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Developing Dynamic and Flexible Façade Design with Fractal Geometry

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Abstract

The fact that built environments, which are necessary for people to survive by hosting organizations such as shelters, work, and service cannot meet the functional needs over time, creating a problem for investors, owners, and users. The way to deal with these problems is to have a flexible building design to suit the new conditions to change the capacity, function, and performance. The façade, which is highly affected by indoor and physical environmental conditions; should have a modular, similar, adaptable, and detachable system. In this study, façades with these systems are designed with fractal geometry features that mathematically define the complexity, self-similarity, and access to the macro scale from the micro scales. In conclusion, a façade system that can adapt to changes by making use of a fractal pattern and provide daylight and solar control in the interior with the electrical voltage applied to the glass surface has been proposed.

***Keywords:** Fractal geometry, dynamic and flexible façade, electrochromic glass, façade design.*

Fraktal Geometri ile Dinamik ve Esnek Cephe Tasarımı Geliştirilmesi

Öz

Barınma, çalışma, servis gibi organizasyonları içinde barındıran ve insanların yaşamlarını sürdürebilmeleri için gerekli olan yapılı çevrelerin zaman içinde fonksiyonel ihtiyaçları karşılayamaması yatırımcılar, mal sahipleri ve kullanıcılar için sorun oluşturmaktadır. Bu sorunlarla başa çıkmanın yolu, kapasiteyi, işlevi ve performansı değiştirmek için yeni koşullara uygun esnek binalar tasarlanmasıdır. Binaların işlevi ile fiziki çevre koşullarından üst düzeyde etkilenen bina elemanı olan cephenin esnek tasarıma sahip olması için modüler, uyarlanabilir, benzer, sökülüp takılabilir özellikte olması gerekmektedir. Bu çalışmada, bu özelliklere sahip cepheler, karmaşıklığı, kendine benzerliği ve mikro ölçeklerden makro ölçeğe erişimi matematiksel olarak tanımlayan fraktal geometri özelliklerinden faydalanarak tasarlanmıştır. Sonuç olarak, cam yüzeye uygulanan elektrik voltajı ile iç mekanda gün ışığı ve güneş kontrolü sağlayan, fraktal desenden faydalanarak değişikliklere uyum sağlayabilen dinamik ve esnek bir cephe sistemi önerilmiştir.

***Anahtar kelimeler:** Fraktal geometri, dinamik ve esnek cephe, elektrokromik cam, cephe tasarımı.*

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1. Introduction

The service life and potential obsolescence of buildings cause significant problems for investors, building owners, and users. The usefulness of the buildings weakens due to their inability to meet the needs in the process. The benefits to be obtained from the building, which reaches the end of its service life early, decrease, and economic problems arise due to the need for a new building. For this reason, it is an obstacle for designers to determine minimum performance levels for the life cycle of the building and solve problems arising from future environmental and functional needs. Rather than specifying minimum functional requirements for a particular functional use, it is necessary to set minimum levels of flexibility for buildings with long service life, providing a better way to cope with future changing demands.

For buildings with long service life, it is necessary to define and design the flexibility levels of elements such as structure, façade, service, circulation, and interior. The façade, which separates the exterior from the interior and is the source of the building's natural lighting and natural ventilation, is a critical building element for flexible design, as functional and comfort demands are highly affected. The façade has a long physical life but is only built according to current needs, is difficult to adapt to changes in the building use process. Similarly, façade systems unchangingly constructed with non-transparent and transparent surfaces cannot provide indoor comfort and efficiency against physical environmental conditions that change even during the day. In this direction, similar, addible, modular, and adaptable forms should be integrated with a dynamic system to change the transparent and non-transparent surfaces of the façade.

In a flexible façade, design features can be easily provided by developing an algorithm. Within the scope of the study, additive, modular and adaptive features are created with a dynamic and flexible façade design consisting of similar forms by benefiting from the elements of fractal geometry like similarity, incompleteness, and reaching from the micro scale to the macro scale. Also, a system that can be easily assembled and disassembled, be attached with similar forms, and switch from transparent to coloured for indoor solar control is developed.

The concept of the fractal comes from the Greek "fractus" and means fragment, fragmented, breaking, breaking, fraction, and irregularity. Fractals are defined as clusters with self-similarity between scales, formed by copying small-scale patterns from themselves. Introduced by Benoit Mandelbrot in the 1980s, fractal geometry is a link between the mathematical chaos of nature and Euclidean geometry. Euclidean geometry contains the concepts of certainty and solidity, while fractal geometry includes the concepts of uncertainty and disorder (Mandelbrot, 1982). Fractal geometry is used to define forms that are different from the forms of Euclidean geometry such as circles, squares, and rectangles, and cannot be defined by Euclidean geometry. Fractal geometry mathematically explains the complexity of an object in nature based on the order within that object (Yıldırım, 2018).

