A proposal for the use of fractal geometry algorithmically in tiling design

Asli Agirbas [1]

[1] Department of Architecture, Fatih Sultan Mehmet Vakif University, Istanbul, Turkey
asliagirbas@gmail.com

Abstract. The design inspired by nature is an ongoing issue from the past to the present. There are many design examples inspired from nature. Fractal geometry formation, which is focused on this study, is a system seen in nature. A model based on fractal growth principle was proposed for tile design. In this proposal made with using Visual Programming Language, a tiling design experiment placed in a hexagonal grid system was carried out. Thus, a base was created for tile designs to be made using the fractal principle. The results of the case study were evaluated and potential future studies were discussed.

Keywords: Fractals, Tile design, Biomimetic design, Algorithmic design.

1 Introduction

In the field of architecture and design, from the past to the present, there is a design approach which is inspired by nature [1, 2]. This approach is often referred to as biomimetic [3]. We come across this design approach in many architecture and design products. This approach was initially developed as an imitation of nature. Later, it took its place as learning the mathematical principles of nature and apply these principles to design. With the inclusion of algorithms to the architecture and design field, the use of these mathematical principles, especially in the design process, has accelerated.

This study focuses on fractals. We can observe the formation of fractals in nature. The stages of the formation of the fractal form continue to be a source of the inspiration for the designers. Examples of the use of fractal growth principle are encountered in the field of architecture and design. Especially in architecture, it is used in the form-structure relation [4, 5], and in urban design, it is also used in relation to urban growth principles [6- 8].

The applications of fractal principles to tile designs are limited. However, the repetitive structure of tile is similar to the fractal principle. Taking advantage of this situation, innovative products can be produced in tile design. In the development of such a model, algorithms will be helpful tool in the rapid and correct implementation of the fractal principle in design. Therefore, in this study, it is aimed to create a model using Visual Programming Language (VPL) for the use of fractal growth principle in tiling design.

2 Background

2.1 Nature-inspired design

Many studies have been conducted on the study of the morphology of the formations in nature and the interpretation of this subject in the field of science and design. For example, Raoul Francé, known as the pioneer of biological technology, carried out the studies with considering the structural properties of plants using the term *biotechnics* and this way, evaluated the natural forms as structural. Francé [9], in his work: *Die Pflanze als Erfinder* (The Plant as Inventor), mentioned that forms such as crystals, spheres, planes and branches were seen in the areas such as architecture, chemistry and geography [10, 11]. D'Arcy Thompson's [12] *'On Growth and Form'*, Ernst Haeckel's [13] *'Kunstformen der Natur*' (*Art Forms in Nature, 1899-1904)* and *'Die Natur als Künstlerin' (Nature as Artist)* [14], and Blossfeldt's [15] *'Wundergarten der Natur' (Wonder Garden of Nature)* studies can be given as examples of other studies in this area [16].

Human beings have begun to develop the first building techniques by observing or imitating the formations in nature. Thus, throughout history, we see the imitation/synthesis of nature in architecture and design [17 - 19].

Gaudi's use of skeletal systems and bones as metaphors to capture the differences and aesthetics in his buildings and to construct suitable structural systems for the designs can be given as an example of nature's reflection in design. In addition, the Allen Lambert Gallery (1987) of the BCE Palace in Toronto designed by Santiago Calatrava, the Bauschanzli Restaurant (1988) in Zurich, St. John Divine Cathedral (1991) in New York, Oriente Station in Lisbon (1998), Reina Sofia Art Museum (1999) in Madrid, and Stuttgart Airport Passenger Terminal (1996) designed by Meinhard von Gerkan can be given as recent examples of tree-shaped formations [20]. In addition, one of the architects who worked on mathematical formations in nature was Frei Otto. As a result of the experiments, he called "Soap Experiments", Frei Otto revealed many curvilinear formations and reflected these forms to his buildings as structural elements. Otto has gained importance on designs with organic forms that emerged by mathematical evaluation of nature. One of the most important buildings that reflect this perspective is the Munich Olympic Games Stadium, which he designed in 1972.

