Biomimicry Green Façade: Integrating Nature into Building Façades for Enhanced Building Envelope Efficiency

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Abstract

Incorporating natural elements into the design of building façades, such as green façades, has emerged as a promising strategy for achieving sustainable and energy-efficient buildings. Biomimicry has become a key inspiration for the development of innovative green façade systems. However, there is still progress to be made in maximizing their aesthetic and structural performance, and the application of advanced and generative design methods is imperative for optimizing green façade architecture. This research aims to present a generative design-based prototype of a biomimicry green façade substrate with photosynthetic microorganisms to enhance building façade efficiency. The concept of green façades offers numerous advantages, as it can be adapted to a wide range of building structures and implemented in various climates. To achieve this, Rhino and Grasshopper were utilized to design the generative and parametric substrate, optimizing the architectural form using a genetic algorithm. Consequently, a bio-façade prototype was developed, determining the optimal number and shape of coral envelopes to maintain cyanobacteria within a generative and parametric façade. Furthermore, the photosynthetic microorganism façade acted as an adaptive façade, effectively improving visual and thermal comfort, daylighting, and Indoor Environmental Quality performance.

Keywords: *Parametric Design; Generative Design; Green Façade; Bio-façade; Bio-Architecture; Vertical Greenery Systems*

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1. Introduction

The global trend towards low-carbon cities and societies is gaining traction as a means of mitigating and adapting to the effects of climate change. This strategy promotes energy efficiency, renewable energy utilization, and reducing greenhouse gas emissions through sustainable mobility. Despite its increasing popularity, this approach encounters significant challenges when it comes to implementation. Addressing buildings, in particular, presents a significant challenge in achieving this goal, as they contribute substantially to global energy demand and consumption. buildings are responsible for roughly 23% of global primary energy consumption and 30% of the world's electricity consumption (Al-Obaidi, Ismail, et al., 2017; Lead & LA, n.d.; Munaaim et al., 2016; Serrano et al., 2017). Notably, heating and cooling account for the majority of the energy used in buildings, accounting for approximately 60% of the total energy consumed (Omrany et al., 2016).

The building envelope plays a crucial role in managing energy usage and maintaining internal comfort (Al-Obaidi et al., 2015, 2016; Oral & Yilmaz, 2003; Y. Wang et al., 2017). Historically, the building envelope has been designed as a thermal barrier to minimize heat loss or gain and manage solar radiation (Al-Obaidi et al., 2014; Barbosa & Ip, 2014; Liu et al., 2017; López et al., 2017). However, most building envelopes have been constructed with static architectural solutions that do not adjust to changing climatic conditions or the needs of the occupants (López et al., 2017). The rigidity of conventional building envelope systems in accommodating contextual requirements and individual needs has created a demand for building designs that prioritize flexibility, innovation, energy efficiency, environmental sustainability, and user-friendliness. Integrating features such as natural ventilation, passive solar heating, shading mechanisms, and insulation, along with other relevant elements, can be an effective approach to meet these criteria.

Kinetic architecture has been defined by Zuk and Clark (1970) as a design discipline that incorporates kinetics in deformable, reversible, gradual, and mobile forms to enable structures to react to changes. Despite its theoretical potential, the implementation of these ideas has been limited by technological restrictions (Riddle, 2014). However, in recent years, there has been a growing trend towards the design of envelope systems, particularly façades, using dynamic systems that utilize layered façades. These façade layers perform distinct functions, and their combination results in a complex system (Aziz & El Sherif, 2016). Dynamic and kinetic systems in architecture include a wide range of innovative technologies such as automatically controlled shutters (Wigginton & Harris, 2013), adaptive skins (Hasselaar, 2006), climate-adaptive building shells (Boer et al., 2011; R. Loonen, 2010; R. C. G. M. Loonen et al., 2013), interactive architecture featuring robotic and kinetic designs (Hasselaar, 2006), acclimated kinetic envelopes (J. Wang et al., 2012), adaptive building skins (Grosso & Basso, 2013), and kinetic systems integrated into architectural design (Ramzy & Fayed, 2011). (Wigginton & Harris, 2013). The concept of a biomimetic green façade, an adaptive building skin that takes inspiration from natural shapes, processes, and systems to develop sustainable and innovative solutions, has gained traction as a means of integrating nature into the design and technology (Zari, 2007). Biomimicry involves three stages: form, process, and ecosystem. The forming stage focuses on replicating an organism's characteristics and design, while the process stage delves deeper into mimicking its biological development and procedures. The third stage, ecosystem, is a more complex replication of an ecosystem's structure and processes on a larger scale, with an emphasis on identifying its impact on the environment (Pathak, 2019).

The generative method is a process for finding forms that mimic the evolutionary approach of nature in design. It is widely used in various design fields, such as creating images, sounds, and architectural models. Generative design is based on algorithmic and parametric modelling, where designers start with the initial design requirements and explore multiple solutions to determine the optimal one. With generative design, designers can efficiently generate a vast number of design possibilities and select the best option for the given design problem.

As façades are a crucial element in minimizing energy waste in buildings, the implementation of double skin façades (including green façade systems) and photosynthetic microorganism façade systems as adaptive façades could help in decreasing energy waste and consumption (Tabadkani et al., 2018). These systems provide shading, insulation, and evapotranspiration (Bakhshoodeh, 2023), thereby improving thermal comfort in buildings (Kuru et al., 2019; López et al., 2017), and also contribute to reducing CO_2 emissions (Rezazadeh et al., 2021). Table 1 compares the performances of different types of façades (i.e., micro-algae, green, and double skin façades).

Table 1. Comparison of photosynthetic microorganisms (Micro-algae) façades to double skin and green façades in terms of their performances.

Function	Photosynthetic Microorganisms Façade	Double-Skin Façade (including green façades)

Shading	Solar absorption based on the density of microalgae culture (adaptive shading)	Solar absorption through shading (Bagheri Moghaddam et al., 2020; Bakhshoodeh et al., 2022a, 2022c; Jiru et al., 2011), plants (Bagheri Moghaddam et al., 2020; Bakhshoodeh et al., 2022c; Hes et al., 2014), or photovoltaics (PV) (Elarga et al., 2016; Peng et al., 2013; M. Wang et al., 2017)
Insulation	Reducing heat gain through the utilize the microalgae façade systems and air	Reducing heat gain using air cavity and shading devices (Bagheri Moghaddam, Delgado, et al., 2021; Gratia & De Herde, 2007; Li et al., 2017; Lou et al., 2012; Pacheco Torgal et al., n.d.; Schnurr & Allen, 2015; Stec et al., 2005), plants (Bagheri Moghaddam, Fort Mir, et al., 2021), and PV (Gaillard et al., 2014)
Natural Ventilation	N/A	Floating and wind force (Ghaffarian Hoseini et al., 2016); convective air movement (Hes et al., 2014)
Evapotranspiration	N/A	Air moistening through plant leaves and soil (Bakhshoodeh et al., 2022a; Cheng et al., 2010)
Solar-thermal cell	The generation of heat via microalgae façade systems. Production of biomass and biofuels (Elrayies, 2018)	Feasible since integrated with PV/T cells (Saadon et al., 2016) and PV-PCM (Elarga et al., 2016)
Convective Shielding	N/A	Wind effect reduction through plant leaves (Bagheri Moghaddam, 2021; Bagheri Moghaddam et al., 2020; Bakhshoodeh et al., 2022b; Coma et al., 2017; Hes et al., 2014)

* N/A: there is no information available.