In studies that started with Benoit Mandelbrot and developed later, fractal geometry was classified as follows according to the degree of similarity and formation type (Mandelbrot, 1982; Mandelbrot, 1989; Vrdoljak & Miletić, 2019; Upadhayay & Maru, 2021):

Degree of self-similarity

1. Exactly self-similar fractals - Contains full-scale replicas of the entire fractal. Also known as geometric fractals

2. Semi-self-similar fractals - Contains several scaled copies of fractals and several unrelated copies of fractals. Also known as algebraic fractals.

3. Statically self-similar fractals - Do not contain copies of themselves, but some fractal properties remain the same.

Category of formation

1. Iterative fractals - These types of fractals are created after translation, rotation, copying, and replacing elements with duplicates. These fractals are self-similar.

2. Recursive fractals - These types of fractals are described from recursive mathematical formulas. These fractals are semi-self-similar.

3. Random fractals - This type of fractal includes partial properties of iterative fractal and recursive fractal. Clouds, snowflakes, etc. occurrences like these are the best example of random fractals.

The fractals' mathematical history began with the mathematician Karl Weierstrass in 1872, and Weierstrass introduced a "Weierstrass" function, that is perpetual everywhere but nowhere distinguishable. The Weierstrass function was studied by Helge von Koch in 1904. He improved the "Koch Snowflake" function (Figure 1a) that was more geometric description of the Weierstrass function (Lui, Croome & Viljanen, 2012). While Waclaw Sierpinski described self-similar patterns and the functions that produced them in 1915 (Figure 1b), Georg Cantor gave an example of a fractal self-similar (Milad, Akhmet & Fen, 2018). The fractals were further developed by Henri Poincare, Felix Klein, Pierre Fatou, and Gaston Julia in the 19th and early 20th centuries, after in 1975, Mandelbrot brought these studies together and introduced the concept of fractals (Lui et al., 2012).

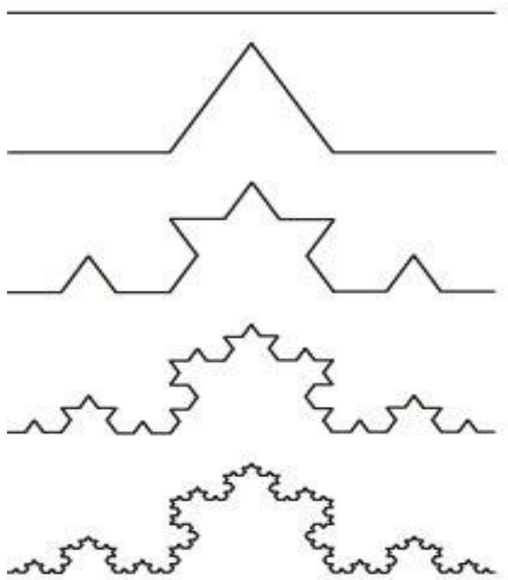


Figure 1a. Koch snowflake (Weisstein, 2022a)

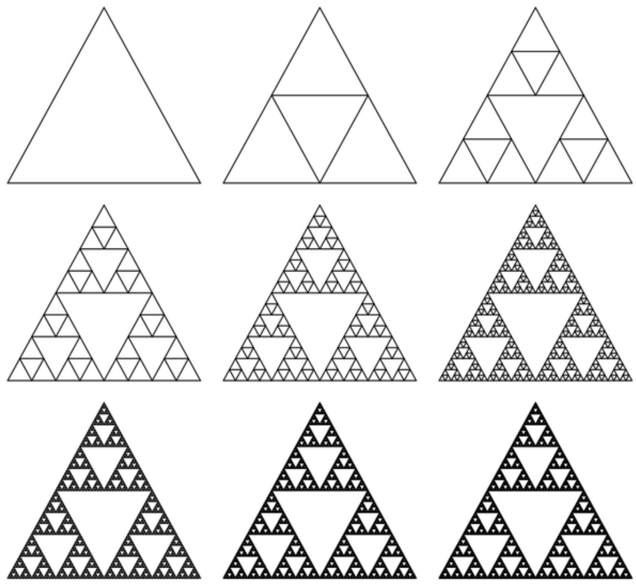


Figure 1b. Sierpinski triangle (Milad et al., 2018).

Benoit Mandelbrot stated that the metric measurement of the coastline is not sufficient in the studies on the measurement of the coastline, and it is wrong to reduce a beach with many shapes to one line. Mandelbrot introduced the concept of fractal by explaining that it is insufficient to represent some forms in nature such as mountains, clouds, and plants with Euclidean geometry (Bovill, 2000). In his studies on a fractal, Mandelbrot explained complex forms consisting of repetitions of similar forms with fractal geometry, based on the Koch Snowflake, which is formed by dividing a straight line into three equal parts, placing an equilateral triangle on the middle part, and the endless repetition of these operations (Ediz, 2003).

Ever-changing fractals have the advantage that they can create a wide variety of forms from a prespecified first structure. Fractals are models of dynamic systems that are improvable and modifiable. Fractal geometry relies on creating a whole from parts, as the emergence of the following step depends on the improvement of the previous one. The whole object is uniquely dissimilar from the first piece (Mayatskaya, Kashina, Gerlein & Yazyev, 2021).