Besides nature-inspired design examples created in the form bases, there are also nature-inspired methods that are algorithmically included in the design process. For example, there is Genetic Algorithm (GA), which is inspired from the natural selection process in nature. The studies are carried out to achieve the best solution in design with including this algorithm to the design process [21-27]. Similarly, the swarm intelligence principle in nature could be transformed into algorithms. There are design studies using these algorithms [28].

From the past to the present, different names are used for nature-biology-design relationship such as *biomorphism, bionics, biomimetics* and *biomimicry*. Otto Schmitt [29] mentions about the use of systems, processes and models in nature to solve the problems of people and this issue has taken place in the literature as biomimetics [30]. Janine M.Benyus [31] revived the concept with his work 'Biomimicry: Innovations Inspired by Nature' and argued that nature should be treated as a model and source of ideas [32]. Benyus says that human beings have acquired experiences by observing nature at first, but are now taking lessons from it as a mentor rather than as a model [20]. According to Pawlyn [33], biomimetics and biomimicry concepts are used as synonymous. He says that only the concept of biomimicry is mostly used for issues focused on the production of more sustainable solutions. In the same sense, Jack Steele named this subject as bionics, which refers to imitate nature and learn from biology [34]. Charles Jencks, in his Theory of Evolution Table that was prepared for architectural movements, describes the beginning of the new search for architecture in the end of the twentieth century, as biomorphism. According to Pawlyn [33], this concept is used to reflect the existing natural forms in design.

2.2 Fractals

The word Fractal comes from Latin *fractus*. Fractus means irregular or fragmented [35]. Benoit Mandelbrot [36], describes fractals in the definition of various forms (coasts, mountains, etc.) in nature [37]. Fractal geometry is the mathematical production as repetition of the form. This formation may occur by repeating a unit in the form of growth, or by dividing the unit into smaller units. As repetitions increase, more dense structures are formed [38]. The basis of fractal geometry embodiment relies on self-similarity. According to this embodiment in fractal geometry, there is a similarity relationship between entire form and its smallest unit. As you go into detail, each unit carries the characteristics of the whole. This form-based repetition feature of fractal geometry inspires many designers to develop their designs. In this study, the starting point of the proposal of a method for tiling design based on fractal geometry is the form-based repetition.

Other than Mandelbrot [36], some mathematicians also contributed to this issue. Various theories have been produced on fractals. Some of these people and their theories are these: Cantor's Comb (1872), Helge von Koch's Curve (1904), Sierpinski's Triangle (1915), and Gaston Julia's Sets (1917) theories [39]. Henri Poincare, Felix Klein and Pierre Fatou are also the names who worked on this subject [40].

Kitchley [39] mentions that many ancient African settlements have fractal properties. An example for this, she mentions about the "Ba-lla" settlement in southern Zambia. She also mentions that the fractal characteristic exists in the temples of India. The units in this architectural design get smaller as they go upwards layer by layer repeatedly. This is also present in many Baroque cathedrals in Europe. Kitchley [39] also mentions about the presence of fractal characteristics of contemporary architecture. The followings can be given as examples for these: Peter Eisenmann's House 11a project, Zvi Hecker's Extension for the University of Applied Arts, Hamburg and Ramat Hasharon projects, and Ashton Ragatt McDougall's Storey Hall project in Melbourne. Related to fractal tiling, Burry and Burry [35] also mentions about the project of Heneghan Peng's Grand Egyptian Museum (Cairo, Egypt) and Daniel Libeskind's project on The Spiral Extension (Victoria & Albert Museum, London, UK).

On the other hand, fractal dimension is also used as an analysis method in architecture. This method, for example, has been widely used to identify the visual characteristic elements of historical buildings [41 - 46]. This method is applied in the direction of the elevation or plan drawings. In this method, first, the grid is placed on the designated 2D image. Then, with the 'box counting' method, the ratio of the boxes containing the lines to the empty boxes is calculated. However, this method is excluded from the scope of this study.