By incorporating biomimetic design into building envelopes, sustainable design can be achieved that goes beyond using nature as a source of inspiration in building envelopes. The biomimetic approach can develop relations between biology and architecture to propose innovative façade design solutions (López et al., 2017). Few investigations in the literature looked at a variety of definitions of façade case studies (Böke et al., 2020), typologies (Al-Obaidi, Azzam Ismail, et al., 2017; Attia et al., 2020; Romano et al., 2018), interactions with occupants (Luna-Navarro et al., 2020), and structural requirements and performance (Bedon et al., 2019). Even so, the terminology used to describe differences, limitations of applications, and the fundamentals of design approaches for façades as the main and the most effective component of the building's envelope remain vague (Tabadkani et al., 2021).

The primary objective of this research is to develop a functional prototype of a biomimicry green facade substrate by incorporating photosynthetic microorganisms, particularly cyanobacteria, as an alternative to traditional plant-based systems. This innovative substrate will be utilized to create an adaptive facade system for buildings, offering numerous benefits in terms of sustainability and environmental responsiveness. In addition to the creation of the biomimicry green facade prototype, this study places particular emphasis on exploring the adaptability of the parametric and generative structure of the substrate. The research aims to investigate how this structure can be effectively tailored to accommodate diverse building types across various contextual settings. By understanding the optimal design parameters and characteristics required for different architectural contexts, the study seeks to provide valuable insights and recommendations for the implementation of biomimicry green facades in real-world scenarios. Ultimately, through the development of the biomimicry green facade substrate prototype and the exploration of its adaptability, this research strives to contribute to the advancement of sustainable building practices and inspire innovative design solutions that harmonize with the natural environment.

2. Methodology

The proposed article suggests a two-part methodology to design and implement the cyanobacteria double-skin façade. The first part focuses on designing the double-skin façade using generative and parametric methods, which can optimize the environmental benefits of cyanobacteria. Generative design is an innovative approach that uses algorithms to generate design options that meet specific criteria, while parametric design is a method that uses parameters to create design variations. The use of generative and parametric methods in designing the double-skin façade can create an environmentally friendly façade that maximizes the benefits of cyanobacteria. The second part of the methodology is dedicated to implementing the cyanobacteria on the generative and parametric double-skin façade. This involves selecting suitable strains of cyanobacteria, determining the optimal growth conditions, and creating a suitable environment for the cyanobacteria to thrive. The proposed methodology aims to create a sustainable and eco-friendly solution that can contribute to improving the environmental performance of buildings.

2.1. Design Method

The generative design method is used because of a comprehensive CAD-based generative design exploration method designed to work at all stages of the design development process from conceptual to detailed design. In this study, parametric modelling was done with feature-based systems, which allow users to create parametric models with two main tasks: individual parts and assemblies of parts. For this aim, Rhino-Grasshopper was employed as the design generation software to create a parametric substrate. Rhino-Grasshopper is a graph-based system that supports implicit multi-operation iteration and also uses nested list data structures (Janssen & Stouffs, 2015). Furthermore, Grasshopper not only has an appealing interface but also has a robust set of geometric functions that works transparently with values and lists of values (Lopes & Leitão, 2011). Several parameters should be considered during the design stage of a building façade in general, including solar gain control, natural ventilation, daylighting and artificial lighting, view of the outdoors, heat control, moisture control, and noise. Among the previously mentioned environmental factors, this article focuses on visual and thermal comfort, daylight, and Indoor environmental quality (IEQ) performance enhancements that can be most effectively improved by the photosynthetic microorganism façade as an adaptive façade.

The design method process started with an exploration of the project concept in terms of the coral colony’s morphogenesis and behaviour which is depicted in Fig. 1. The concept of this research, which was inspired by nature, can be described as a biomimicry design in which nature is the primary principle. The chosen generative design technique starts with a predetermined design concept and quickly applies iteration to generate numerous potential solutions. This phase was performed in five steps to implement the generative design method and ended with integrating the parametric design phase. To develop the research hypothesis, the findings of existing studies in this area and the hypothesis of concern are to be tested quantitatively (Yin, 1981).

As exposed in Fig. 1, the integrated parametric design platform of Rhino-Grasshopper is established through the simulation method using the ladybug plugin for environmental analysis. This includes diagrams such as the sun's path, the wind rose, psychrometric chart, and so on, and geometric studies such as radiation analysis, shadow studies, and view analysis. Researchers can examine the cause and effect of various variables, as well as the influences or potential ramifications of various scenarios through simulation tools. With this respect, a simulation workflow should be designed, parametric design algorithms must be developed by the Rhino-Grasshopper generative tool, and the datasets should be generated for running the simulation (Banihashemi et al., 2018).

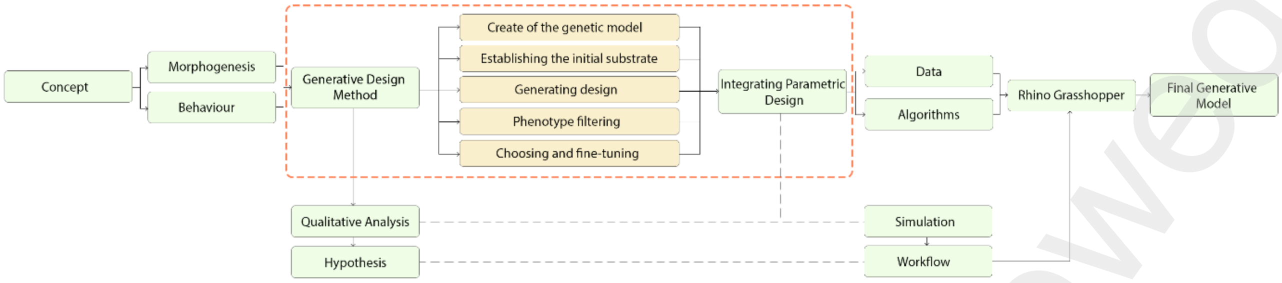

Fig. 1. The research design process.

Hence, in this research, the following steps were taken to implement the generative design simulation method; i) creating the genetic algorithm model; ii) establishing the exploration substrate; iii) generating design variants; iv) filtering phenotypes; and v) selecting and fine-tuning.

2.1.1. Creating the genetic algorithm model

For the aim of this research, the Voronoi diagram is utilized which is a data structure that has been extensively applied in the field of computational geometry, to create a substrate with the same morphology and functionality as coral colonies, and this diagram has been optimized by Genetic algorithms that is one of the most classical and well-known types of Evolutionary Algorithms (Benavides et al., 2011). Genetic algorithms are computational techniques based upon the evolution theory and, many other evolutionary techniques alike, which are required to create genetic models and use them in architecture and construction as optimization or form-generation tools (Latifi et al., 2016). A genetic algorithm that balances the load among envelopes has been used to determine the final assigned areas. Additionally, the Voronoi polygon enclosing any point (individual envelope) is defined as the polygon enclosing the space (typically 2D Euclidean) that is closer to the envelope than to any other envelopes (Jiménez-Estévez et al., 2008). The direct Voronoi neighbours of any point are those that share a boundary with their Voronoi polygons.

2.1.1.1. Voronoi Diagram

The Voronoi diagram was utilized in this study in terms of the geometrical construction and the morphology of the substrate (Fig. 2). This decision was made in light of the many similar empirical structures such as the "H.O.R.T.U.S.XL" bio-digital project (Pasquero & Poletto, 2020) including the coral colony geometries through the direct applications of Voronoi concepts in their modelling and design (Pasquero & Poletto, 2020; Reinhardt, 2016). Therefore, to apply the Voronoi morphology here, the most common form of the design should be considered when setting up the initial parameter values. The qualitative classification of the object (the substrate) configuration can reveal information about the internal processes of the design concept. To assign the model, which is the Voronoi growth model, this project used biological morphology methods to create a parametric substrate inspired by the behaviour and morphogenesis of coral colonies. Voronoi polygons were used to feed the information of coral envelopes to this substrate assembly. Furthermore, the genetic algorithm was applied as the morphological algorithm to optimize this substrate.

