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Research Article

APPLICATION OF VORONOI DIAGRAM AS AN ARCHITECTURAL AND URBAN PLANNING DESIGN TOOL

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ABSTRACT
The main question about geometric patterns is how to use these techniques in the design, in such a way that it does not imitate natural forms and as a tool, being a solvent for problems facing the designers. This paper introduces Voronoi diagram and algorithm and its application as a design tool in architecture and urban planning. Voronoi diagram is a mathematical and geometric system. This process-oriented theory puts the design methods that cause evolutionary space in front of architects and designers and with the support of computer programming they form their design process. This geometry is a design tool in architecture and structural engineering and is a graph for topology optimization. These graphs provide all information related to the distance between a set of points (or objects in general). Executive logic of this study is posteriori and the process to achieve its fundamental result is qualitative.

Keywords*: Voronoi Diagram, Architecture, Urban Planning, Parametric Design Tool*

INTRODUCTION

Problem - Geometric Interpretation

Suppose a chain store wants determine locations to build a store. To assess the suitability of the new store location it should check how much the new store can be successful in attracting customers. For this, it should determine the area each store covers.

We assume:

- The price of each item is the same everywhere.
- The cost of obtaining the product is equal to its price and the cost of transporting goods from the store.
- The cost of transporting goods from a store to a place is proportional to their distance.
- Customers will try to minimize the cost of obtaining a product.

With these assumptions a spot should be determined to build the store which has great distance from all existing stores. More accurately, a spot should be determined that its distance to the nearest a store is as great as possible. The geometric model of this assumption is subdivision of the area under consideration into regions that the residents of each region all go to the same store. With previous assumption, people choose the nearest stores. So for each store t an area can be determined in such a way that the nearest store of all its points is t. This structure is Voronoi Diagram. (Berg *et al.*, 1997). Beside an introduction of calculation in design process, architects and structural engineers have examined more features of complex geometries and comparative forms and structures; In the meantime Voronoi diagram is discovered (Friedrich, 2008). Due to the lack of methods and tools and increasing development in design software's, this paper introduces a new geometric design method based on a mathematical algorithm, which has already attracted the attention of architects and urban planners. In the meantime first the history and then definition, applications, components, and how to build this algorithm in two-dimensional and three-dimensional has been discussed and at the examples of the use of this diagram in architecture and urban planning and as a result the advantages and disadvantages of using this method in architectural design has been said.

Historical Background of Voronoi Diagram

The usage of Voronoi diagram in different ways backs to many years ago. Unofficial use of Voronoi algorithm backs to 1644 to Descartes draws. In 1850 Dirichlet in studies of quadratic forms used 2D and

3D charts of Voronoi. British doctor John Snow in 1854 for representing the distribution of deceased people took advantage of this diagram. In mathematics, the Voronoi diagram is named in honor of Georgy Voronyi, in 1908 he conducted research on the n-dimensional shapes and he defined them. This diagram is also known as Voronoi tessellation, Voronoi decomposition or Dirichlet tessellation (in honor of Lejeune Dirichlet), that certain types of decomposition specified metric space with distance to a particular set of discrete objects in space, such as a set of discrete points.

The diagram is a technique, which enables dividing a multi-dimensional space in to sub-spaces. Its application is defining equivalent geometric areas with sub-spaces by defining different vectors as center of sub-spaces. Any other vector in the space can be related to the most closely center vector which divides the whole space into sub-spaces effectively, the result is an excellent choice for splitting semantic vector spaces. Aurenhammer defines Voronoi tessellation as "one of the most fundamental data structures in computational geometry", that is used for modeling natural phenomena and study of their mathematics, especially geometry, combinatorial and stochastic properties and their calculation representative. Also suggests various methods for clustering multidimensional data (Park *et al.*, 2008).

Voronoi is used for compressing CAD and CAM files, as well as the mathematical calculations of molecular structure in micro technology. With further development, it may be used as a mean to explain tangible natural phenomena and non-tangible social phenomena. Moreover, since the Voronoi diagram has roots in geometric structure, thereby further work can be done on the formation of spaces. The purpose of Voronoi diagram is establishing a communication system and active response to changes and properties of the environment which the space itself belongs to it.

