Biophilic Architecture:
Sustainable Materialization of Microalgae Facades

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Contents

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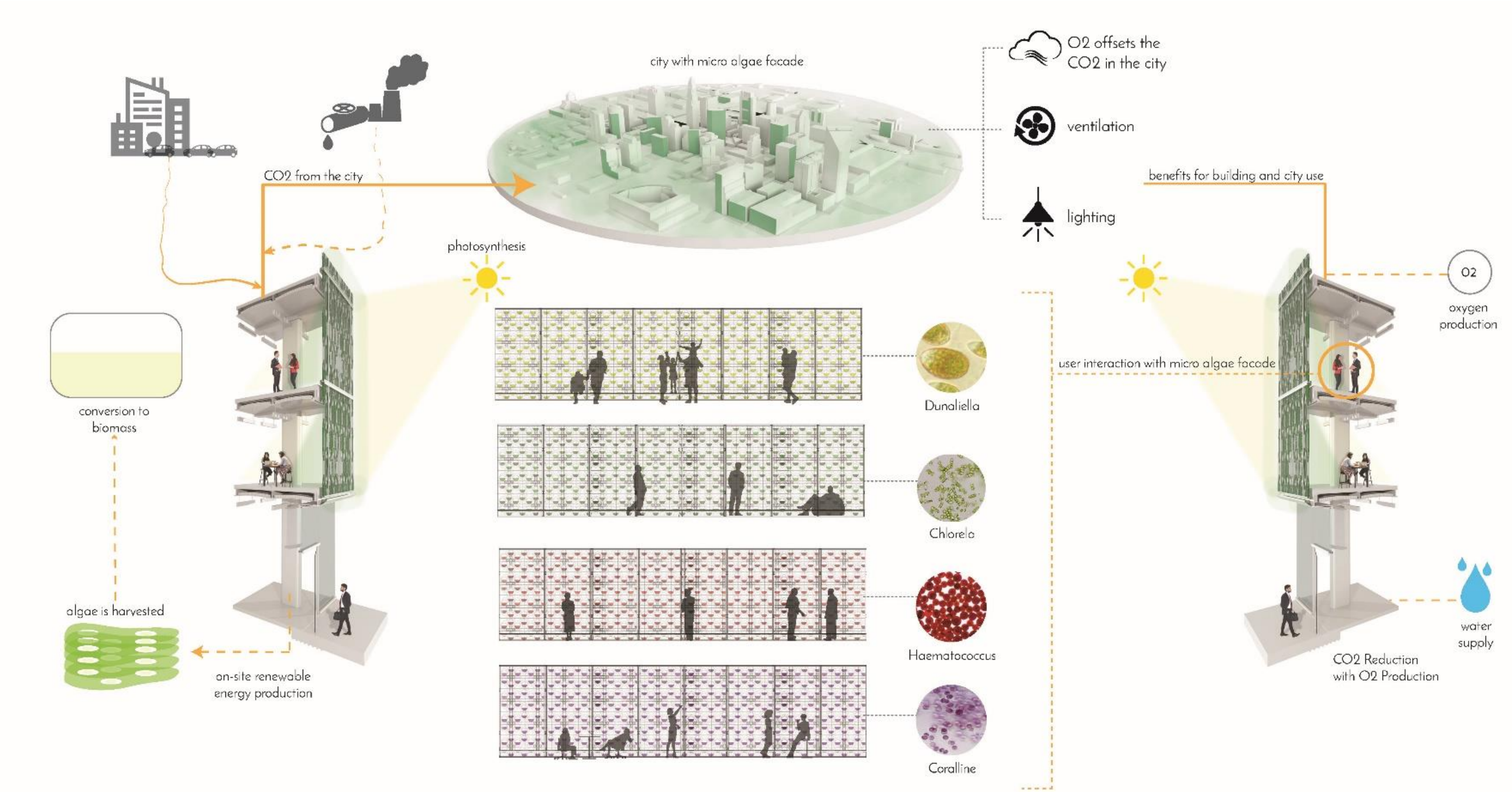

Figure 1 Closed-loop microalgae architecture and green cities: the microalgae façade is a closed-loop social-ecological system that provides energy efficiency, good air quality, and daylighting during building operation while incorporating a high level of user interaction, leading to user satisfaction with greater cognitive performance and well-being.

I=PAT Design Imperatives

The I=PAT framework, put forward in the 1970s, is an analytical tool for identifying the forces driving environmental impacts. It assumes that environmental impact (I) is affected by population (P), affluence level (A), and technology (T) [1].

According to I=PAT framework, Environmental impact is expected to rise substantially due to growing population, affordability, and technological advancement. For example, the world's urban population has grown rapidly from 746 million in 1950 to 3.9 billion in 2014 with 54 percent of the world's population living in urban areas [2]. It is expected that additional 2.5 billion people will reside in cities by 2050, totaling over six billion of urban populations [2].

As a result of fast growing cities, we have been faced numerous challenges in meeting the needs of their growing urban dwellers, including housing, infrastructure, transportation, energy, and employment. These demands led to the increase in environmental issues in cities such as air pollutions, water shortage, heat island effect, and increased energy consumption.