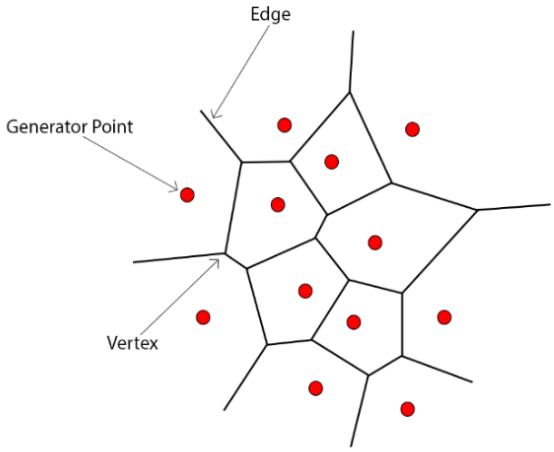

Fig. 2. Voronoi diagram.

As given in Fig. 2, a Voronoi polygon contains the Voronoi boundary within a closed set. A Voronoi polygon's boundary can be made up of line segments, half-lines, or infinite lines and are called Voronoi edges. Noting that a Voronoi edge can be also defined as a line segment, a half line, or an infinite line shared by two Voronoi polygons with their endpoints. As the next component, a Voronoi vertex is the endpoint of a Voronoi edge and can be defined as a point shared by three or more Voronoi polygons.

The initial design based on the Voronoi diagram generation process of the substrate is illustrated in Fig. 3. Corals, as colonial modular organisms, were formed from groups of asexually produced, genetically identical modules ('polyps' or 'zooids') that are interrelated to generate an integrated super-organism. Modules were connected via tissue during the design phase, allowing for intra-colony communication and resource sharing. Different colony topologies can be created by coordinating module growth, as explained in the following sections.

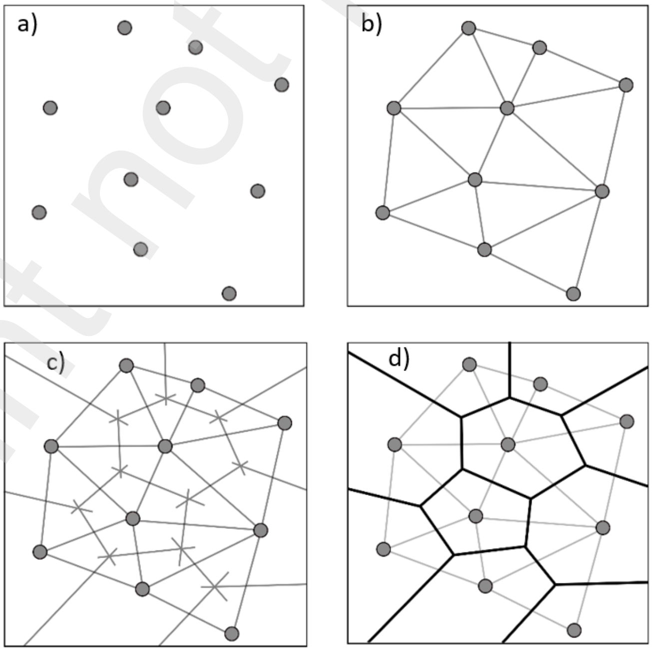

Fig. 3. The Voronoi diagram generation process; a) Seed distribution within the design domain (Adaptive node definition); b) Delaunay triangulation; c) Bisector line identification; d) Voronoi tessellation (2D polygons meshing).

Because of the mechanical properties of the Voronoi patterns which are primarily influenced by their geometrical properties, it is necessary to delve deeper into the process of generating the Voronoi tessellation and its dual, the Delaunay triangulation, to fully comprehend this dependence. The Voronoi pattern was made up of a spatial region that is discretized by convex polygons and fills the domain without overlapping. As shown in Fig. 3. The construction process commenced with the definition of a set of points (also known as seeds, sites, or generators) within the generic design domain.

As a result, each point was connected to the closest adjacent points without overlapping; this is known as Delaunay triangulation (Fig. 3b). To locate the centres of Delaunay triangles, the midpoints on each segment were marked and the bisector lines were drawn (Fig. 3c). The edges of the Voronoi regions were represented by the lines formed by the union of these orthogonal segments and highlighted as Voronoi tessellation in Fig. 3d). The result is a collection of the polygonal cells that form the Voronoi diagram.

2.1.1.2. Genetic Algorithm

The objective pursued with the implementation of the genetic algorithm is to find an optimized Voronoi diagram in substrate design considering the following attributes: population size, envelopes dimension, extrusion, and distribution of envelopes in the substrate. To that end, the genetic algorithm should be able to adequately explore the search domain in the beginning phases, considering the environment's constraints and avoiding premature convergence. In the final phases, the genetic algorithm can use the knowledge gained during the search process to achieve a result that is as close to optimal as possible.

The architecture of a genetic algorithm, as a type of evolutionary algorithm, is depicted in Fig. 4. As demonstrated, the process begins with the generation, usually at random, of an initial population, the size of which represents only a small fraction of the total number of potential solutions.

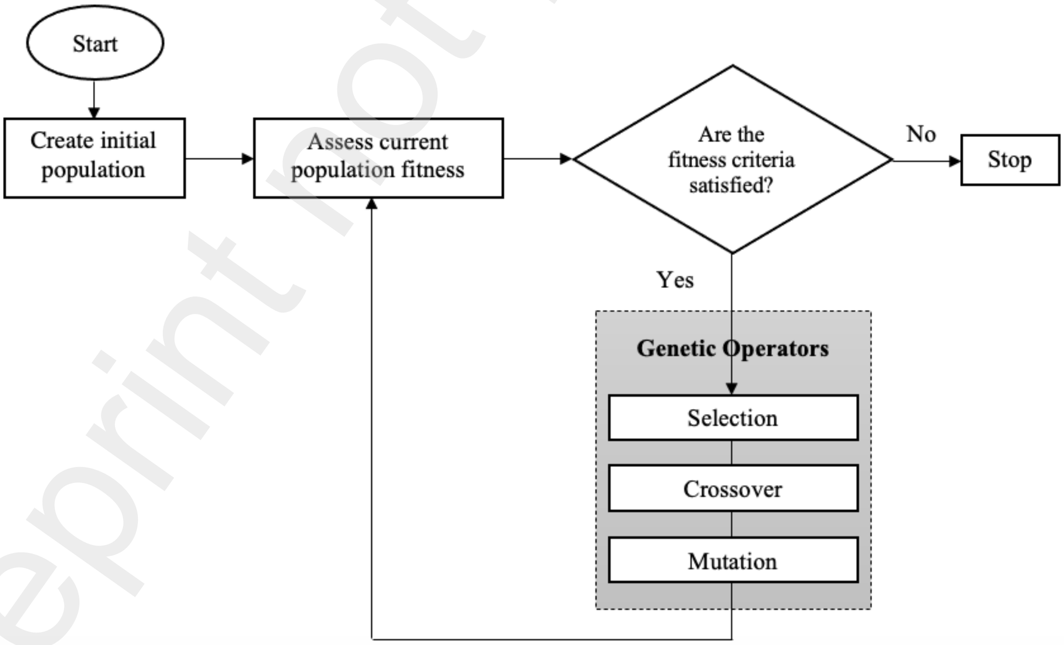

Fig. 4. Genetic algorithm architecture.