The task of architecture is creating a space with the complex of society and nature by collecting information around it, as the solution to the architectural requirements. Thus, the Voronoi theory can increase the usage of computer technology in architecture with the support of the information focusing on change, adapt and adjust of spaces (Kang *et al.*, 2008).

Voronoi Geometry (Boulder)

In this period of exploration for computing tools in architecture and design process, to investigate more complex and adaptive geometry, much attention has been given to Voronoi charts.

These charts are unique modular structures, with the potential in using for a variety of complex geometries (Friedrich, 2008). Voronoi geometry is an organizational phenomenon that sometimes is named “nature’s rule.” They can happen at a variety of scales with different material and forms. Boulder geometry occurring naturally forms Voronoi (Ferre *et al.*, 2007).

Voronoi diagram is a tool, that its aesthetic potential remains largely unknown. One prior art use of it is to produce natural fractal patterns using the Voronoi diagram in a series of steps back (Shirriff, 1993). The Voronoi diagram is suggested as an attractive and non-repetitive design tool that has a quality parameter that may be more adaptive to a common modular system. Inherent to the concept of spatial relations, adjacent and neighborhood can be cited as Voronoi interesting structural features.

In general Voronoi cells involve direct geometrical equivalence. This features show the use of Voronoi diagram to model parametric spatial relationships and thus different applications in architecture and urban design programs. Architects and designers can come up with new cellular complex geometries with creative potential of Voronoi diagram (Friedrich, 2008).

The Voronoi structure has been used as a tool for form finding, M-any is a research project in Zurich which explores the formal spectrum of emergent geometries of a parametrical Voronoi structure (Figure1). Process control parameters, are related to topological aspects of the cells in the first place. This geometry is rarely limited, but sometimes have unexpected results as well.

The work of these researchers is like the work of architects such as Toyo Ito, Fuller or Frei Otto, that is inspired by formation principles, geometries, spatial effect and constructions in nature (Friedrich, 2008).

Figure 1: Parametric design based on Voronoi diagram (Friedrich, 2008)

Voronoi Diagram Components

Voronoi diagrams have simple components in different dimensions.

Implementation of Voronoi diagram simulates the topological structure of space-filling, natural data exchange of particles in architecture and also divides the entire space into a set of sub-spaces according to data of objects (Pottman *et al.*, 2007).

A simple Voronoi diagram has the following forms: (Figure 2)

- Voronoi diagram of a point is just made of the same point.
- Perpendicular line segment connecting the two points is their Voronoi diagram.
- For non-directional three points Voronoi diagram is made of three half-lines.
- Perpendiculars of the sides of the Voronoi diagram triangle form its vertices (Berg *et al.*, 1997).

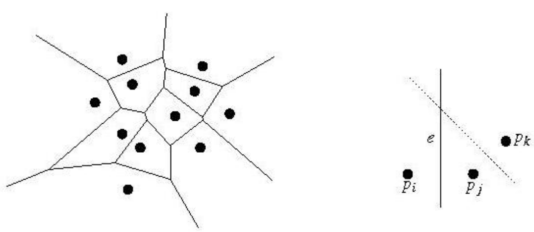

Figure 2: Simple Voronoi diagrams (de Berg *et al.*, 1997)

Voronoi diagrams consists of Voronoi Cell, Voronoi vertex, Voronoi Foam and Voronoi Space. (Pottman *et al.*, 2007) (Figure 3)

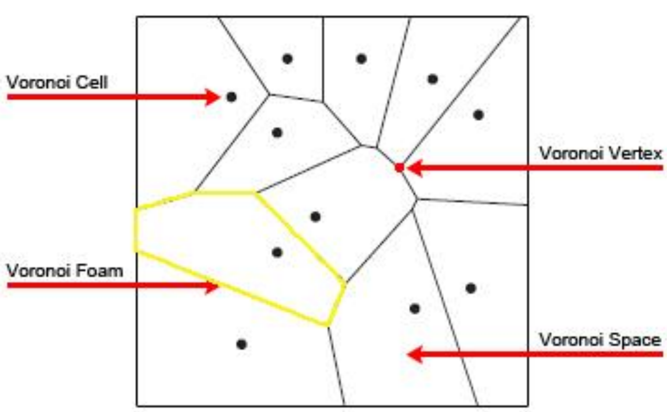

Figure 3: Voronoi diagram form (Pottman *et al.*, 2007)

Two-Dimensional Study of Voronoi

Studies show that Voronoi tiles have been created by a series of points.