One way to reduce environmental impact of I=PAT equation is to incorporate nature in the built environment as a carbon sink, phytoremediation, and renewable energy potentials.

$$I = PAT / N$$

I: environmental impact
P: population
A: affluence level
T: technology
N: Nature

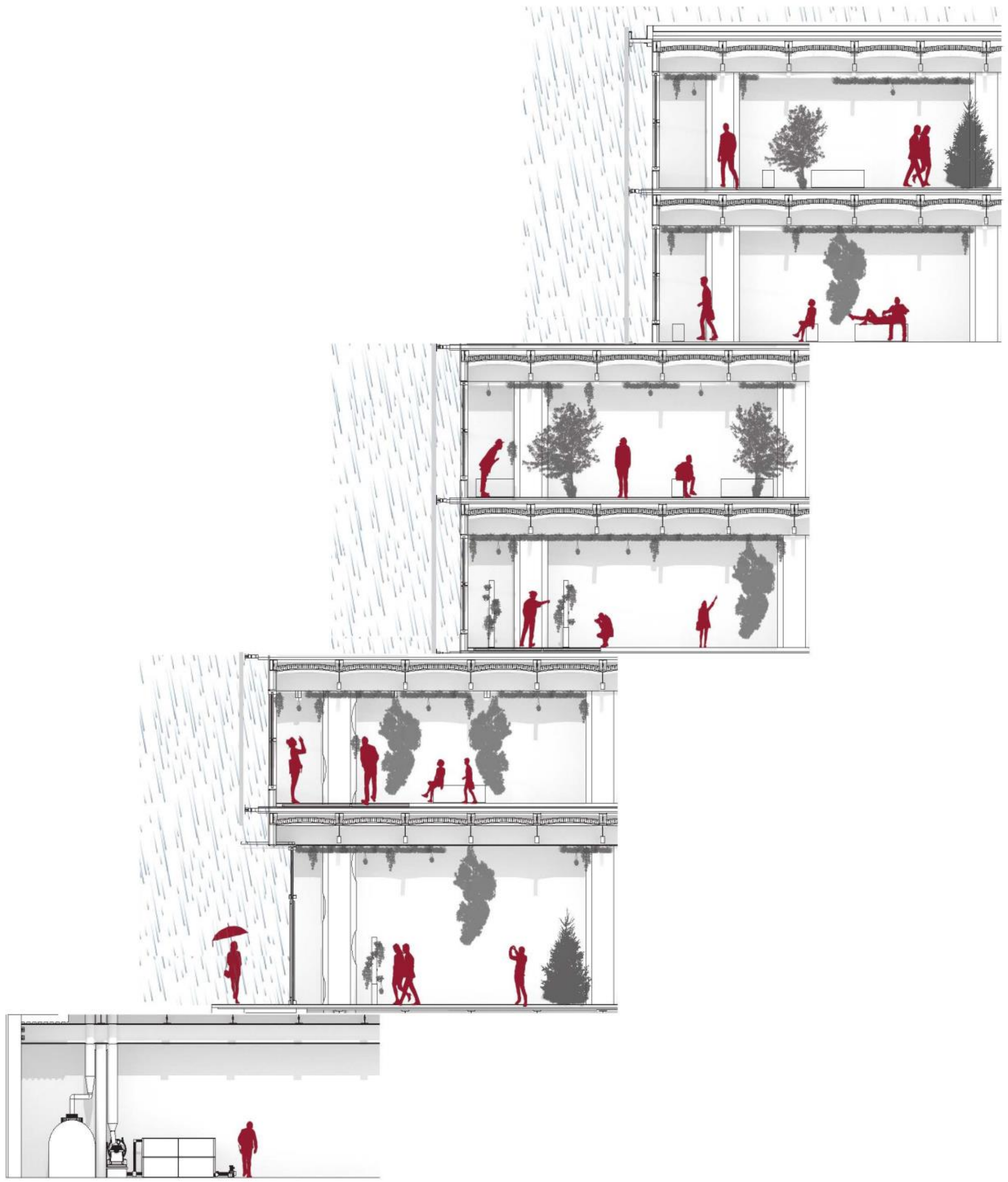

Figure 2 Biophilic Architecture promotes physiological & psychological health and well-being through dialectic relationship between built and natural environments.

Why Microalgae?

Microalgae, unicellular organism, refers to aquatic microscopic plants that is widely growing in biosphere. It is oxygenic photosynthetic bacteria, and uses light energy to convert water and CO2 into biomass. Since microalgae was promoted as protein resource in the 1950s, industrial scale of production of microalgae reached the production level of thousands of tons per year since 2000s [3]. Over the past few decades, microalgae have been cultivated for various uses in agricultural, aquacultural, pharmaceutical, and food industries due to its fast growth rate and a wide array of biodiversity growing in an extensive range of habitats. Microalgae is known to offer ecological sustainability by improving water quality, air quality, and soil quality while encouraging biodiversity and minimizing greenhouse gas emissions.

Scientific data indicate that microalgae produces 60% of the oxygen on Earth while using up CO2 [4]. Another use of microalgae has attracted an attention to bioremediation of soil pollution. Research suggest that microalgae can fixate pesticides, heavy metals, and toxic pollutants in soil. Furthermore, it serves socioeconomic sustainability by offering social well-being (e.g. employment, food security), energy security, and resource conservation [4]. Its potential to generate biofuel can reduce our dependence on non-renewable resources and offer ecological and economic benefits. Currently the algae biofuel industry is growing with remarkable investment from government and private companies.

Microalgae Architecture as Carbon Sink and Renewable Energy System

Recently, microalgae integrated building systems have also drawn the attention of architects and designers in the field of net zero architecture due to its potential and effective role in enhancing building energy efficiency, renewable energy production, and good air quality. Bibliographic analysis reveals that microalgae integrated building systems occurred as niche experimentation in early 2000's and are incrementally active and fast growing area into research and practice.

One theoretical promise of the microalgae integrated architecture is possible symbiotic nature between microalgae and the built environment. In a symbiotic system, different microorganisms live together by benefiting each other and develop a synergetic relationship. In microalgae architecture, photosynthetic microalgae is grown within building systems, and the bio-catalysis outputs of microalgae benefit the building and occupants by providing O2, good environmental quality, and on-site renewable energy production. In return, microalgae uses CO2, wastewater, and contaminants from soil produced by buildings and inhabitants and maximizes biomass growth.