Each member of the population represents a possible solution to the problem under consideration. When searching for a solution(s), a genetic algorithm samples as many points in the search space as there are individual members of the population at each step (assuming no two members are identical). This is one of a genetic algorithm's strengths, allowing it can sample widely throughout the search space and identify areas of high performance (i.e., good solutions) on which the search can begin to converge. The use of a population allows for the identification of multiple high-performing areas and aids the genetic algorithm in avoiding convergence on local optima. Once the initial population is established, the genetic algorithm's basic process would be to adapt and change the individual members of the population based on feedback on how good a solution each member in the population is, until one or more proper solutions are found.

The fitness function oversees determining how well each member of the population performs. The other processes are shown in Fig. 4 and then take over the adaptation and modification, and there is an iterative procedure, represented by the loop, that continues until some condition is satisfied. There is a population of solutions, which is like Darwinian evolution. These solutions are subjected to an environment (the fitness function) that favours the reproduction of solutions that are best suited to that environment. As a result, solutions that are appropriate for the defined environment are developed over several iterations (called generations).

2.1.2. Establishing the exploration substrate

This section illustrates the minimum and maximum bounds of the substrate design to be explored, mostly to avoid wasting computational resources on infeasible portions of the design. Thus, the starting substrate design has been determined based on the approximate geometric boundaries of possible design outputs. As a hypothetical case study, a façade with 15 meters of width and 30 meters of height, was modelled with a maximum of 100 coral envelopes. The main façade is glazed, and the design constraints of research are set to prevent blocking the glazed façade from solar radiation.

As illustrated in Figure 5, the thickness of the substrate on the façade varies due to neighbouring structures and the building's orientation. The amount and direction of solar radiation received by various areas of the façade are heavily influenced by building orientation. Depending on the direction of the building, certain places may be subjected to more strong sunlight, while others may be subjected to more shadowing. Variations in solar exposure and shading patterns can alter substrate growth and development, resulting in thickness disparities across the façade. For example, places that receive more direct sunlight may have more robust substrate growth, whereas shadowed areas may have weaker substrate layers. When implementing this concept, it is critical to consider building orientation since it provides a better understanding of how solar radiation interacts with the façade and affects the growth dynamics of the substrate. Designers can optimise the distribution of cyanobacteria or other biomimetic features to achieve desired aesthetic, performance, and environmental objectives across the entire façade by analysing the impact of building orientation on substrate thickness.

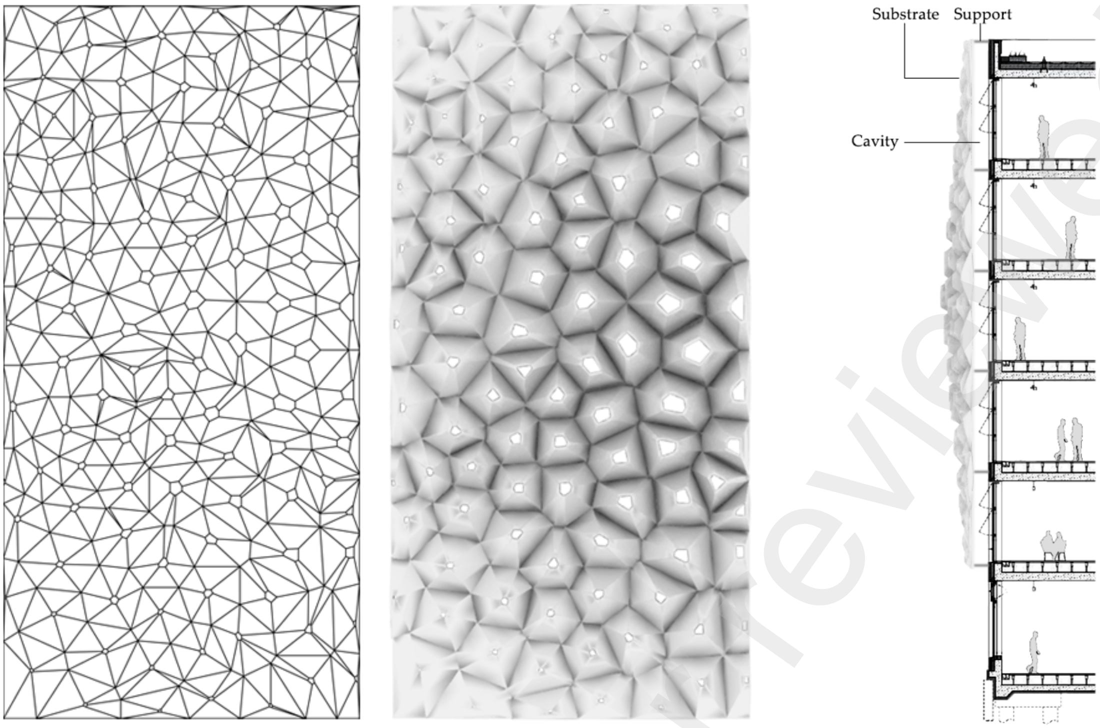

Fig. 5. Right view of the substrate indicates a section of the modelled double skin on the building façade and demonstrates the varied thickness of the biomimicry substrate throughout the building façade and the left view depicts the optimized arrangement of the envelopes in the substrate.

After determining the conceptual case study, location, orientation, and design parameters, plant species that will be used in the green façade concept should be investigated. In this concept, as mentioned so far, Cyanobacteria as a plant species is proposed Fig. 6 demonstrates the substrate functions of the coral envelope containing Cyanobacteria. As can be seen, in this process there are inputs (solar radiation, carbon dioxide, nutrients, H_2O) and outputs (oxygen, biofuels, biofertilizers, nutrition, bioremediation, and medicine) which inputs will be processed in each envelope that contains Cyanobacteria.

Cyanobacteria known as blue-green algae is one of the potentially useful resources for environmental issues that require a sustainable solution from nature. They have a simple genome and require simple ingredients to grow (Paerl & Paul, 2012; Sukenik et al., 2012). Cyanobacteria have several distinct characteristics that have prompted researchers and scientists to consider their potential industrial application on a global scale, such as they can produce molecular oxygen as a by-product of oxygenic photosynthesis, which is discussed in this article. They are famed for being the first oxygenic photosynthetic microorganisms on Earth, and they have contributed to the production of oxygen in the Earth's atmosphere over the past 3 billion years (Rasmussen et al., 2008). Cyanobacteria have been found to produce a wide range of bioactive compounds. As can be seen in Fig. 6, cyanobacteria's remarkable growth rate allows for its potential use in a variety of applications in bio-energy, biotechnology, natural products, medicine, agriculture, and the environment simply by absorbing solar radiation, CO_2, H_2O, and nutrients (Zahra et al., 2020). Inputs to the cyanobacteria envelope include solar radiation, carbon dioxide, nutrients, and water (H_2O). The envelope processes these inputs, and as outputs, it generates oxygen, biofuels, biofertilizers, nutrition, bioremediation agents, and even certain medicines.