2.3 Tiling

Tiling is an architectural tradition coming from a long time ago. Old-fashioned tiling designs are usually 2-dimensional. Some of them have reliefs. Tiles are known being used in the interior and exterior coating in buildings. The material of tiles can be ceramic, plaster, brick, stone and timber. They are usually arranged in a repetitive manner, but may also be formed by a combination of different forms [35].

According to Van Lemmen [47], tiles and bricks were first used by nomadic people who settled along the Nile River in Egypt and along the Euphrates and Tigris Rivers in Mesopotamia. These people began to establish permanent settlements and in doing so they used local materials (sand, clay, reed).

If it is specifically focused on the tile, it can be seen that, from the past to the present, different types of tiles have been produced in different parts of the world. Tiles were made of different sizes, shapes, and colors. They can include different reliefs on them. Different patterns, geometries, symbols and writings can be found in these reliefs.

Nowadays, the use of 3D printing technology, which allows the use of new materials, is advancing rapidly. This brings innovations to the tile industry. 3D printing technology allows various materials to be tested in design as well as the production of different forms of products.

3 Fractal Software

Nowadays, there are various softwares that can produce 2D and 3D forms based on the fractal principle. Some of these are: Mandelbulber, Mandelbulb3D, ChaosPro, Fractal Zplot, QuaSZ, Fractal ViZion, Fractal Scope, Ultra Fractal, Apophysis, Fractal Science Kit, Incendia Fractals, Fractal Extreme. These programs allow different forms to be complexized, based on fractal principles (Fig 1) In addition, these programs can also offer options of high quality rendering, coloring, lighting and animation creation. These programs are frequently used by people interested in digital art.

In this study, a preliminary study was conducted to test the production of forms based on fractal principles. Mandelbulb3D program was used in this preliminary study. Mandelbulb form, which is known as 3-dimensional fractal form, was selected to use. Iterations of Mandelbulb, which were used as the first form, were increased and more complex forms could be produced. For example, in Fig. 2, states of the form with 1, 3, 5 and 7 iterations can be seen. In Fig. 3, the details of the form with 5 iterations can be seen.

However, in this program, it was seen that producing a form from scratch and the possibility of obtaining a new form from this form by applying the fractal principles was limited. The situation is the same in many other fractal creation programs. Therefore, in a design to be made by considering the principles of fractal, it was thought that a method should be developed in which the designer might be more involved in the application of these fractal principles on the form. Thus, a method, in which Visual Programming Language is used to apply the fractal principles, was proposed.

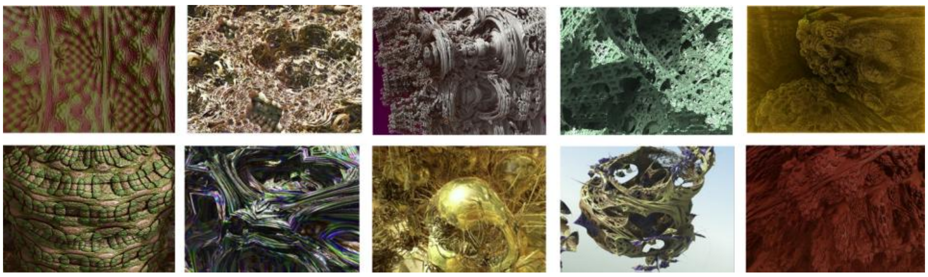

Fig 1. Various forms designed by the author with using various software based on the principles of fractal

