Biologically Informed Design - Towards Additive Biofabrication with Cyanobacteria

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Abstract. As sustainability awareness is increasing within architecture, we witness the emergence of new design approaches seeking to minimize greenhouse gas (GHG) emissions and production of waste. Biodesign addresses such challenges by integrating living organisms within processes of design and manufacturing harnessing their natural performances. This paper aims to outline design principles integrating a living organism, cyanobacteria, in an additive co-fabrication process by utilizing its three main performances: photosynthesis, calcium carbonate precipitation ($CaCO_3$) and carbon dioxide (CO_2) fixation. Cyanobacteria, through photosynthesis, precipitate $CaCO_3$ which enhances the adhesion between cells and surfaces. Through microbially induced $CaCO_3$ (MICP), cyanobacteria can bind sand particles together and enhance soil stability as seen in the formation of biological soil crusts. With the rise of additive manufacturing (AM) techniques, integrating cyanobacteria within additive biofabrication processes can be advantageous in improving sustainable architectural production. Leveraging computational design tools, this paper aims to construct design guidelines that cater to cyanobacterial needs towards optimizing biomass production and, consequently, the architectural performance of the printed components.

Keywords: Biodesign · Additive Manufacturing · Cyanobacteria · MICP · Carbon Dioxide fixation · Material Driven Design

1 Introduction

Buildings, being among the largest consumers of natural resources, account for a significant portion of greenhouse gas (GHG) emissions [1, 15]. To date, the most used unnatural building material is cement concrete which is responsible for 8% of the overall global emissions. The Architecture, Engineering and Construction (AEC) industry is gradually starting to address this concern by developing more sustainable alternatives such as blending cement with recycled materials, designing for minimal material

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use and integrating new biobased materials [1, 6, 9]. Another perspective lies within the field of biodesign which utilizes living organisms within construction materials in order to develop materials that can inherit and potentially perform natural processes observed in nature such as carbon dioxide (CO_2) fixation, degradability, recyclability, self-growth, self-healing, and adaptability to the environment [21, 22]. Such processes can be seen in the formation of ant hills through the natural cementation of sand grains and in the binding of coral reefs by the presence of calcium carbonate ($CaCO_3$) [1]. Contrary to construction procedures, natural processes consume a negligible amount of energy, therefore, adopting such processes within construction has great potential in promoting sustainability. Microbially induced $CaCO_3$ precipitation (MICP) is one of the biological processes that are investigated in relation to construction restoration. It is mainly examined within concrete, being the most used construction material, as it can potentially improve compressive strength, offer self-healing properties, and prevent water penetration damages [20, 27].

Within architecture, the effect of cyanobacterial MICP on sand has also been studied in order to develop a new living building material within casting processes [22]. Expanding on such knowledge, we propose to introduce cyanobacteria within an additive manufacturing (AM) process that utilizes computer-aided design tools (CAD) and adopts a geometrical-driven design method towards enhanced performance of architectural components. CAD tools provide designers with informed performance criteria throughout the design phase and establish a better connection between the digital model to the manufactured outcome [9]. In our case we can design geometrical forms that take into consideration basic cyanobacterial needs such as light exposure within an AM setup. By constructing a new workflow for harnessing the biological data of cyanobacteria ($CaCO_3$ precipitation) as an input in the fabrication process, we can potentially bridge the gap between microbiological and architectural processes to produce printed structures that take advantage of additive properties in both biological (micro) and architectural (macro) scales.

In previous experiments, we demonstrated the behavior of cyanobacteria within a developed biomixture and were able to define suitable environmental conditions for cyanobacterial growth (See Fig. 1) [3]. Our preliminary results determined that a 1:1 quartz sand agar ratio at an initial bacteria concentration of ~2×10^6 CFU/mL is suitable for cyanobacterial growth within regulated environmental conditions for light and temperature (22 ± 1 °C) [3]. Relying on our previous work, here we focus on design guidelines that enhance the potential biological performance of cyanobacteria within 3D printed components. We present a computational strategy to analyze geometrical iterations for increased light exposure to enable fabricating with cyanobacteria towards carbon-efficient architecture.

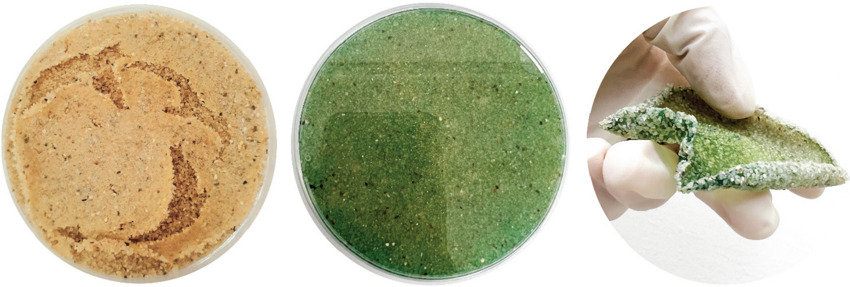

Fig. 1. Images. (Left) Petri dish containing a sample of the non-living mixture. (Middle) Petri dish containing a sample of the biomixture demonstrating cyanobacterial growth within quartz sand type 1. (Right) Sample of the biomixture demonstrating MICP after 2 weeks of incubation [3].

2 Cyanobacteria

Diverse implementations of living organisms such as algae and mycelium have been demonstrated in various design applications [16, 21]. Similar developments are currently being examined with living bacteria and highlight a wide range of potential applications for construction materials, building processes and products [10, 13, 25]. Cyanobacteria, the organism utilized in this research, demonstrate three main behaviors that can be advantageous for developing sustainable construction processes: 1) photosynthesis, 2) carbon fixation, and 3) calcium carbonate precipitation.