This symbiotic microalgae and architectural process result in CO2 fixation, wastewater treatment, contaminant reduction, and biomass production for various end uses (e.g. food and feedstock to cosmetics, pharmaceutical and biofuels).

Figure 3 Microalgae curtainwall serves as a primary building skin while promoting biophilic built environment

Microalgae Architecture as Biophilia

The lack of direct interaction with nature is one of the main characteristics of urbanized cities. Contact with nature in the built environment improves human performance and well-being, but many working environments lack our link with the constructs of natural systems [5]. Scientific data confirm that the biophilic design defined by inherent affinity of human to nature has a strong correlation to workplace performance and human well-being [6]. It is expected that Microalgae integrated built environment could provide a great potential to promote physical and psychological health while providing environmental, economic, and social benefits.

The microalgae architecture as biophilic strategy faces design challenges: 1) objectify biophilic design strategies for user satisfaction in working environments, 2) integrate natural elements with building systems through aesthetics and complex order of functionality, and 3) measure workplace productivity in relationship to biophilic design strategies (e.g. connection to nature, integration of nature, geometrical features, daylight efficacy, shading efficacy, and Indoor air quality).

BIQ House
Hamburg, Germany

The BIQ building located in Hamburg, Germany, is the first microalgae powered building in the world. Designed by Splitterwerk architects and Arup engineering, the BIQ is a 4 story high building with 15 apartments and a penthouse in a site area of 839m2.

The microalgae facade consists of the photobioreactors (PBRs) which are embedded in a steel frame and flat panel glass. The total number of PBR's are 129 and cover 200 m2 of the southeast and southwest façade for maximum sun exposure.
Each PBR is sized at 70cm x 270cm X 8cm which are filled with microalgae and 24 litres of nutrient rich water in 18mm thick cavity.

The biomass produced within the RBR panels is supplied to another location for biogas extraction for heating heating purpose and to create heat energy for generating domestic hot water. These operations are controlled by a centralized building management system (BMS), which forms a closed loop for energy generation and reuse. The annual electricity production is approximately 4500 kWh with 6 tons per year CO2 reduction.
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Figure 4 Bio Intelligent Quotient (BIQ) multi-story housing building in Hamburg, Germany; Image source: (Author, 2019)

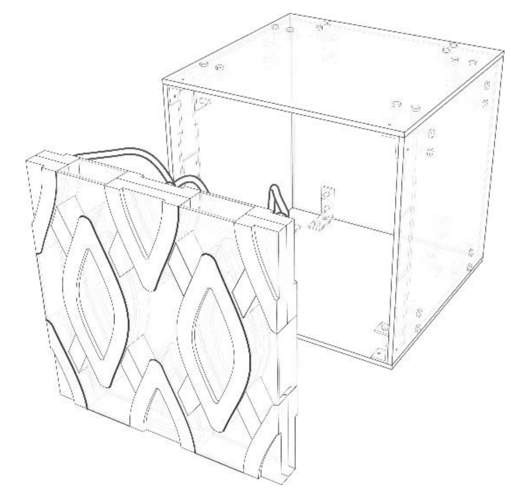
Microalgae Facades:
Five Typologies

Divided Microalgae Facade
Inflated Microalgae Facade
Stranded Microalgae Facade
Suspended Microalgae Facade
Woven Microalgae Facade

This section discusses five design typologies of microalgae façades synthesized with building science and biotechnical performance requirements discussed in the previous section. Development of each typology involves determination of the geometrical and material properties of key components of photobioreactor and primary building enclosures.

Materiality being considered includes plate, extrusion, tubing, and membrane based on its potential to a cost effective and integrated microalgae façade assembly. These inherent material characteristics improve structural integrity, constructability, and pragmatism that can further support symbiotic relationship between built environment, occupants, and nature (biodiversity). A series of parametric façade geometries have been developed under each façade typology in the following sections, accounting for materiality, fabricability, aesthetics, and operating conditions as an integrated photobioreactor façade system.

Divided Microalgae Facade



Typology 1. Divided: The *Divided* microalgae façade system utilizes plate-glazing materials and divide a microalgae façade system with a photobioreactor area and a vision area.
The vision area is a visually unobstructed and leftover area after photobioreactors are populated within the Divided microalgae façade system. The vision area allows viewing, daylighting, energy conservation while photobioreactor is configured to encourage microalgae growth. The photobioreactor contains a wet cavity containing micro algae cultures. Its top and bottom are connected with microalgae-growing apparatus. The microalgae-growing apparatus consists of distribution pipes and mechanical system. The distribution pipes distribute air, water, nutrients, and cultures between photobioreactor and mechanical systems. Mechanical systems consist of pumps, storage tanks, and biofuel prep system.