2. Material and Method

Within the scope of the study, dynamic and flexible façade design with electrochromic glasses is proposed by the use of self-similarity as the degree of similarity and the iterative as the formation type of the fractal geometry. It is seen the literature that fractal geometry uses the features of self-similarity, repetition, imperfection, harmony, and the formation of macro forms from micro patterns in architectural design. Accordingly, first, fractal geometry and architectural design were analyzed, electrochromic glasses were detailed and finally, the study method was presented.

2.1. Fractals in Architectural Designs

The fractal dimensions seen in architecture include self-similarity, repetitions, and details that reach the macro scale from the micro-scale. Fractals are also seen in many details from urban design to the formation of a building mass, from building materials, and elements to the smallest elements in the interior. In the past, sub-concepts of fractal geometry were seen in many examples of different architectural processes. Reflection from fractal geometry in nature and repetition of certain forms or patterns were used in architectural designs in different periods, cultures, and geographies. Similar and repetitive patterns at different scales are seen in cathedral and church buildings in Gothic, Renaissance, and Baroque Architecture in Figure 2 (Jencks, 1997). In modern architecture, especially in Frank Lloyd Wright's buildings, in addition to the relationship between scales and inspiration from the forms in nature, complex forms were developed outside of the basic rules, and some structures had the same characteristics from small to whole (Figure 3) (Vaughan & Ostwald, 2011).

Figure 2. Notre Dame Cathedral repetitive rose windows and arches at different scales (Jencks, 1997)

Figure 3. The Robbie House building was designed by Wright: making a whole from identical parts (Vaughan & Ostwald, 2011)

When the existence of fractal geometry in today's architecture is analysed, examples are seen in the formation of holistic forms that come together from similar forms and modules in the design of the structure, shell, and interior elements (Figure 4, 5).

Figure 4. Moshe Safdie - Habitat ’67: Formation of holistic forms from similar forms (Gendall, 2017)

Figure 5. Louvre Abu Dhabi Museum designed by Jean Nouvel: The interior effect of the shell design (Mudhaffar, 2019)

Peter Eisenman designed the House XI project based on Mandelbrot's book “Fractals: Form, Probability, and Dimension” (Figure 6). The concepts of iterative, and self-similarity of fractal geometry were included in Eisenman's design. House XI was a composition formed because of the iterative of the letter "L" shape with rotation and vertical symmetry at different scales. Because, the letter L could scale efficiently many times and create a fractal architecture (Papasterevski & Cenovski, 2020).

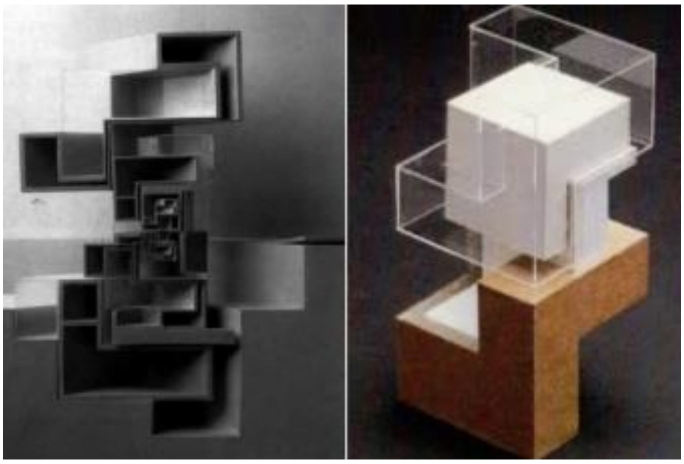


Figure 6. Peter Eisenman House XI: Holistic forms designed from similar parts of different scales (Papasterevski & Cenovski, 2020).

The dormitory building designed by Steven Holl is one of today's structures with fractal characteristics. The Menger Sponge described by Karl Menger was the inspiration for the building form. (Figure-7a). Accordingly, the form started with a cube; it was formed by dividing the cube into equal parts, first 9 and then 27. The hollow structure in the building, where there are gaps of different sizes in a hierarchical arrangement, continued as the scale gets smaller (Mutica, 2016) (Figure 7b).

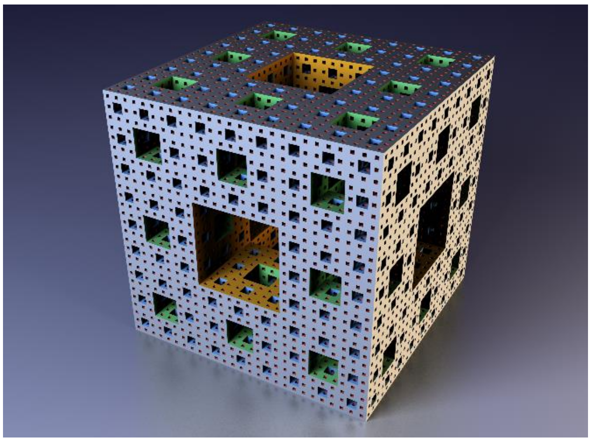


Figure 7a. Menger sponge (Weisstein, 2022b)

Figure 7b. Steven Holl MIT Building (Perez, 2010)

The Federation Square project with public buildings in Melbourne by Lab Architecture Studio; is an impressive example because of the use of fractal geometry in many areas such as interior, structure, and façade. Designers used fractal geometry to create geometric patterns consisting of simple components that allow repetition and differentiation. In the geometric patterns used in the shell structure of the atrium and amphitheater structures (Figure 8), in the facade cladding panels used in the buildings in the square, and in the ceiling coverings in the interior spaces, the smallest triangular form comes together to create holistic and similar forms (Figure 9,10) (Osama, Sherif & Ezzeldin, 2014).