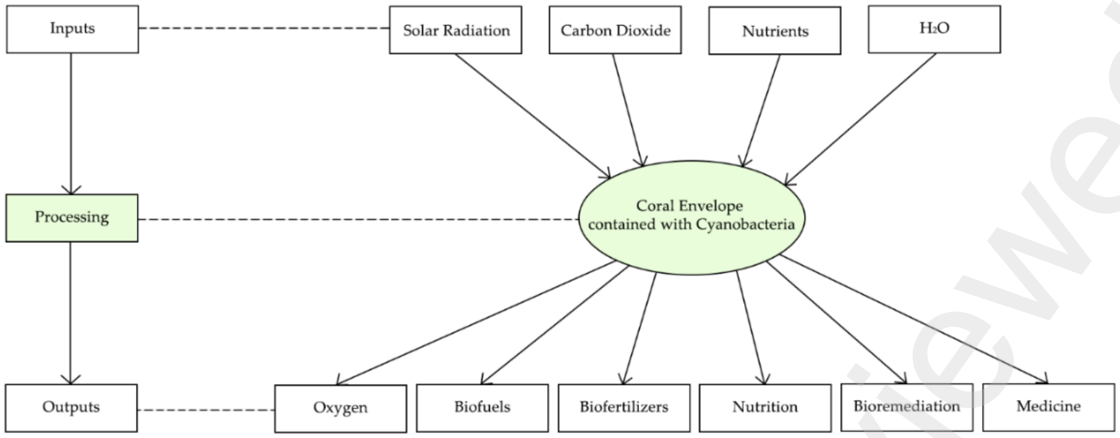

Fig. 6. The potential of substrate coral envelopes containing cyanobacteria.

As highlighted in Figure 5, the building orientation plays a crucial role in determining the performance of green facades, particularly in the context of double-skin facades (Bagheri Moghaddam et al., 2020). In this scenario, the hypothetical facade is oriented towards the south, and the analysis focuses on evaluating the impact of solar radiation on the parametric substrate. For examining the performance of the proposed biomimicry facade, this research selected a semi-arid climate context which is Denver, Colorado, with the sky conditions in the Summer and Winter seasons from the 21st of July to the 21st of September (cooling period) and the 21st of December to the 21st of March (heating period) are indicated in Fig. 7. a and b respectively. These data were applied by Ladybug (Fig. 8) which is a plug-in tool in the Rhino that allows designers to visualize and analyse weather data and imports standard EnergyPlus Weather files (.EPW) into Grasshopper and provides a range of 2D and 3D designer-friendly interactive graphics to aid decision-making during the design process.

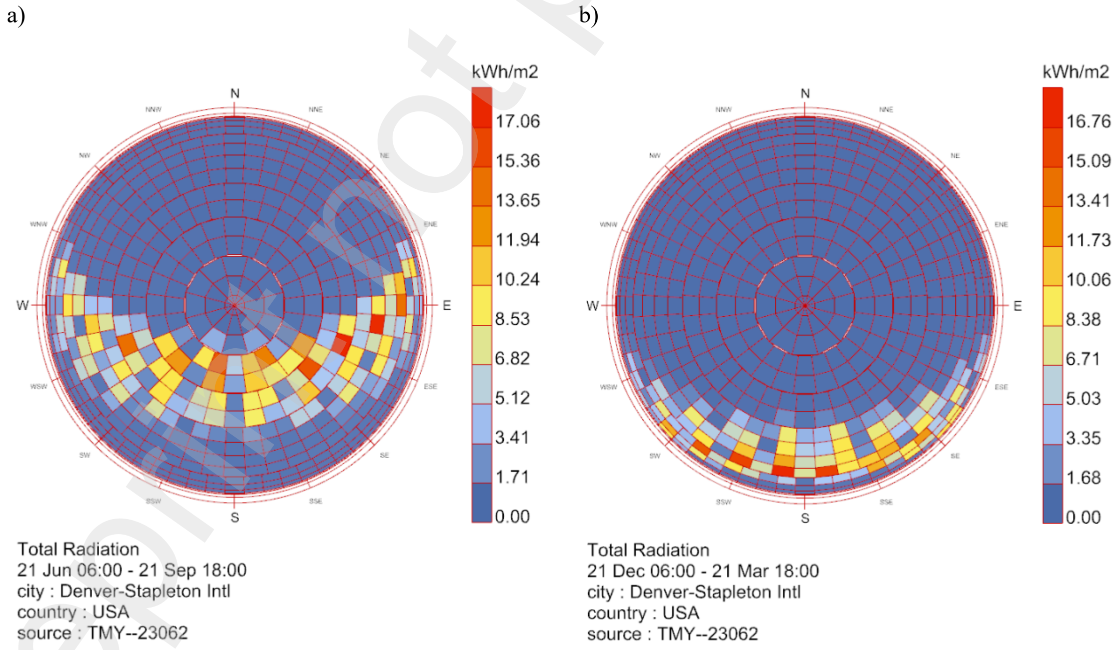

Fig. 7. a) Sky condition of Denver from the 21st of June to the 21st of September and **b)** from the 21st of December to the 21st of March.

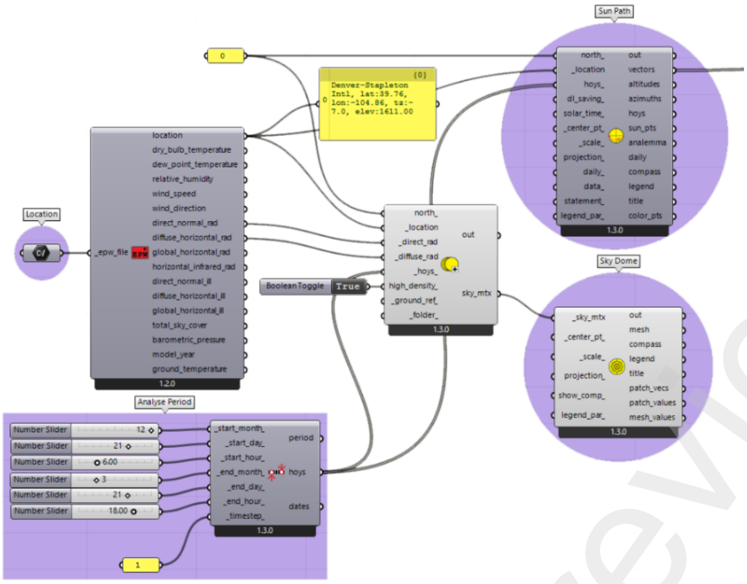

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Fig. 8. Utilizing algorithm with Ladybug component in Grasshopper to simulate the climate of Denver.

2.1.3. Generating Design Variants

The process of generating variety refers to the way how the distinctiveness of the biomimicry substrate embodiment can be created. Its primary focus is on biomimetic substrate structures. This type of variety fulfilment is linked to each differentiation enabler. According to Ulrich's (Ulrich, 1995) definition, there are three basic variety generation mechanisms: i) attaching/removing, ii) swapping, and iii) scaling. Even though attaching/removing, swapping, and scaling are fundamental mechanisms of variety generation, more complex mechanisms can be constituted by recursively employing these fundamental methods. This is known as variety nesting, and it was used in this generating substrate design. While attaching/removing, swapping, and scaling is only applicable to a particular component at a specific decomposition level, nesting can include multiple components at different hierarchical levels (Du et al., 2001).

From an ecological perspective, it has been proposed that the two primary variables driving coral colonies' resilience are coral colonies (the parametric substrate) framework and their capacity, both of which can be quantified using 3D topographic structure measures (Burns et al., 2015; Fisher et al., 2007). Simultaneously, with the optimization of the substrate by the evolutionary genetic algorithm engine Galapagos which is demonstrated in Fig. 9 and 10, fabrication analysis and topology validation can help to qualify for the final geometry.

Since the biomimicry substrate as a green façade structure is a prototype for assessment, the design variables are controlled by mathematical sliders that automatically change the properties of the model geometry in terms of the number of seeds and count envelope population by modifying the value of the corresponding design element, as shown in Fig. 9. The first algorithm has been designed and developed to implement parametric substrate dimensions on the surface of the glazed façade. This is achieved by analysing the behaviour and morphology of coral colonies, which are influenced by the parametric substrate model for all components. This process enables the designer to iterate the model based on the intention of the space by simply adjusting the value of any sliders. This process is completed by an evolutionary solver, which employs genetic fitness to eliminate undesirable characteristics and select genes that have evolved toward genetic success as seen in Fig. 10. The fitness function in Grasshopper is a computer method or script that is used to evaluate design ideas based on particular criteria and objectives. Energy performance, structural stability, aesthetics, cost, and other important design goals can all be taken into account. Each solution is given a fitness value, which indicates its overall adequacy. These fitness ratings are used by Grasshopper's genetic algorithm to steer the evolutionary process. Solutions with higher fitness values are more likely to be chosen for reproduction. Then, genetic operations such as crossover and mutation are used to develop new offspring solutions. The method tries to improve the entire population via successive generations by repeatedly analysing and refining design options based on their fitness scores.