① *divided photobioreactor*
② *double glazed unit*
③ *vertical mullions*
④ *horizontal transoms with growing apparatus*

Divided Microalgae Facades©

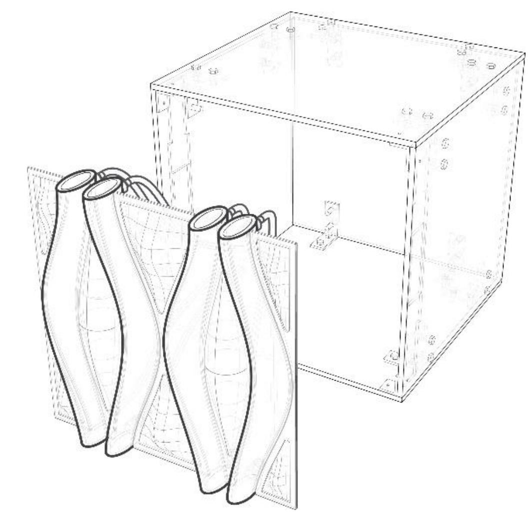
Inflated Microalgae Facade

Typology 2. Inflated: The *Inflated* microalgae façade system integrates ETFE micro- photobioreactor on the surface of ETFE pillows, providing a primary enclosure with good structural, thermal and solar performance as well as energy production potentials and CO2 sequestration. The integration of ETFE micro-photobioreactor within the ETFE pillow is further able to attenuate noise from rain droplets. The ETFE micro-photobioreactor consists of a wet cavity containing microalgae cultures, and the microalgae-growing apparatus is attached at the top and bottom of ETFE photobioreactor. The view-out could be achieved with the ETFE photobioreactor filled with air cavity without cultures.
Similar to the Divided system, the microalgae-growing apparatus consists of distribution and the mechanical systems. The distribution systems consists of distribution pipes, valves, and sensors, and distribute air, water, nutrients, and cultures between the photobioreactor and the mechanical systems. The mechanical systems consist of pumps, storage tanks, and a biofuel prep system.

① *inflated photobioreactor*
② *ETFE vision infills*
③ *x-bracing mullions*
④ *horizontal transoms with growing apparatus*

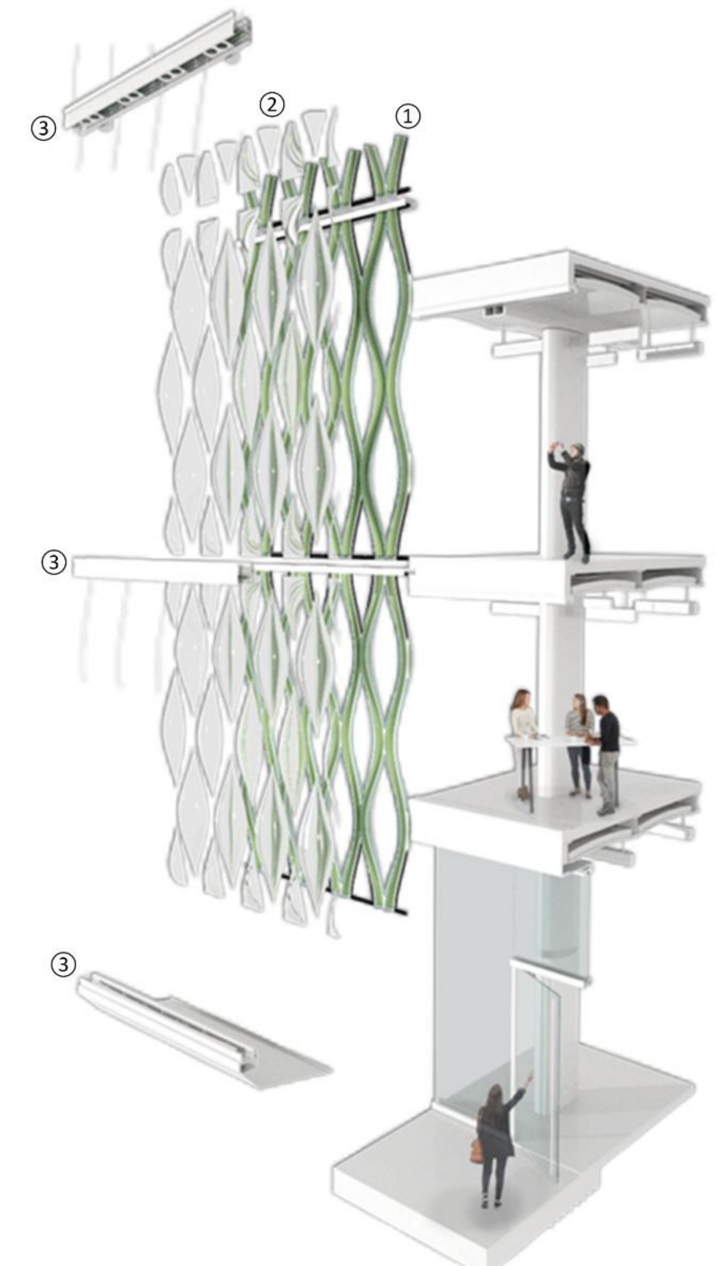
Inflated Microalgae Facades©

Stranded Microalgae Facade



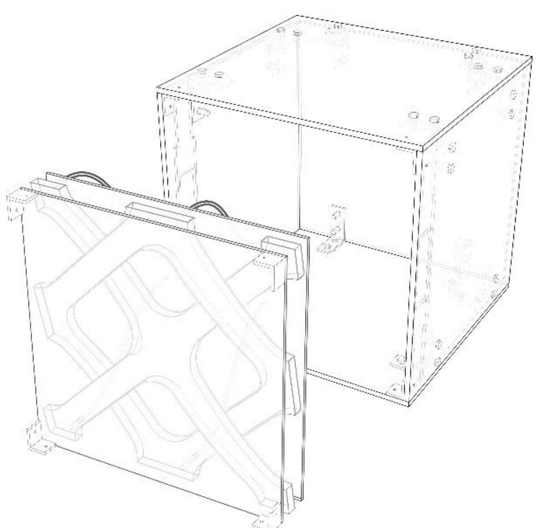
Typology 3. Stranded: The Stranded microalgae façade system consist of bioplastic extrusions as a photobioreactor and a vision panel. Bioplastic extrusions are deformed 3 dimensionally to enhance structural stiffness & integrity, biotechnological performance, and aesthetics. The extrusion further serves as a façade framing system and support a infill glazing system. The infill glazing system can made of ETFE pillow or glazing plate depending on aesthetic preference. They are designed to provide view-out, daylight transmittance, waterproofing, airtightness, thermal insulation, and natural ventilation when necessary. Similarly to other typologies, the microalgae growing devices of the Stranded façade system are located at the top and bottom of the extrusion and linked to valves, pumps, and storage system in a mechanical room.