The similar triangular patterns used in the facade panels, structures, and interiors of the Federation Square project designed by Lab Architecture Studio transformed into very different forms and produce solutions in many different areas such as facade, interior, and structure. For these reasons, triangular patterns were the reference for dynamic and flexible facade design from fractal geometry developed within the scope of that study.

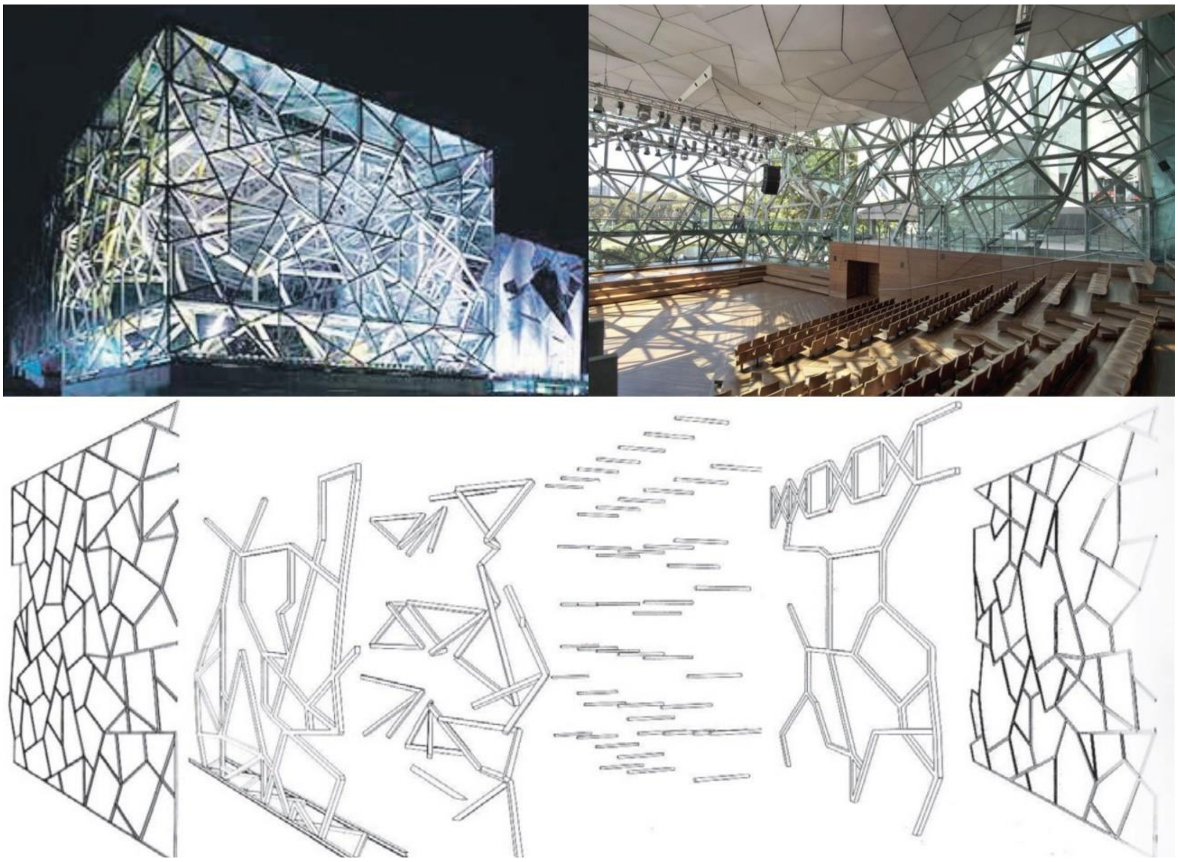


Figure 8. Fractal geometry in the Federation Square shell structure design (Osama et al., 2014)