The efficient reduction of genetically modified variables is a distinguishing feature of this optimization. According to all possible topologic and parametric variations, and restricting the persistent parameters of the substrate, 100 designs were automatically generated that have been optimized by using Galapagos, 7 optimized designs of biomimicry substrate which are shown in Fig. 11.

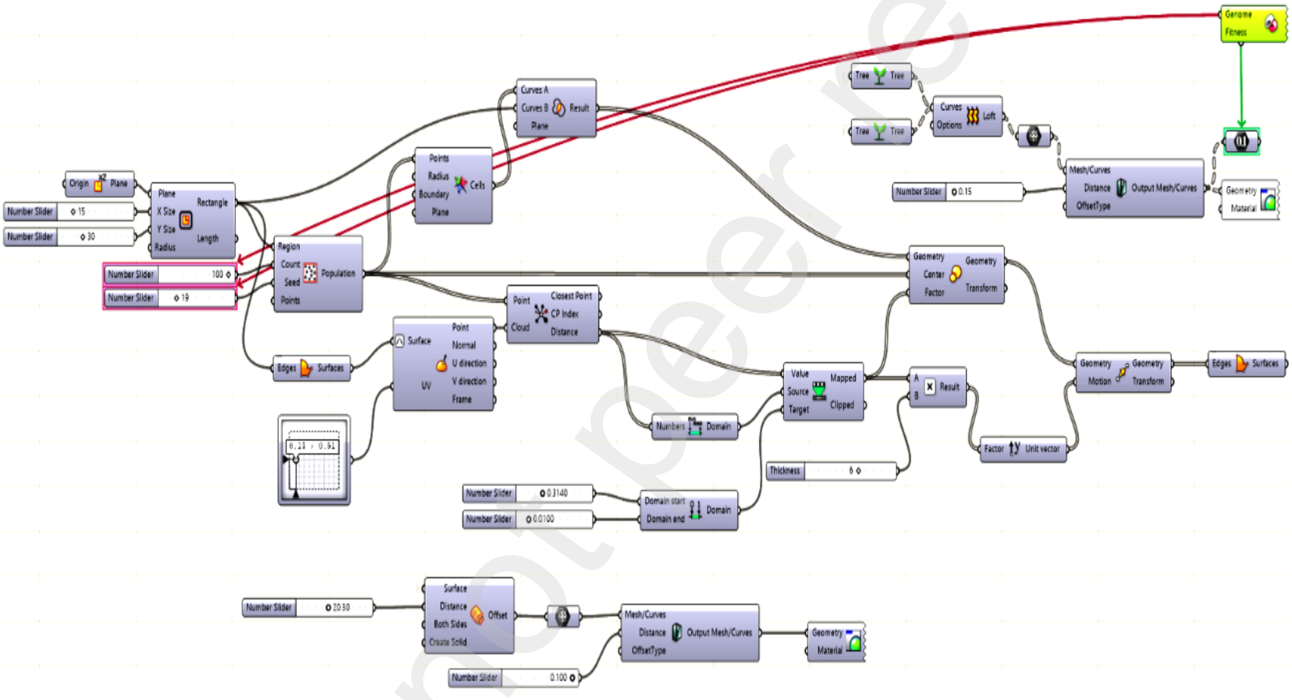


Fig. 9. The generative algorithm utilized in the biomimicry substrate design.

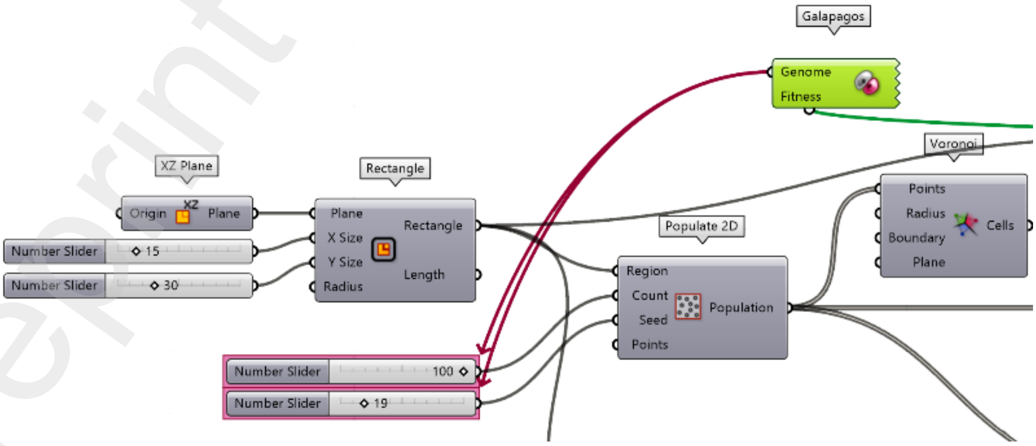
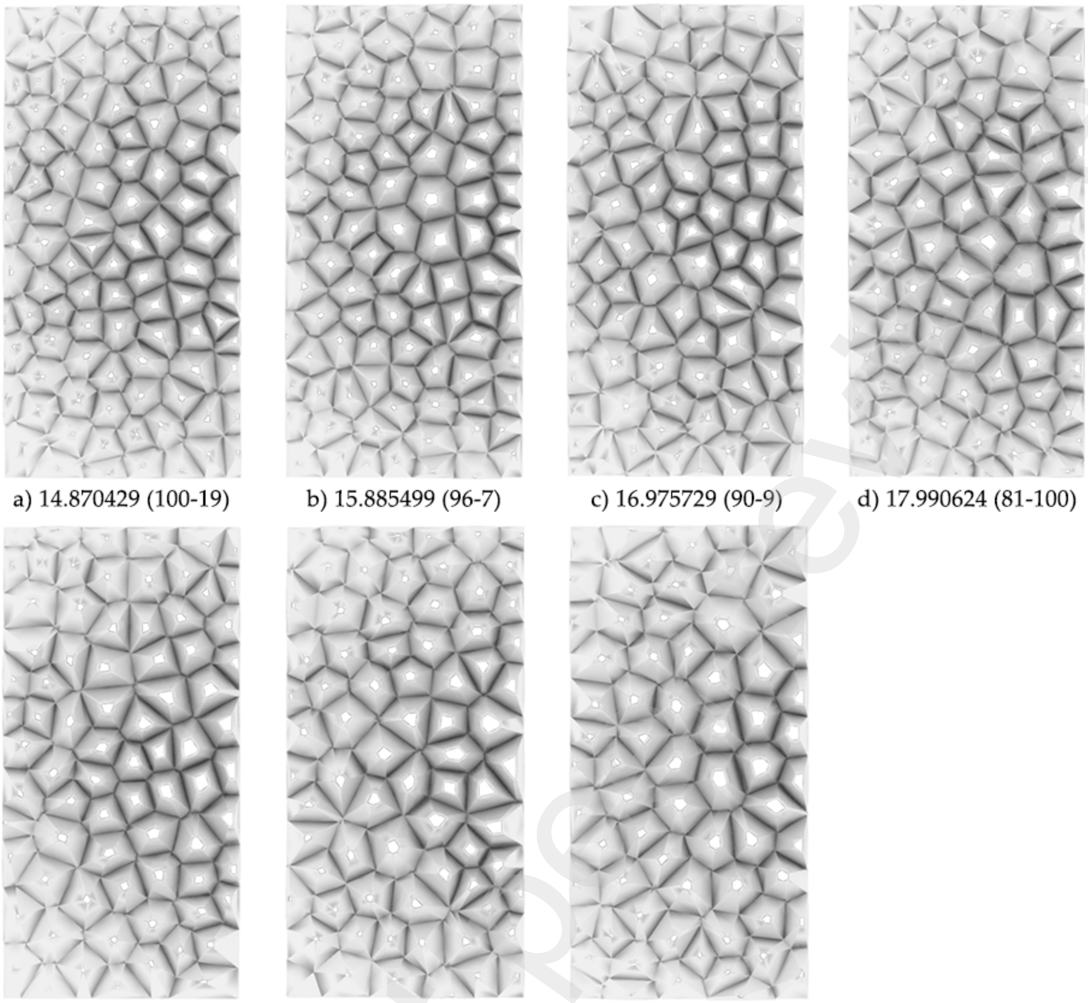