① *stranded photobioreactor*
② *ETFE vision infills*
③ *horizontal transoms with growing apparatus*

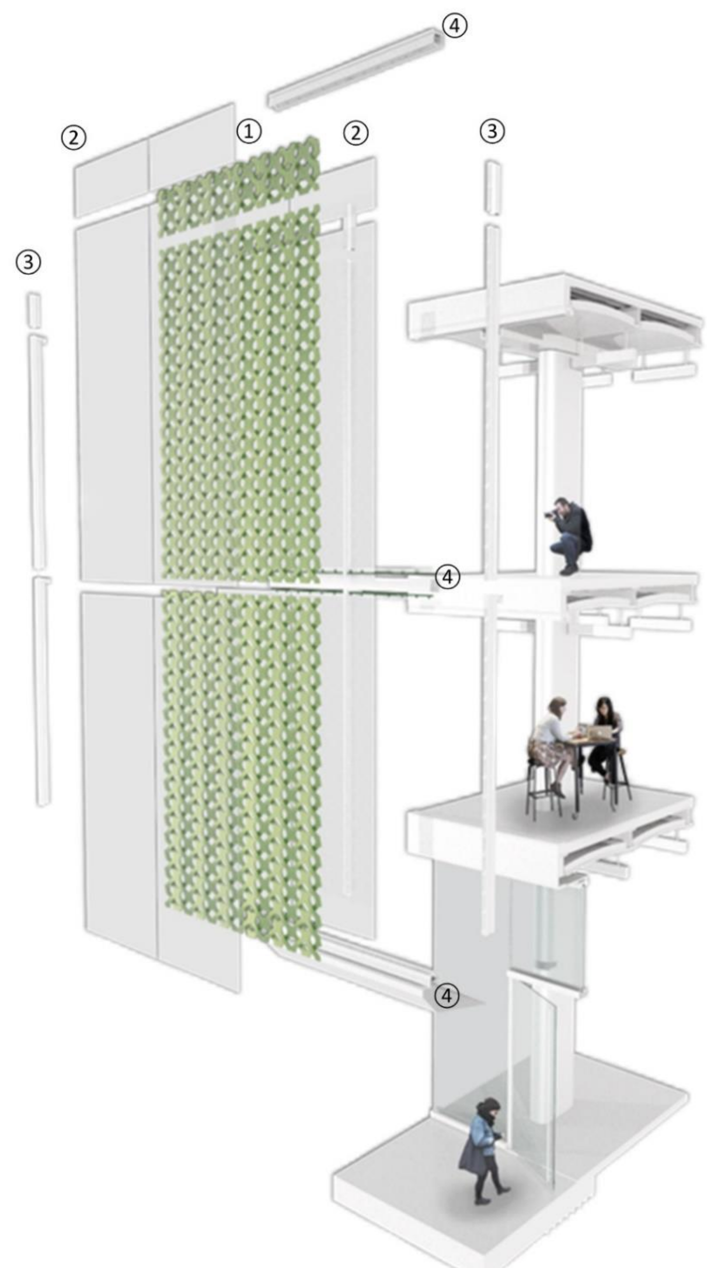


Stranded Microalgae Facades©

Suspended Microalgae Facade



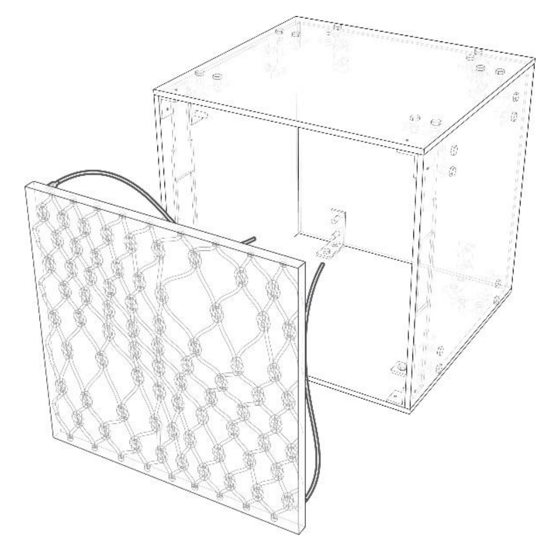
① *suspended photobioreactor*
② *double glazed unit*
③ *vertical mullions*
④ *horizontal transoms with growing apparatus*



Suspended Microalgae Facades©

Typology 4. Suspended The *Suspended* microalgae system is composed of micro photobioreactor hung within the air cavity of an insulated glass unit. The suspended micro photobioreactor could be configured in various designs with different materials and typologies. They could be screen types and louver/fin types, resulting in the regulation of energy transfer between indoor and outdoor while balancing daylighting, view-out, and solar radiations and encouraging microalgae growth and CO2 reductions. The Suspended photobioreactor in this report is made of continuous and plaited 3D tubes, where a nutrient-rich microalgae culture is contained. The microalgae-growing apparatus is attached to the top and bottom of the microalgae system. The distribution systems are connected between the microalgae system and mechanical system, and made of pipes, valves, and sensors. The mechanical systems consist of pumps, storage tanks, and a biofuel preparatory system.