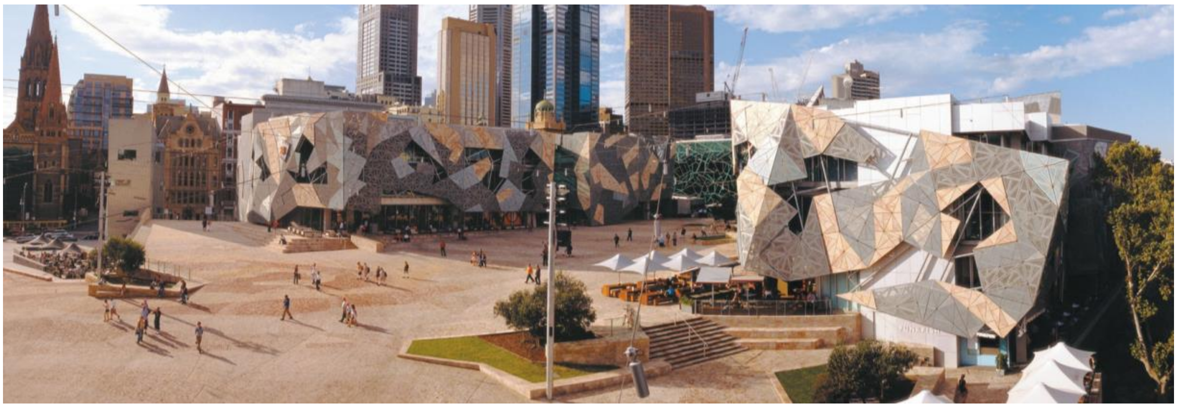


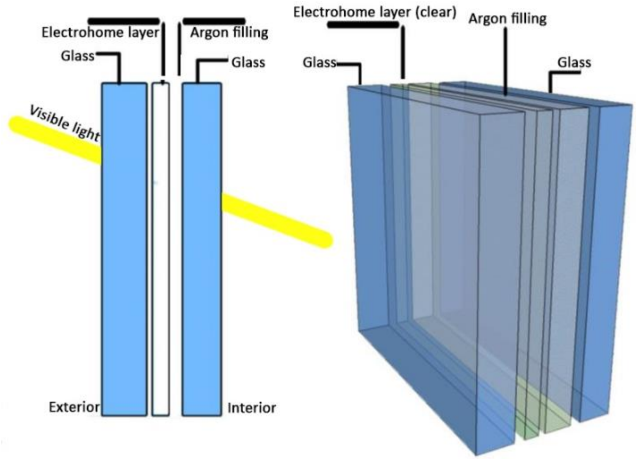
Figure 9. Fractal geometry in the Federation Square façade panel design (Osama et al., 2014)

Figure 10. Federation Square Buildings' interior fractal geometry effect (Osama et al., 2014)

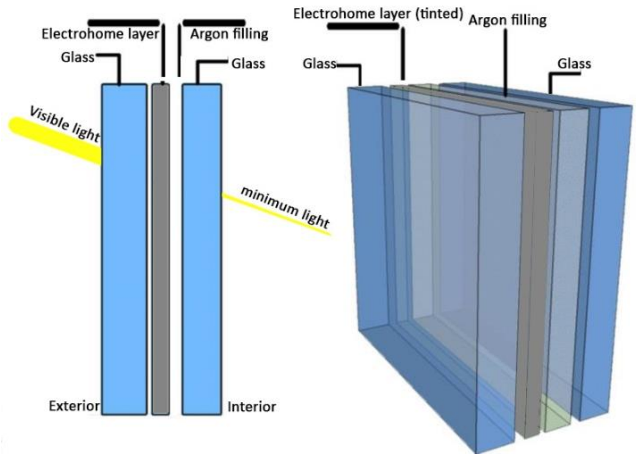
2.2. Electrochromic glasses

Electrochromic glasses are materials that change their colour and/or optical properties activated by the action of electric fields, ions (electric energy), or electrons (Ritter, 2007). Electrochromic glasses utilize a small electrical voltage to adjust the shading coefficient and visible light transmission. After turning off the power, they maintain the same degree of dimming. In this way, it is probable to control the façade' shading also the lighting and temperature of the inside (Savić et al., 2013).

Electrochromic glass takes advantage of the properties of some elements to change the transmission, reflection and absorption parameters of solar radiation according to electrical stimulation. The change of properties of these elements occurs through the addition or removal of mobile ions from the electrochromic layer. When the electric field is activated, the added ions form compounds that change the colour of the material and react with the compounds. The amount of energy required by the system to switch between different coloration states is minimal (1-2.5 Wp/m^2), and the amount of energy required to maintain is even less, thanks to the bistable configuration of electrochromic materials (Casini, 2015). An electrical voltage of 1-5 Volts is applied to the tungsten oxide film layer, which is applied to the glass surfaces as a multi-layer film with a thickness of about 1 micron, and the glass surface is transformed into different colours (Tavil, 2004) (Figure 11).



Transparent electrochromic layer without voltage applied



Coloured electrochromic layer with voltage applied

Figure 11. The method of benefiting from daylight with the energy applied to the electrochromic layer

2.3. Method

The features of fractal geometry that contain similar forms, allow additions and subtractions, be modular, and consist of systematic and harmonious patterns are compatible with dynamic and flexible facade designs. Accordingly, a façade design that can adapt to changing physical conditions and changes in the interior caused by user demands is proposed by developing an algorithm in which a similar whole is formed from the smallest piece with the repetition of similar patterns. The façade, created with fractal geometry and electrochromic glass, is a system that, thanks to its dynamic and flexible formation when any functional transformation is required or new spaces are organized with dimensional changes, protects against unwanted radiation levels, prevents glare, prevents unwanted heat gains on the condition of providing visual comfort inside.