Fig. 10. Genome parameters and the fitness function procedure.



a) 14.870429 (100-19) b) 15.885499 (96-7) c) 16.975729 (90-9) d) 17.990624 (81-100)

e) 18.86471 (77-84) f) 19.879582 (73-76) g) 20.047238 (69-39)

Fig. 11. The results of optimization by Galapagos as a genetic algorithm solver, which this figure shows just 7 selected models between 100 models that were optimized (the first number is the fitness value (sorted from fittest to least fit), the second number shows the number of individual coral envelopes, and the third number depicts the number of seeds in the populated 2D component in the grasshopper).

2.1.4. *Filtering phenotypes*[*]

This stage is for developing accurate design constraints, provided with the most important parameter of light and oxygen for the used bio-agents, so the parametric substrate should get access to fresh air and light. It was mentioned in the previous section (Fig. 6) that each coral envelope in the substrate should be filled with hydrogel and cyanobacteria, resulting in CO_2 absorption and oxygen production. Therefore, each coral envelope was incorporated with a small open space that could meet the outside ambient. Fig. 12 shows how these holes can be incorporated into the substrate design.

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[*] The set of observable characteristics of an individual resulting from the interaction of its genotype with the environment.

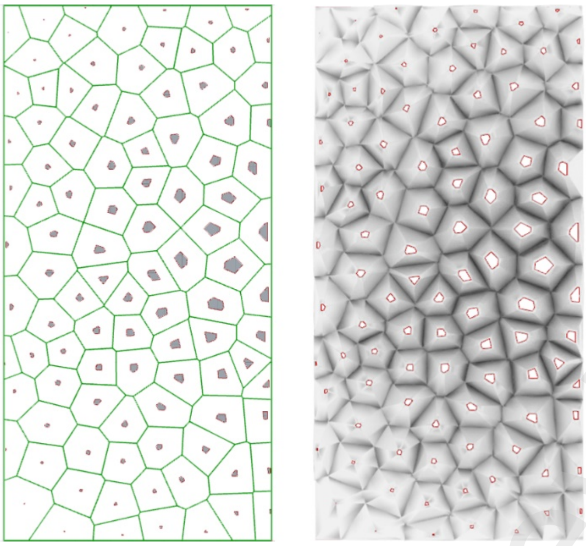

Fig. 12. Incorporating a small open space (hole) for each coral envelope in the design stage.

2.1.5. Selecting and fine-tuning

As previously stated, generative design is a design process that employs artificial intelligence to generate outputs based on the constraints which in this article are explained in detail in the exploration substrate section. This allows designers to select, fine-tune and test their designs before finalizing or printing them. This section developed generative algorithms for integrating parametric design into a green façade substrate, and the prototype findings demonstrate great performance.

By generating design variants, considering all possible topologic and parametric variations, and constraint parameters of the substrate, 100 designs were automatically generated and optimized using Galapagos, a plugin in Grasshopper to apply genetic solver function and optimize the biomimicry substrate. Accordingly, 7 optimized designs of biomimicry substrates were achieved, demonstrated in Fig. 9. Out of these resultant designs, the biomimicry substrate design (a) has been chosen given its fitness value which was minimized between all optimized models.

2.2. Implementing Cyanobacteria into Generative Double Skin Façade

To implement the cyanobacteria double-skin façade, this research proposes the use of a bio-gel to keep the cyanobacteria alive. The bio-gel provides a suitable environment for the cyanobacteria to grow and perform their function of absorbing CO_2 and producing oxygen (Fig. 13). The use of bio-gel also helps to regulate the temperature and humidity around the cyanobacteria, ensuring that they are in an ideal environment to thrive.

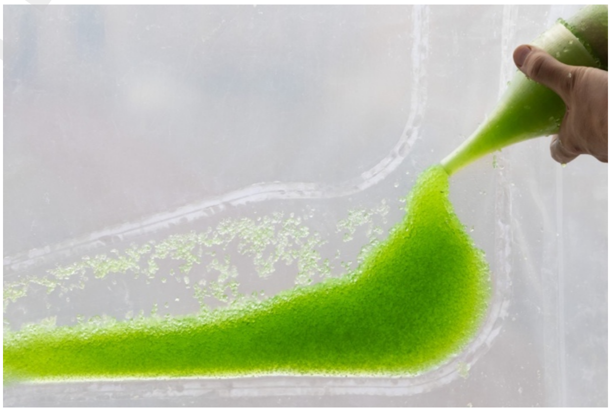

Fig. 13. This figure shows the use of bio-gel as a substrate for the cultivation and maintenance of algae (cyanobacteria) in the PhotoSynthetica Curtains (Pasquero & Poletto, 2020) (https://www.photosynthetica.co.uk/cladding).

Bio-gel is a type of hydrogel that is made of natural polymers, such as agar, alginate, and carrageenan. It is commonly used in biotechnology and biomedical applications. Bio-gel has a three-dimensional network structure that can absorb and retain large amounts of water and nutrients, providing a suitable environment for the growth and survival of microorganisms such as cyanobacteria.

In the generative double-skin façade, the bio-gel can be applied to the outer layer, creating a layer that houses the cyanobacteria (Fig. 14). The generative and parametric design can be employed to create a unique and visually appealing façade while still providing an environment-friendly solution. The bio-gel layer can be incorporated into the design in various ways, such as different patterns or shapes, to create a unique and aesthetically pleasing look.

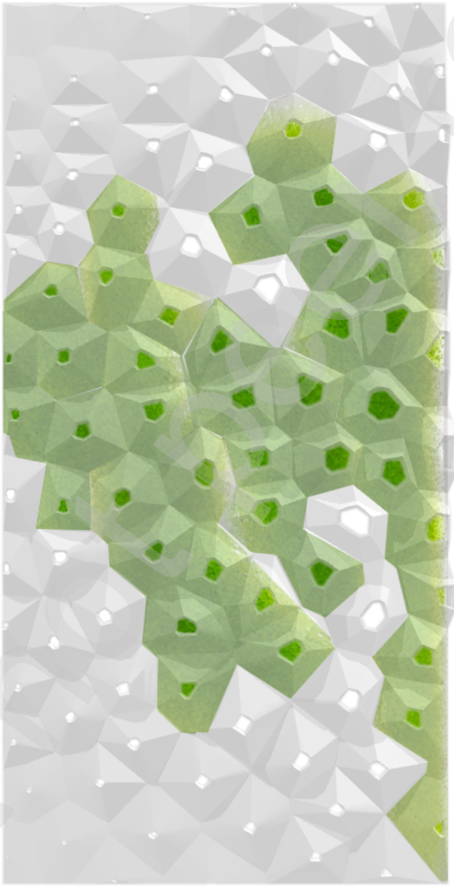

Fig. 14. The conceptual model of generative double skin façade that cyanobacteria embedded in each coral envelope.