Woven Microalgae Facade



① *woven photobioreactor*
② *double glazed unit*
③ *vertical mullions*
④ *horizontal transoms with growing apparatus*

Woven Microalgae Facades©

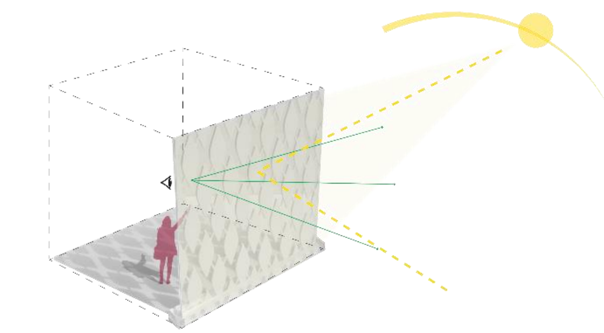
Typology 5. Woven: Additional driver of the woven typology is its ability to provide a continuous watertight microalgae culture container while the density of wefts and warps is adjusted to balance the solar exposure for maximum microalgae growth, access to view-out and daylighting potentials while regulating thermal and visual environments. The woven photobioreactors is made of continuous flexible tubing while woven knots provide the geometric stability of tubing as a photobioreactor. The woven photobioreactor can be hung at the air cavity of a double pane glazing system or be casted with resin as a glazing layer. The small diameter of tubing and its flexibility guarantee even solar exposure for microalgae growth. The microalgae growing devices are connected to both ends of photobioreactor tubing.

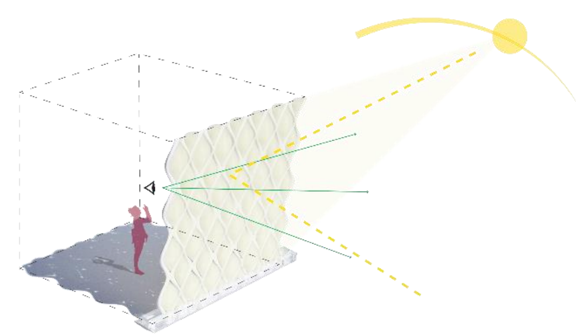
Preliminary Proof of Concept: Prototyping

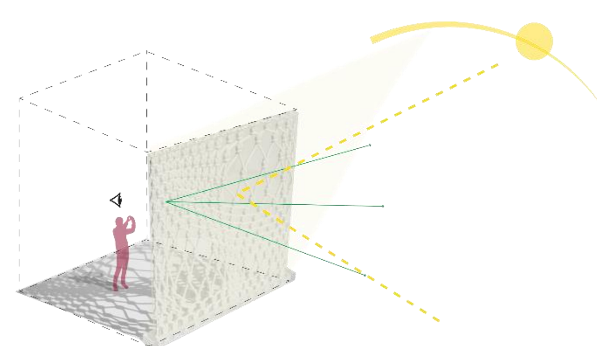
The objective of prototyping is to check the system integrity and proper performance of the microalgae façade system after assembled and installed on building enclosures. The microalgae façade assembly resists environmental loading and external and internal impacts, and be durable under dynamic outdoor environments. A further challenge is to establish material compatibility and jointing methods between the photobioreactor microalgae façade system and the glazing system. The microalgae façade system is a preassembled unitized façade system that serves as a primary building enclosure with additional benefits such as better occupant response, good indoor air quality/CO2 sequestration, and biofuel production.

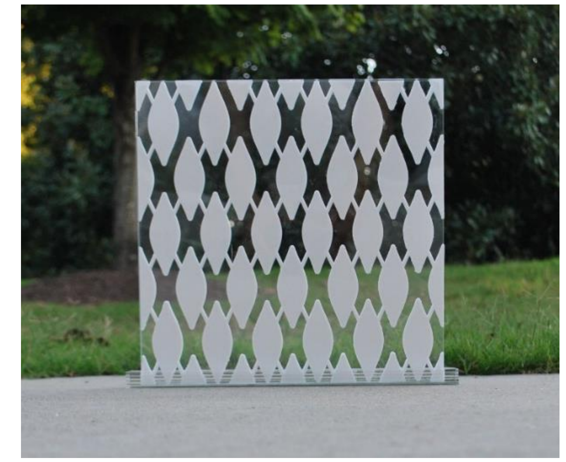
Specific design strategies of microalgae facades should be employed depending on building massing and site location, façade orientation, building program needs (view, daylight, solar gain, ventilation etc). While the prior microalgae façade utilizes domestic water and additional nutrients and aeration to cultivate microalgae strains, it is intent to establish additional design strategies to use rainwater and urban wastewaters for the microalgae biomass and lipid yield for biofuel production.

The microalgae façade system is supported by metal frames typically extruded aluminums on four edges, which are thermally broken to prevent cold bridging and condensation during winter time. The aluminum extrusion incorporate cavity to run algae growing hose lines as well as stiffening nibs, screw races and pockets to receive gaskets to provide watertightness. Furthermore, the photobioreactor of the microalgae façade offers heat storage capacity and adaptable utilization of solar energy across a day and seasons (low SHGC in summer and high SGHC in winter).