Fig. 2. Mandelbulb form with different iterations

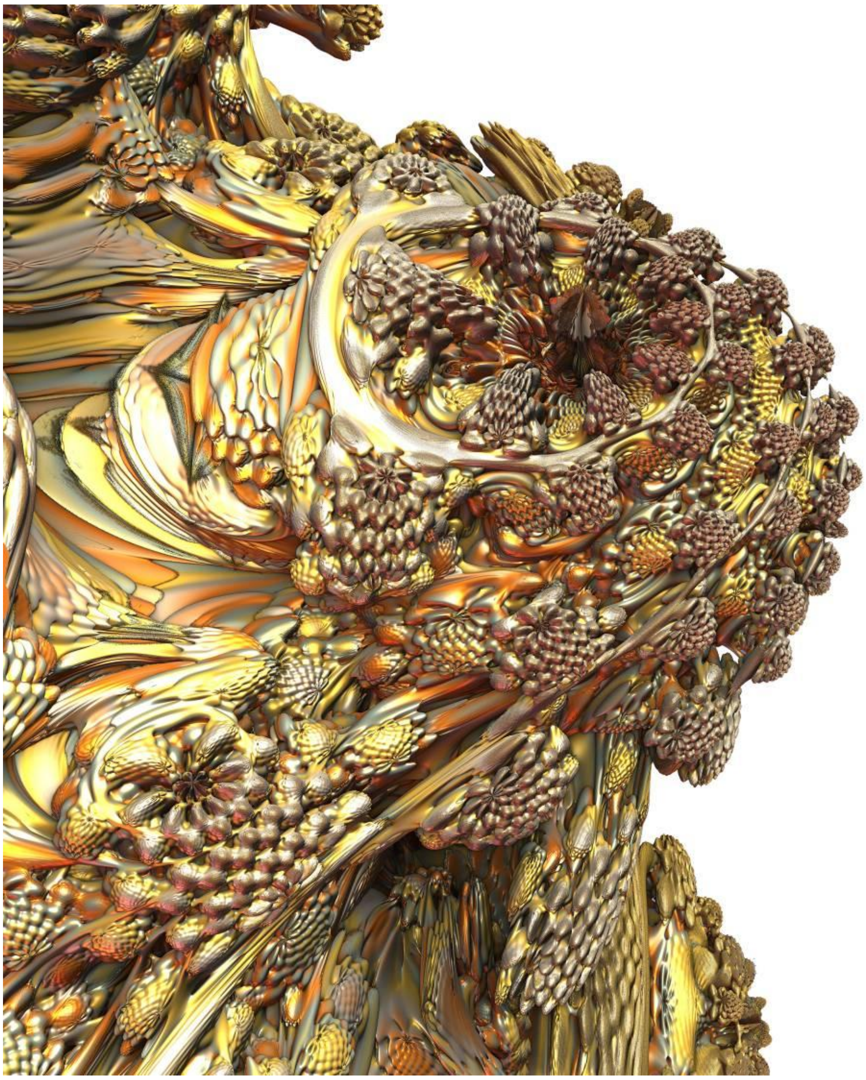

Fig. 3. Detail of Mandelbulb with 5 iterations

4 A Proposal

4.1 Methodology

The fractal form formations in this study were created using Grasshopper, which works as a plug-in to Rhino. Grasshopper is a Visual Programming Language (VPL) program. The HoopSnake add-on was used to create a repetition in the geometry. HoopSnake enables feedback loops within Grasshopper.

In this study, the repetitive process, which is the basics of the fractals, was created parametrically in Grasshopper (Form 1 and Form 2). Then, the repetitive process was repeated as required and the unit cell was created (Form 3). Afterwards, through Form 3, the form was brought to the third dimension, and various arrays were made (Fig. 4).

If we consider in more detail, first, a hexagon was created in the repetitive process (The number of hexagon grid cells can be increased to obtain a pattern). Then, the midpoint of each edge of this hexagon was defined. In this process, it was benefited from 'explode', 'list item' and 'evaluate curve' components. The midpoints of the edges of hexagon were obtained as an output. New lines were created using these points. In order to conduct this process, 'create a line between two points' component was used. Then, these created new lines were joined with the help of the 'join curves' component (Fig. 5).

This process was then turned into a loop using the Hoopsnake component. The first created hexagon was connected to the 'starting data' input of HoopSnake component. The joined secondary hexagon, which was connected to 'Data' input of HoopSnake, was defined as the starting form of the repetitive process. The Feedback output was connected to the beginning of the repetitive process which was the explode operation. The repetitive process starts with explode and ends with join.