The “1-2- √5” triangle, which is used to create texture areas of the facade and interior with panel elements, and steel structure designs in architectural designs with fractal fiction, is the recommended pattern for flexible and dynamic facade design. The right triangle “1-2-√5” to be used as a fractal facade pattern within the scope of this study is a special triangle, and the five triangles come together to form the larger “1-2-√5” triangle at the same rate. The patterns consisting of five “1-2-√5” triangles can come together to form a similarly larger triangle. These patterns can come together endlessly and turn into forms made up of similar patterns (Figure 12).

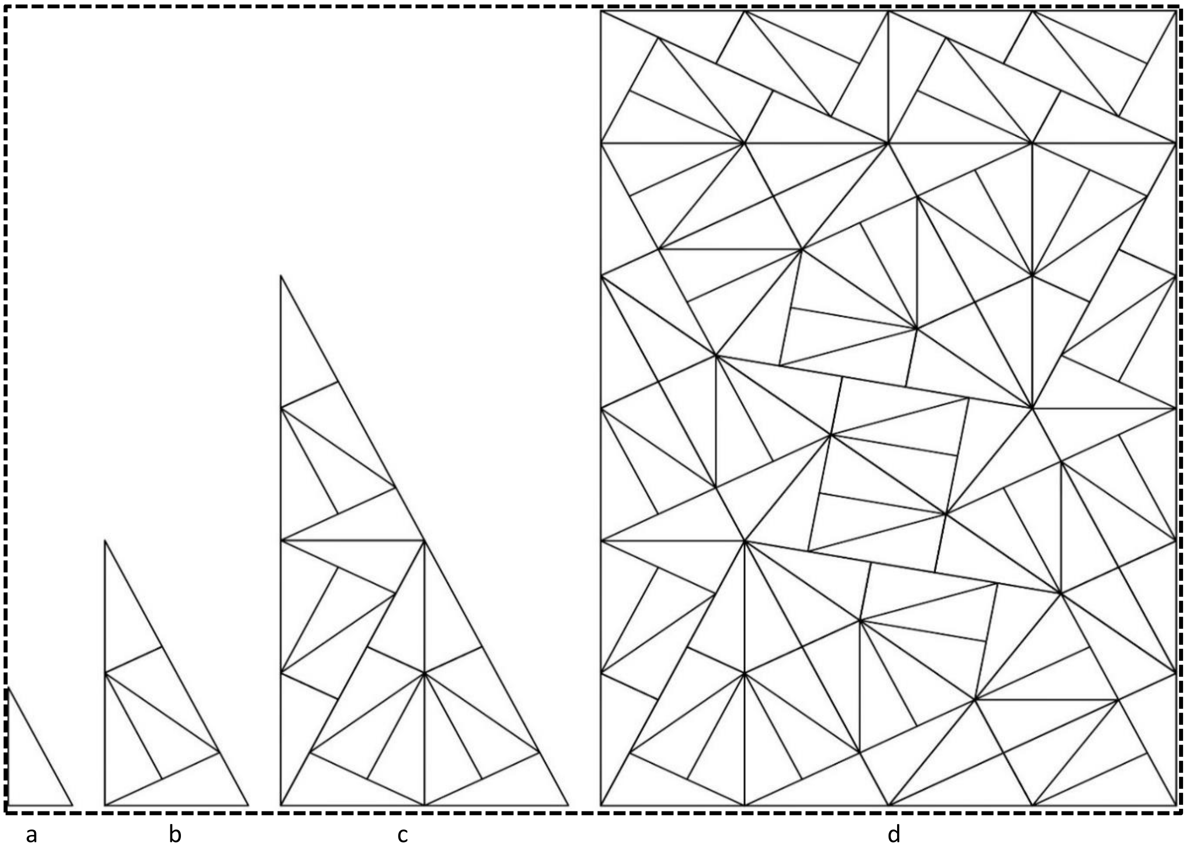


Figure 12. Example façade form created with a 1-2-√5 triangle (a-1-2-√5, b- five triangle, c- twenty triangle, d- example rectangle form)

The shading and visible light transmission on the glass are adjusted by electrochromic glasses utilizing a small electrical voltage. Thus, the glass surface is transformed into different colours. In this study, different voltages are applied to the electrochromic glass to create transparent and non-transparent glass surfaces according to the daylight requirement and solar control in the interior. That system allows changing a similar, modular, addable glass facade form in the interior by fractal geometric design and transforming transparent glasses to be coloured glasses by the electrical voltage.

3. Findings and Discussion

Fractals consisting of natural forms are used in different fields due to their harmony, aesthetic, and efficiency features, including architecture and urbanism. While fractals focus on urban planning and aesthetics in the architectural area, fractal designs are limited functionally and spatially. Since fractals are regular, modular, and can be articulated infinitely, they can also enable flexible design. The study also shows the suitability of fractal geometry for flexible architectural design. However, there are very few studies advocating a flexible design approach with fractal geometry, which allows adaptive and flexible design setup by responding to changing environments and enables to create of changing perspectives in the geometric framework (Belma, & Ayyıldız, 2016; Abdullah & Ismail, 2022; Nakib, 2010). In addition to academic studies, design applications related to fractal geometry in different ways were developed independently with flexibility and discussed under the title of "Fractals in Architectural Designs." In particular, the plan system and building envelope formed by the combination of amorphous and triangular shapes with a fractal pattern in the building designed by Lab Studio, and the building form formed by the repetition and coming together of cubes in the dormitory building designed by Steven Holl have taken their place in the literature (Osame et al., 2014; Mutica, 2016). They are crucial examples that contribute to that study.