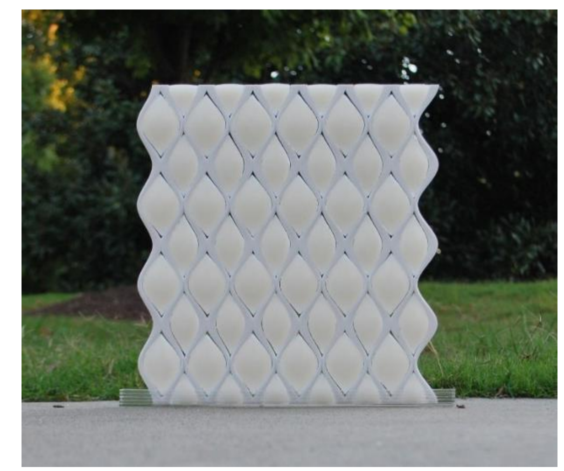






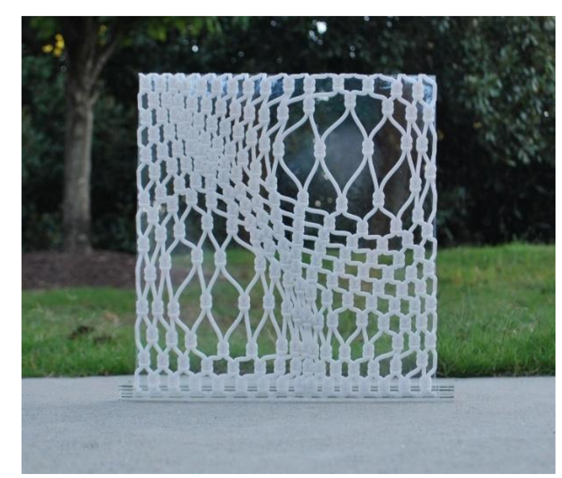
Divided microalgae façade

Inflated microalgae façade



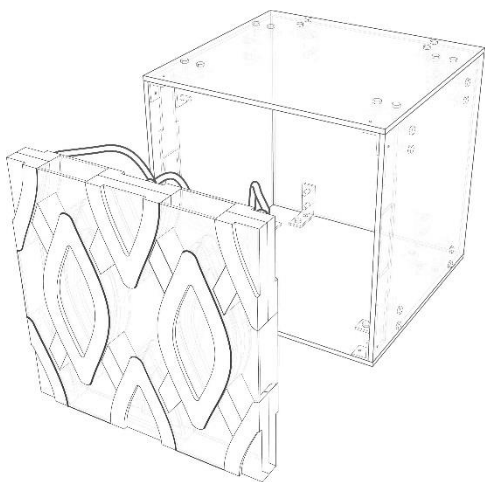
Stranded microalgae façade

Suspended microalgae façade



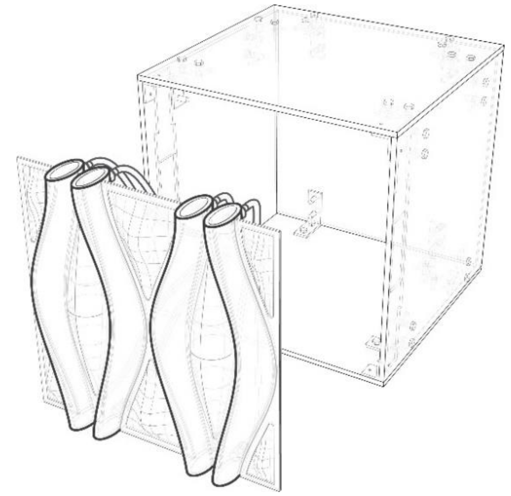
Woven microalgae façade

Figure 5 Concept design of five microalgae façade systems

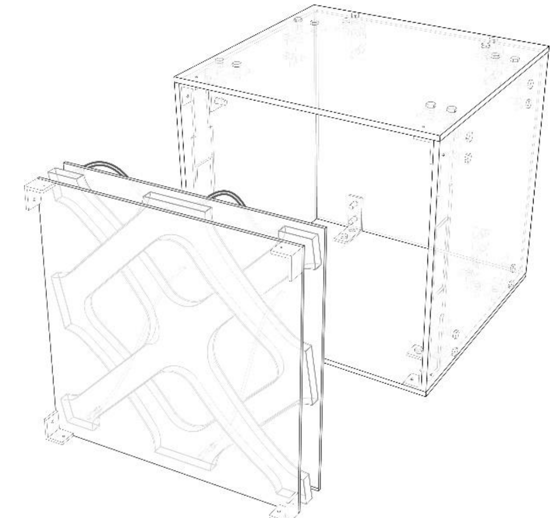


Divided microalgae façade

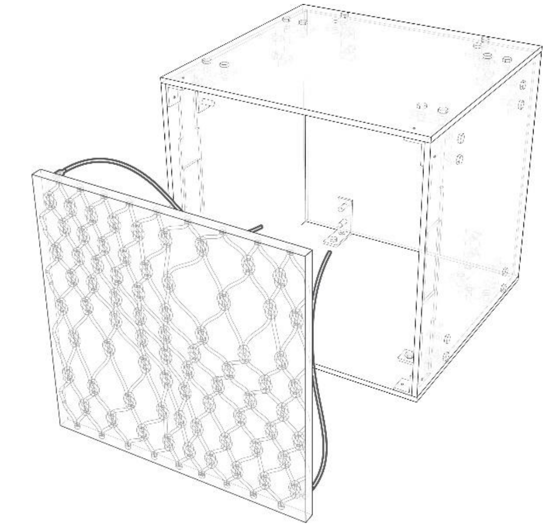