They create a cellular pattern that each of these cells includes the space surrounding the point. Place of the rest of the shapes created with these pattern fits into a close system. They form a collection of shapes that look like squares, honeycombs, crystals or boulders (Figure 4).

The study of Voronoi geometry with a wider perspective includes a part of Terraswams, In plain language they call it "Tooling." From Toolings, Tilings is extracted. Tiling is one of seven algorithmic techniques, this technique is used to make Voronoi and make it reasonable (Figure 5) (Ferre *et al.*, 2007). In other words, the personal space of each point is separated by a neutral zone lines from its neighborhood. These lines are equidistant from both the surrounding area (Okabe *et al.*, 1999).

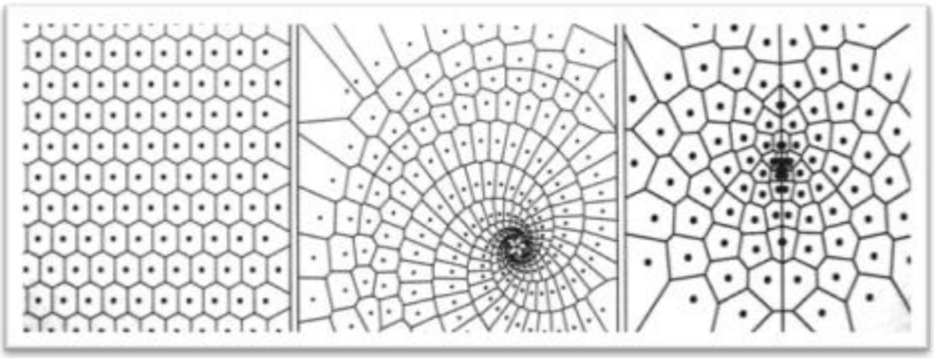

Figure 4: Natural shapes as a Voronoi diagram (Ferre *et al.*, 2007)

Figure 5: Voronoi making technique (Authors)

Instruction for Making Tilings

These charts are made through the bisectors of available points. Its description is as follows. Assume a set of points. Draw the bisector of each point with others. Voronoi cell is made of connecting these bisectors. (We delete any intersection occurred in the outer space of the bisectors.) We do this for every point in the set (Figure 6).

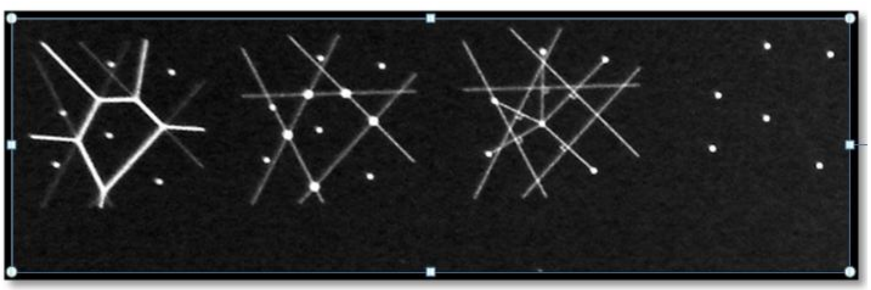

Figure 6: Instruction for making Tilings (Ferre *et al.*, 2007)

Voronoi diagrams include patterns called Dirichlet Tessellation. These irregular tessellations on a plane occur spontaneously in nature at every scale. They are used in the studies with space making problems such as computer science, growth of crystalline structure, biology, anthropology and etc (Ferre *et al.*, 2007).

From Two-Dimensional To Three-Dimensional

These charts have capability of development in two dimensions and three dimensions. Along with the repetition of modules, adjacency of tilings inspires tectonics.

The minimal enclosure system of these bubbles and cells shows that tilings are a simple system, rather their thickness in three dimensions expands constructive toward infinity without any gaps (Figure 7) (Ferre *et al.*, 2007). Because Voronoi's polyhedral geometry forms under influence of adjacent nucleus cell (influenced by several parameters), it's very difficult to predict or control it.

Geometry and topology of polygonal cells, such as size, proportion and number of edges is sensitive to the slightest change in position of each point anywhere in the neighborhood.