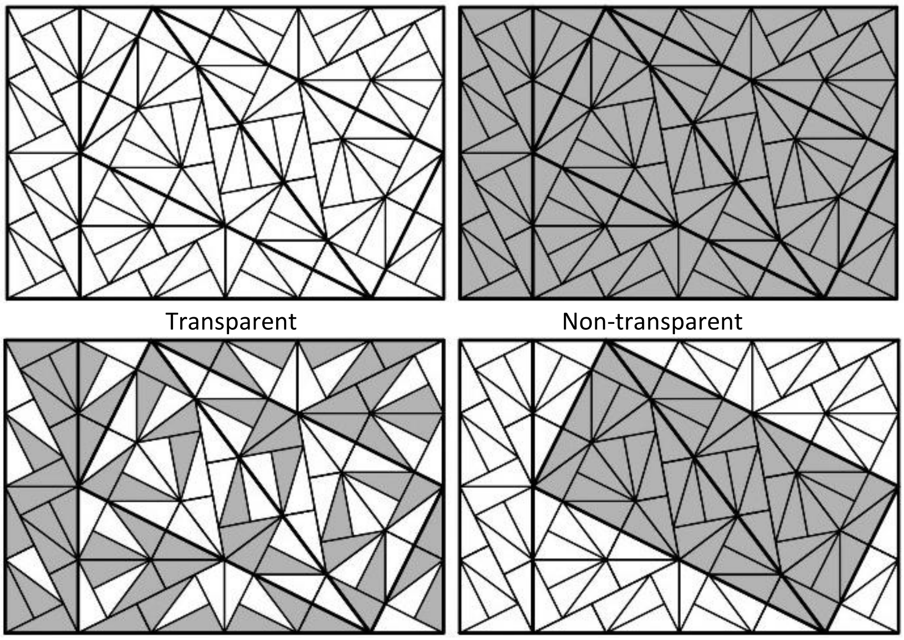
Today, where energy conservation is of utmost importance, façade approaches defined as intelligent, kinetic, adaptable, and dynamic have been put forward to improve energy performance and indoor comfort levels (Bande, Hamad, Alqahtani, Alnahdi, Ghunaim, Fikry & Alkhatib, 2022). Dynamic and flexible/adaptable facades are classified as mechanical systems in which various mechanisms are adapted to the facade, hydraulic systems that provide movement on the facade with pistons placed in the cylinder, and pneumatic systems that can move by pumping air and gas under pressure (Harry, 2016; Yaman & Arpacıoğlu, 2021). In addition to these, facade systems are developed with material technologies. Smart glass systems dynamically manage daylight and solar gain by switching between transparent and reflecting modes to control the flow of natural light into buildings. These systems are frequently encountered material technologies and are transformed by an electric current named electrochromic or change under heat-light named photochromic (Jelle, 2013; Yaman & Arpacıoğlu, 2021).

In the study, a dynamic façade system is proposed based on the electrochromic glass that emerges due to flexible, developing material technologies with fractal geometry properties. The flexibility and dynamism advantages of this type of fractal facade:

- Easy formation and assembly due to repeating patterns,
- Changing transparent and non-transparent surfaces according to different needs due to the electrochromic glass,
- Allowing additions in new space requests due to modular, similar, and single materials,
- Transforming into different forms due to similar and iterative patterns,
- Energy efficiency due to reducing the need for cooling by providing solar control for hot climate regions,

can be listed as. The triangle patterns designed by making use of the self-similarity and iterative features of the fractal geometry will meet the adaptation, change, and transformation flexibility needs expected from the façade in the building. The fact that infinite patterns can be obtained by adding and subtracting congruent and similar triangles from triangles has led to the preference for the “1-2-√5” triangle. In the pattern shown in Figure 12, five of the “1-2-√5” triangles representing the smallest element on the façade, came together to form a larger triangle. The five triangle patterns come together to form larger patterns, and patterns consisting of “1-2-√5” triangles turn into a rectangular form.