Inflated microalgae façade



Stranded microalgae façade



Suspended microalgae façade



Woven micoalgae façade

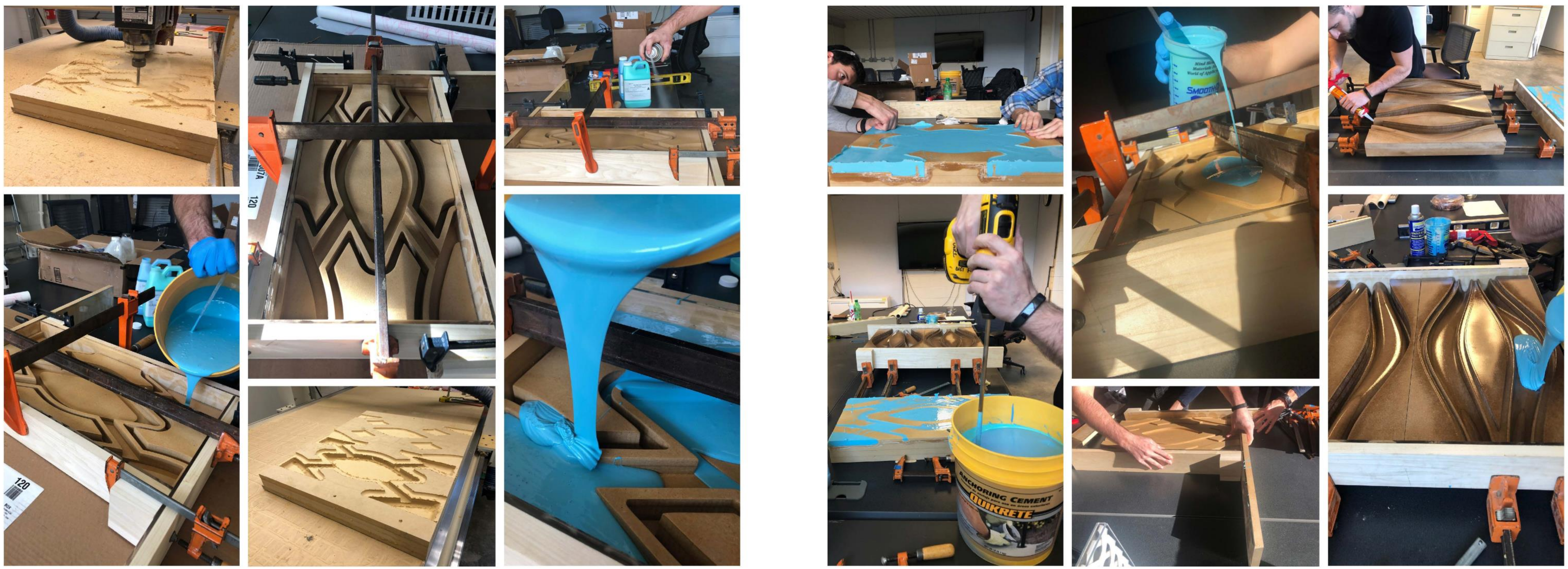


Figure 6 2x2 prototyping process

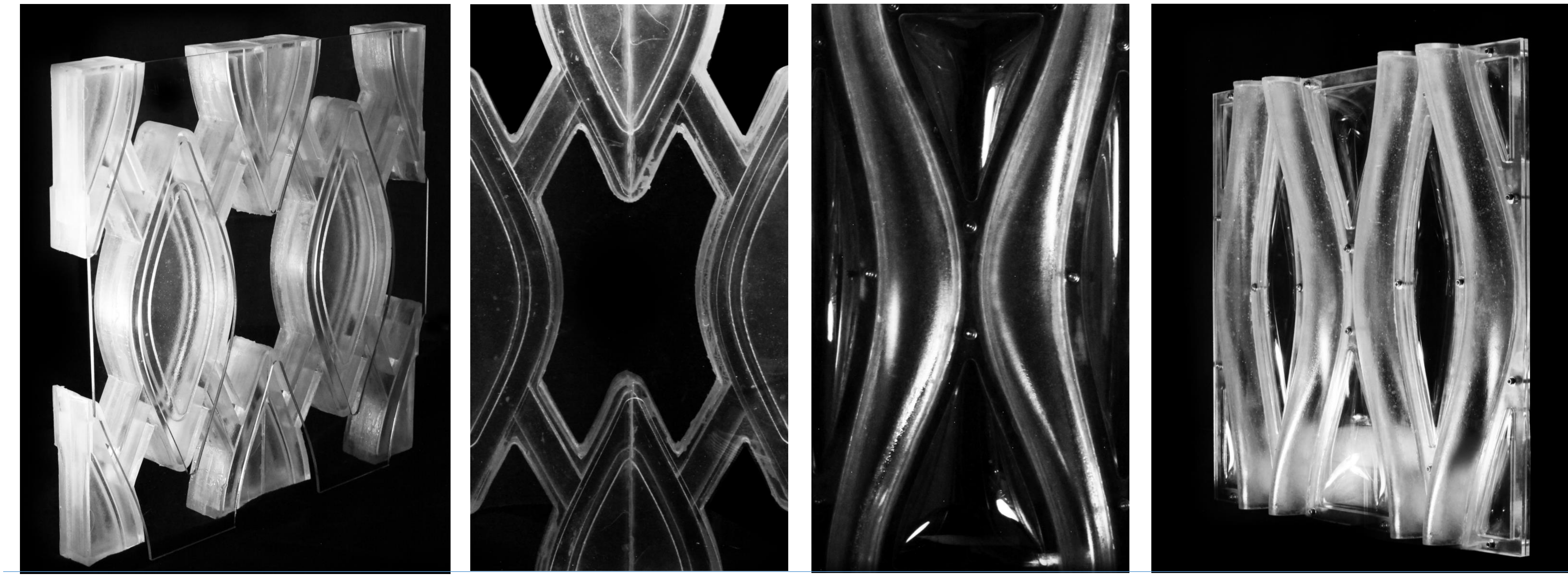


Figure 7 2x2 prototyping for preliminary visual and performance evals; *Divided* microalgae façade (left) and *Stranded* microalgae façade (right)

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Endnote: