and ventilation and using recycled materials while preserving the privacy of the building's spaces.

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