The relationship between the cell nucleus and the resulting geometry is complex in nature (Friedrich, 2008).

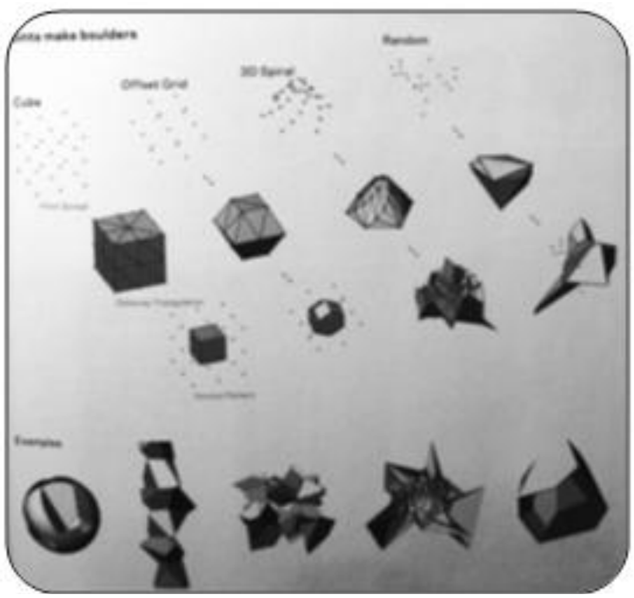

Figure 7: Three dimensional samples of Voronoi (Ferre *et al.*, 2007)

Case Studies of Architectural Styles Using the Voronoi Diagrams

In this section, practical applications of Voronoi diagram, especially in architecture, have been presented and analyzed.

Kaohsiung National Centre for the Performing Arts

The building was designed by Zaha Hadid in a competition. She used Voronoi diagram to analyze the relationship between the environment and site data.

Visitors' access points are controlled using data on the site such as trees, monuments and borders.

The area around points, which is created by the analysis of the relationship between space and the site, is connected to the main flow of human traffic, so that it becomes a tool for space traffic control.

Deformation of visual data and canopie, roofs and facades designs is derived from the Voronoi diagram (Figure 8) (Park *et al.*, 2008).

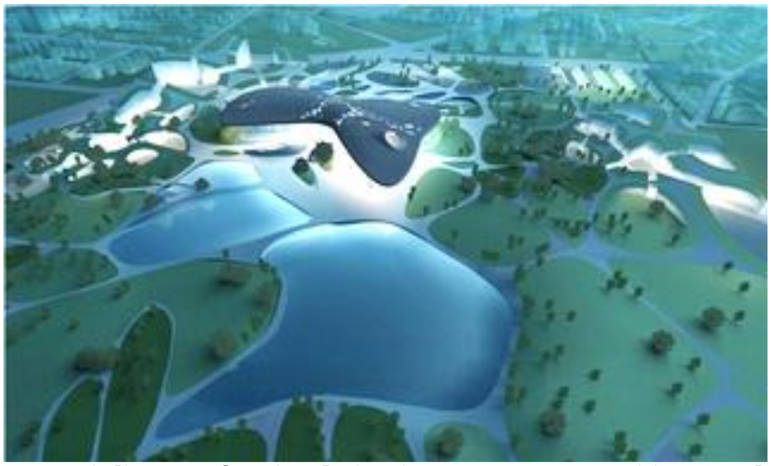

Figure 8: Using of Voronoi diagram for site design in NKPAC competition (Park *et al.*, 2008)

Tulum Museum

This museum is design by Andrew Kudless for a competition. This Archaeological Museum is outside of devastation of Mayan in Cancun peninsula. Researchers in this project used Voronoi system for organizing cells. The walls and roof of the museum is formed from a three dimensional Voronoi tiling. That examines the nature of the structures through holes instead of mass.

Structure is directly related to the Tulum's site rock walls. This structure can be considered a fulfillment of the empty spaces between separate rocks. Thus, structure of the museum refers to the available tectonic and at the same time it is lightweight (Matsysdesign, 2013) (Figure 9).

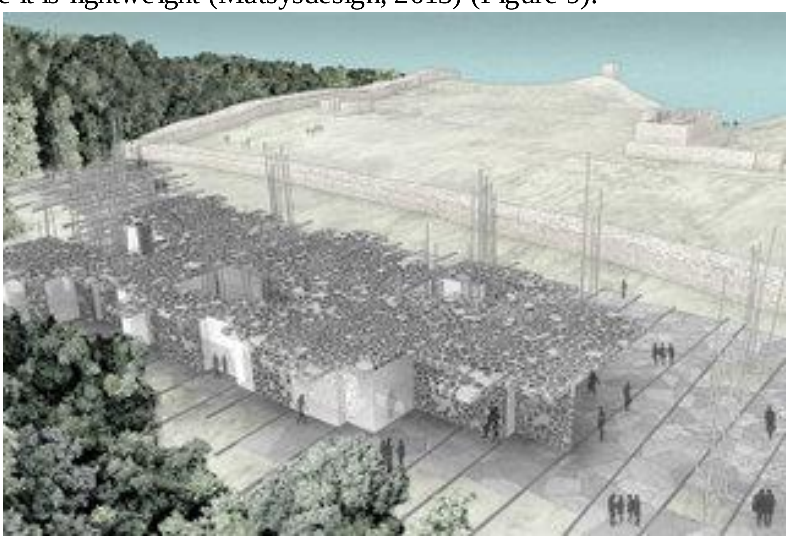

Figure 9: Voronoi three dimensional tiling system for designing Tulum museum in competition

Net Lab

This project is 16 months research of a person called G Nome. The purpose of this research is the use of parametric algorithms, in forming of cell spaces in relation to certain criteria which express different social systems, scale and needs of the users. This design includes a set of computational methods based on Voronoi algorithms summarized in a plugin created during the investigation.

This plugin gives access to an iterative process of feedback, adjustment and optimization of the design. In addition, the project by integrating designs, analysis as a formal process, provides a redefinition of the role of the architect with the use of algorithms in real terms (Nome, 2013) (Figure 10).

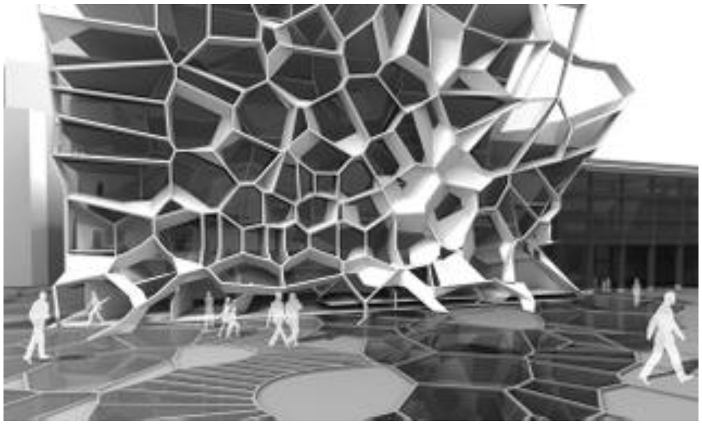

Figure 10: The formation of cell spaces by Voronoi system

CONCLUSION

Architecture is increasingly becoming a simulation. Therefore the study of architecture should assume the simulation as a powerful design tool to understand and implement complex relationship factors of environment. Voronoi diagrams are a way of dividing spaces which formed based on a series of point. Voronoi diagram makes the space organized. For example, the result of this unique process in a city zoning creates a natural structure of urban space, not like a random shape that we usually understand forms, But as a balance between entities relations. Voronoi diagrams have countless applications from statistics and biology to city maps which have become popular in architectural design. Indeed, there are many reasons and benefits for its use in architectural design:

1) Structural properties both In 2 and 3 dimensions.
2) One way to split up, organization of space based on the neighborhood, and closeness proximity.
3) In fact, lots of natural forms can be described with the help of these diagrams like soap bubbles, foam, bone cells and …
4) More interactive and dynamic relationships between the components of the project.
5) Creating a systematic design process for urban design using parametric system.
6) Balancing of forces and tensions in the design.
7) Variety of design options in the design of a balanced hierarchical system.

But there are problems in forming it which makes it a bit difficult to use:

1) A method for construction.
2) High construction costs.
3) It is difficult to predict and control it.

With time and experience has proved that this system is one of the best tools for the design and analysis in the architecture and urban development. Today this method is available as a command in softwares such as Grasshopper. Designers can easily take advantage of this algorithm in their drawings by giving design and environment parameters.

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