After forming a unit, again in Grasshopper, the points on the edges of the unit were determined and these points were moved at the different rates in the Z-axis. Then, lines were created from these points. At this stage, the command 'line between two points' was used. Later, loft operation was done with these created lines and triangular surfaces were created in 3rd dimension. This process was made for a single piece in every iteration of the tile created with the fractal principle. Then, by applying 'array polar' process to these pieces, the whole tile could be created (Fig. 6). Thus, 1 tile unit was brought to the 3rd dimension.

The depths of the tile design can be differentiated by parameterizing the height in the Z axis. The 'number slider' component used allows this operation. For example, in Fig. 7, deepening of a tile in different sizes (1 unit, 3 unit, 5 unit, 7 unit and 9 unit sizes) can be seen. Finally, the cell units were arrayed to form tessellations.

4.2 Outcomes

The formation of fractal geometry with this repetitive process as 2D was achieved (Fig. 5). By changing the number of repetitions in the loop, different units could be created for the tile design (Fig. 8). Using these units, different tessellations can be created (Fig. 9). For example, in Fig. 9, a tessellation was created using only Unit 1 in the first sample. In the following second sample, a tessellation was created using Unit 1, Unit 2 and Unit 3. In this example, 3 columns of Unit 1 side by side, 3 columns of

Unit 2 side by side and 3 columns of Unit 3 side by side were sequenced and the tessellation was created. In the following third sample, a tessellation was created using Unit 1, Unit 2 and Unit 3. However, in this example, single column Unit 1, single column Unit 2 and single column Unit 3 were brought side by side. This process was repeated and tessellation was created. In the fourth sample, a tessellation was created using only Unit 3 and in the fifth sample, a tessellation was created using only Unit 2. In Fig. 10, only the 3-dimensional state of tessellation created using Unit 1, and the 3-dimensional state of the tessellation created using Unit 1, Unit 2 and Unit 3 can be seen.

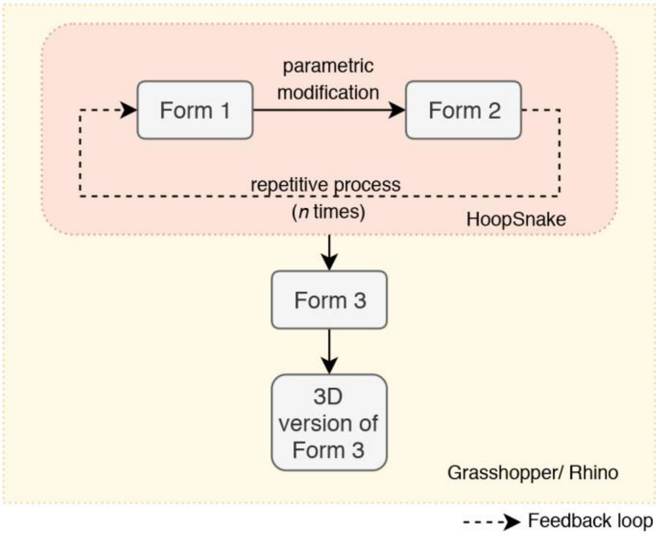

Fig. 4. Fractal form creation with VPL

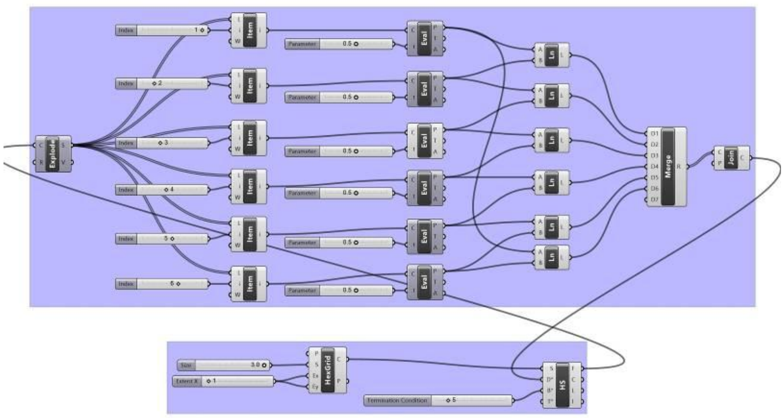

Fig. 5. The creation of the 2D tiling part in visual programming language (Grasshopper)