3. Discussion

The current discourse on green façades considers them as adaptive façades, and this article has proposed the use of parametric and generative biomimicry substrates in the structure of green façades and implementing cyanobacteria as a kind of plant on this substrate. However, the existing typologies and technological innovations require support during the design stage to fully realize their potential. Among the reviewed studies and design approaches, the integration of thermal and visual features is the most commonly utilized physical domain. Successful green façades implement responses at a fundamental level to ensure access to the outside scenery while improving visual comfort and energy efficiency.

Based on the findings, adaptive facades can be categorized into conventional and non-conventional types in which the non-conventional category includes parametric and generative biomimetic substrates, which are highlighted as part of the research (Tabadkani et al., 2021). Biomimetic skins, such as the biomimicry green façade, are typically actuated by smart materials that are limited to predefined boundary conditions or adaptive materials that are only adjustable due to inherent material properties. As a result, they can exhibit instinctive behaviour without direct user engagement and have the potential to control the indoor and outdoor environment through building envelope protection. The use of algorithmic and parametric tools such as Grasshopper and its environmental plugins has heightened awareness of the capabilities of parametric and generative designs, simulation tools, and algorithmic methodologies. These improvements have enabled designers to create non-traditional systems, such as generative biomimicry green facades. These technologies have enabled designers to investigate novel design options and simulate their performance, resulting in the development of unique and ecologically friendly facade systems.

This research highlights the potential of parametric and generative biomimicry substrates in green façade configurations for indoor and outdoor environmental control. Daylight and thermal aspects were the primary focus of the biomimicry substrate design, but other performance criteria such as CO_2 capture and oxygen production were also considered. However, the transformation of the two-dimensional substrate design into a three-dimensional shape can be challenging, affecting both the façade aesthetics and performance. To address this, the study employed parametric and generative methods combined with the genetic algorithm, specifically the built-in Galapagos algorithm, which is fast and robust in adapting to changing environments and can optimize green façade designs.

The study aimed to use evolutionary solvers like Galapagos in Grasshopper to generate and parameterize iterations and find an optimized solution for the new generation of green façades. Ultimately, the bio-façade produced through this approach could function as a high-performance green façade, creating an optimal structure of coral envelopes by finding the optimal number and shape of the envelopes and maintaining cyanobacteria through generative and parametric façades.

According to this research, a biomimicry green facade with cyanobacteria on the building's outside can improve visual comfort by adding a visually appealing and dynamic element to the building's exterior. The cyanobacteria's brilliant green colour can produce a visually pleasing aesthetic, potentially boosting the entire experience and happiness of tenants and pedestrians. Cyanobacteria in the facade can help with thermal comfort by acting as a natural shade and insulation system. During hot weather, the facade can help limit solar heat gain, offering passive cooling benefits to the building. This can aid in the regulation of indoor temperatures, the creation of a more comfortable environment, and the potential reduction of the demand for mechanical cooling systems. Green biomimicry facades with cyanobacteria can improve daylight performance. The cyanobacteria layer in the façade can filter and dilute incoming natural light, resulting in a softer, more evenly distributed light environment within the building. This can reduce glare and produce a more comfortable visual environment, allowing you to make better use of natural light and potentially lessen your need for artificial lighting.

Implementing a biomimicry green facade with cyanobacteria can improve Indoor Environmental Quality (IEQ). By consuming carbon dioxide and releasing oxygen through photosynthesis, cyanobacteria can help improve air quality. This natural process can help to create a healthier and more oxygen-rich indoor environment. Furthermore, the presence of vegetation in the facade might have psychological benefits, such as fostering a connection with nature and improving occupant well-being. It should be noted that the specific performance of a biomimicry green facade containing cyanobacteria would vary based on aspects such as design, maintenance, and local climate conditions. To maximise the visual and thermal comfort, daylight performance, and IEQ benefits given by such a facade system, proper design considerations and frequent maintenance are critical.

A biomimicry green facade's energy performance can be influenced by a variety of factors. Shade and solar heat gain are examples, as are natural ventilation, insulation and temperature regulation, and energy generation. The biomimicry facade, which incorporates cyanobacteria, provides shading to the building's outside, minimising direct solar heat gain and potentially lowering the energy required for cooling systems. Furthermore, the design of biomimicry facades can incorporate natural ventilation solutions, such as using cyanobacteria and other features to increase airflow and improve energy efficiency by lowering dependency on artificial ventilation. Furthermore, the biomimicry facade acts as an extra layer of insulation, enhancing the thermal performance of the building envelope and lowering heat transfer, resulting in lower energy usage for heating and cooling. Furthermore, as photosynthetic creatures, cyanobacteria have the ability to generate energy through photosynthesis. Specially constructed devices can capture and utilise this energy for a variety of applications, including power generation and biofuel manufacturing. This energy generation potential contributes to the biomimicry facade's overall energy performance.

4. Conclusion

The introduction of the concept of biomimicry green façades presents a promising solution for enhancing indoor and outdoor environmental quality and living conditions. The design process should incorporate the analysis of available alternatives and the selection of the most efficient geometry of the generative biomimicry substrate. The use of 3D models and computational design systems, such as the performance-driven generative system and the associative biomimicry geometry system, has shown promising results in exploring alternative optimized designs. Integrating advanced design concepts, such as parametric and generative biomimicry design, into the green façade structure can lead to feasible, cost-effective, and automatically generated workflows for producing substrates such as double skin façades and the new concept of the green façade substrate.

Implementing cyanobacteria on facades as a form of bio-facade technology presents a few limitations. Scaling up cyanobacterial bio-facades to cover larger surfaces or entire buildings can be difficult. Providing uniform and efficient coverage across the facade might be difficult while maintaining stable growth conditions over a vast area. Another constraint is related to durability and lifetime. Cyanobacteria's long-term durability and stability as a facade material are still being studied. Factors such as weather resistance, structural integrity, and lifespan must be considered to ensure the bio-facade system's longevity. Furthermore, environmental limits present difficulties. Cyanobacteria require precise environmental parameters such as adequate light intensity, temperature, and humidity levels to thrive. It can be difficult to keep these conditions consistent on building facades, especially in different climates or metropolitan contexts. These restrictions must be addressed in order to efficiently install and use cyanobacteria as a bio-facade technology in real applications. More study and development are required to overcome these obstacles and maximise the potential of this novel technique in different weather contexts.

However, selecting an appropriate approach for a generative biomimicry substrate at the early stages of design depends on several factors, including the building type, indoor environmental requirements, structural issues at large scales, maintenance, and operational costs, and the role of the occupant in controlling the building's performance. While the article extensively addresses the visual comfort and energy performance of the biomimicry green façade, simulation-based methodologies are required to evaluate the thermal comfort for different climates and geographical contexts. The lack of a control strategy for predicting long-term energy performance and user comfort in the early phases of design remains a significant limitation of the reviewed simulation workflows for biomimicry substrates, which requires further research.

In conclusion, evolving new design approaches toward new concepts of green façades present an innovative solution in comparison to traditional green façades for improving indoor and outdoor environmental quality and living conditions. The concept of biomimicry green façade by using a generative, parametric substrate as a double-skin facade can open up new opportunities for research in the field of generative biomimicry design. It also can enable the exploration of more sophisticated methods to incorporate nature-inspired elements into green facades.

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