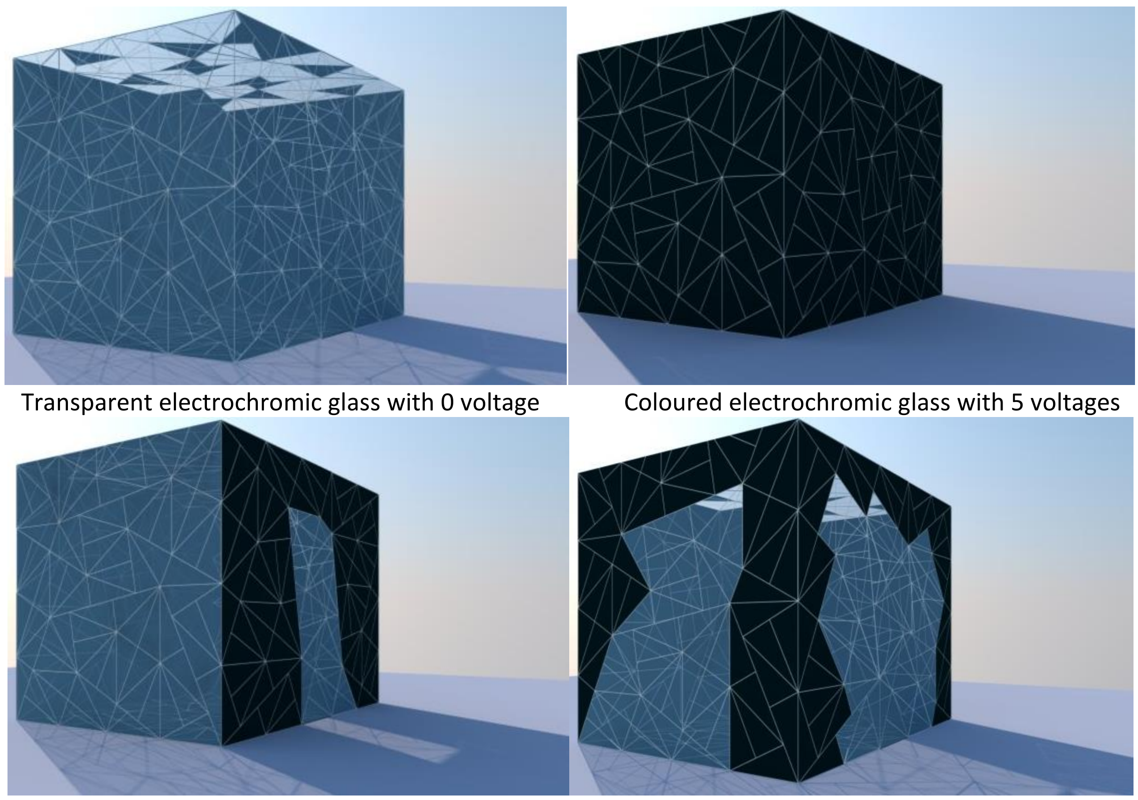
In this direction, the dynamic and flexible façade design with fractal geometry developed within the scope of the study allows daylight and solar control in the interior, physical environment control, different uses of the spaces, and the change of non-transparent and transparent surfaces. In addition, the glass surfaces in the façade design have an electrochromic feature, and the transparency ratios are changed by applying different voltages to the electrochromic glasses. Thanks to the placement of electrochromic glasses on the façade with fractal design in Figure 13, transparent and non-transparent dynamic facades are presented by changing the colours of the glass surfaces.



Dynamic

Figure 13. Dynamic façade design

When a voltage of zero is applied to the electrochromic glasses on the cube surfaces in Figure-14, where the glasses formed from similar patterns by taking the smallest scale of the triangle 1-2-√5 form the building envelope, all surfaces become transparent. With the increase in voltage, the permeability of the glass system decreases, and it becomes coloured. In addition, applying different voltages to each of the fractal patterns provides the desired transparent and non-transparent surfaces on the cube surface. As a result, thanks to the dynamic feature of the façade design with all glass surfaces, design flexibility has been achieved, whose transparent and solid surfaces can easily be changed according to the interior needs.



Glasses with different voltage on different surfaces Glasses with different voltage on the same surface

Figure 14. Solid and transparent surfaces were obtained by applying different voltages on cube surfaces with electrochromic glasses

4. Conclusion and Suggestions

The underlying of productive approaches is the understanding that the elements come together with order and rule to form a whole. In architectural design, rule, meaning, and context in the order of the final product from the architectural elements are similar to the productive approach processes. These similarities enable generative approaches to be included in architecture and offer designers new pursuits and solutions with the definition of the productive architectural design approach. Fractal geometry has been used to support a new approach in productive architectural design in recent years. In the process of designing forms and layouts that cannot be defined with Euclidean geometry, iterative algorithms based on fractal geometry provide solutions and conveniences. Although the form consisting of triangular patterns is a suggestion, the main aim study is to raise awareness among the stakeholders in the construction sector that flexible and dynamic designs can be achieved with façade systems created with fractal geometry.

Within the scope of the study, a facade model of flexible design that can easily adapt to environmental conditions and changing needs of users has been developed, based on the characteristics of fractal geometry, which offers new solutions in architecture, self-similarity, iterative, incompleteness, compatibility and the formation of similar large forms from small patterns. In the design developed by creating similar patterns from the 1-2-√5 triangle, a system that can be added with similar patterns can be adapted to different conformations and can be controlled indoors with the electrochromic glass system is proposed. That system prevents unwanted radiation levels, glare, and unwanted heat gains on facade for interior comfort. In conclusion, thanks to the flexible and dynamic facade design applied in buildings with long life cycle and where change is inevitable, built environments with continuous functional service life, economical, efficient, and environmentally effective will be designed.

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The paper complies with national and international research and publication ethics. Ethics committee approval was not required for this manuscript.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to this manuscript. There is no conflict of interest.

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