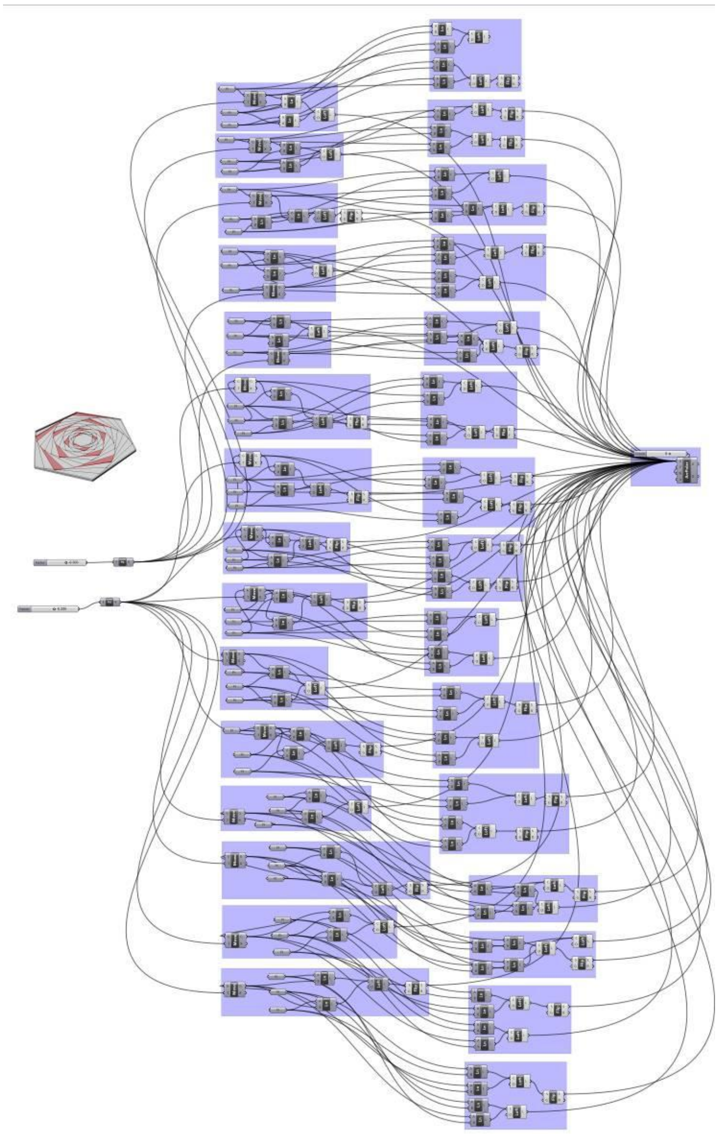

Fig. 6. The creation of the 3D tiling part in VPL (Grasshopper)

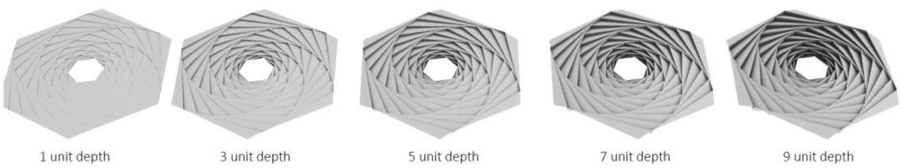

Fig. 7. Parameterization of depths in 3D tile design

5 Limitations and Future work

In this study, the principle of fractal growth was considered on a single cell basis. However, in later studies, models can be created in which the principle of fractal growth is arranged to cover more cells. In this case, tile designs, which do not fit on the rectangular or hexagonal grid (formed by the combination of different sizes of tiles) can be created.

This work is limited to cells which were placed on the hexagon grid and generated by the fractal growth principle. However, the form on a single cell can be changed (for example, square, rectangle, etc.). The formal modification on this cell can be coded in VPL parametrically. Thus, a variety of patterns can be created with different grids through the framework created in this study.

In this study, the script developed to create 1 tile unit and the script developed to convert this tiling to 3D work independently from each other. In the future study, it can be focused on making these two parts working together.

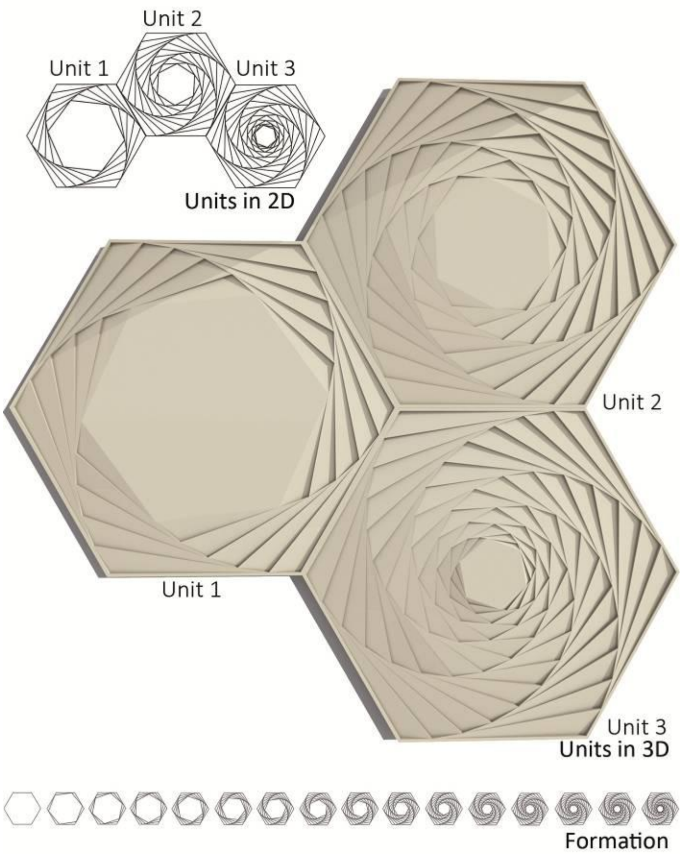

Fig. 8. Different units

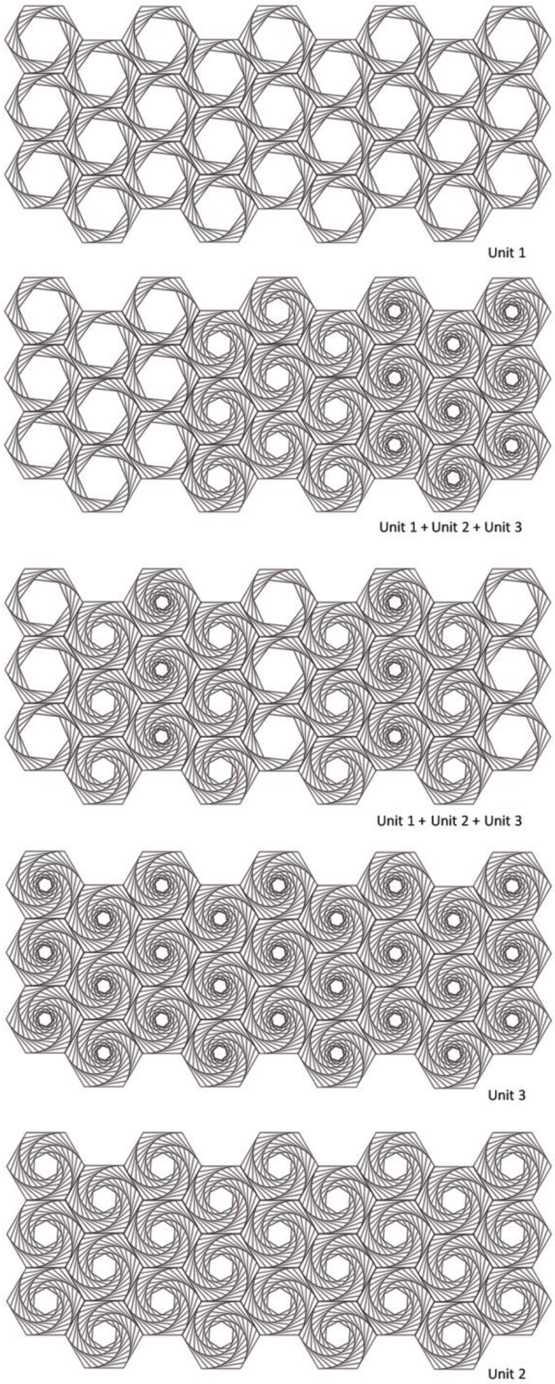

Fig. 9. Different tessellations with using different units

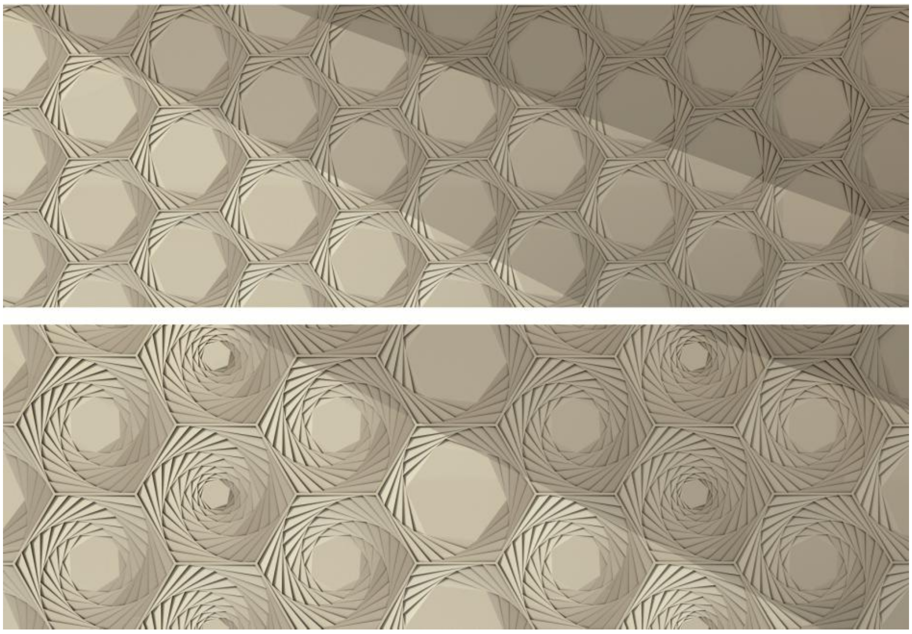

Fig. 10. Tessellation render

6 Discussion

It was observed that, in the end of using fractals in the tiling design containing geometric repetition formed a pattern having continuity. Even if the unit cells of the pattern are the same, when we look at this pattern as a whole, the pattern seems complex. This is also the case in the samples where 3 different unit cells are used. When we consider the complex form exploration in contemporary architecture, this case is a preferred formation.

In this model, the creation of the form using VPL with the repetition principle of fractals parametrically, provides the production of various forms with different complexities.

Since the model in this study is coded with VPL, this script can be easily modified by other designers according to design preferences. Parametric geometry can be differentiated and different components can be included in the script.

Especially, with entering 3D printers into the tiling sector, 3 dimensionality started to become a fashion in tiles. Thus, a search for 3-dimensional form in tiling was started. In the search of this form, 3D tiling forms can be obtained with the biomimetic approach in different forms suitable for the production with 3D printers. Different experiments for 3D tiling can be made considering different formations in nature other than fractals. In addition, the production of 3D tiling tests with the biomimetic approach can be produced with 3D printers using different materials and this can further advance the research in this area.

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