2.1 Microbially Induced Calcium Carbonate Precipitation (MICP)

Biomineralization is among the most notable processes that bacteria can perform. In biologically induced mineralization, microorganisms can secrete metabolic products that react with compounds in the environment resulting in the deposition of mineral particles, mainly carbonate products. These minerals could serve as cementitious materials called biocement [1]. The formation of biocementitious materials relies on the precipitation of microbially induced calcium carbonates (MICP). The MICP process occurs in layers surrounding the cells, mainly in the exopolysaccharide layer (EPS). The secretion and the calcification of the EPS layer serves as a biological glue. The EPS layer increases the cell adhesion to surfaces and the presence of $CaCO_3$ within the EPS layer enhances its mechanical resistance [12, 19] (See Fig. 2).

Cyanobacteria are known for their ability to secrete EPS and for the production of $CaCO_3$ through photosynthesis (See Fig. 2). Cyanobacteria MICP is a natural re-occurring biocementation process in desert soils. Through this biological process, known as biological soil crust formation (BSC), soil stability can be enhanced as the precipitation of $CaCO_3$ interconnects soil particles and binds them together [12]. Recent research indicates that biomediated soils improved the shear strength of soils and prevented wind and water erosion [11, 12, 23]. Within AEC, the biocementation process via MICP, due to its eco-efficiency, has drawn the attention of many researchers for the restoration and reinforcement of construction materials [7, 26]. In limestone and concrete-based materials, MICP has enabled the restoration of structures. MICP for concrete restoration has been favored over expensive chemical treatments and has been reported, in addition to crack repairing, to improve compressive strength and durability [26]. In soils, it strengthened underground foundation conditions for construction. Although the cementation process of porous materials such as soils requires a large amount of $CaCO_3$, the process proved to be less costly than chemical treatments [26]. A recent precedent reported a 25.54% increase in the compressive strength of cement mortar by utilizing cyanobacteria *Synechocystis pevalekii* [24].

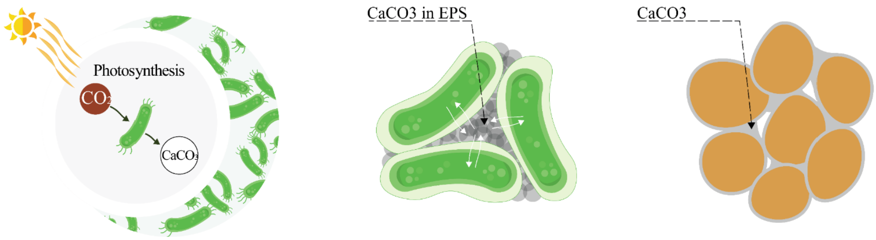

Fig. 2. Diagram. Three target performances of cyanobacteria. (Left) Photosynthesis and carbon fixation. (Middle) Calcification of the EPS layer. (Right) Biocementation of sand particles.

2.2 Cyanobacteria Photosynthesis and Carbon Fixation

Cyanobacteria are a photoautotrophic and oxygen-producing bacteria, and have played a major role in the evolution of different forms of life on earth since over 3500 million years ago [19]. These microorganisms can be found in all potential habitats including freshwater bodies, marine ecosystems, deserts, limestone, soil, and biological soil crusts. Cyanobacteria positively impacts the environment serving as a bioremediation agent that eliminates toxic wastes impact in contaminated sites, and contains multiple strains that can be implemented in human environments [19]. In addition, by harvesting solar energy and performing photosynthesis they fixate CO_2 and generate oxygen in addition to assimilating metabolites and minerals. It is estimated that cyanobacteria accounts for a quarter of the global CO_2 fixation [14, 19].

Effect of Light on Cyanobacteria. Light is the main factor of cyanobacteria metabolism and it directly affects the production of biomass as well as the motility of cells. The motility is regulated by what is known as phototaxis which is defined by the direction, intensity, and wavelength of light [19]. Cyanobacteria are known to move towards or away from the light source depending on its intensity [19]. Cell motility improves with the secretion of the EPS layer which serves as a calcification site for MICP [19]. Thus, increased light exposure could encourage cell motility and consequently encourage MICP through photosynthesis. As we aim to increase the solidification of the printed components through the precipitation of $CaCO_3$, understanding the effect of light on cyanobacterial biomass production is of importance for enhancing the performance of the bacteria. In this context, AM processes could enable increased light exposure due to geometrical articulation and structure porosity of the printed component.

2.3 Cyanobacteria in an Additive Co-fabrication Process

Based on the proven relationship between cyanobacterial MICP, CO_2 fixation and soil stability, we propose to utilize the biosafety level 1 *Synechocystis* being one of the most studied cyanobacterium [19], within an additive manufacturing process of architectural components. Through our previously developed protocols the performance of *Synechocystis* PCC 6803 was examined within different sand-based mixtures and resulted in the binding of quartz sand to a united curved surface [3].

As Belnap [4] suggests that a higher biomass increases soil stability, we aim to leverage CAD and AM to increase the cyanobacterial biomass for the fabrication and solidification of architectural modular components. AM can be advantageous for the photosynthetic nature of cyanobacteria and encourage MICP. For example, through AM techniques we could 3D print porous structures that increase light exposure, therefore encouraging photosynthesis and the production of $CaCO_3$. Contrary to cement concrete production, utilizing cyanobacterial performance within AM processes can promote sustainability since it allows CO_2 fixation throughout the fabrication process. As we recognize that cyanobacteria, throughout their lifespan, are active participants in the fabrication process we will refer to it as a co-fabrication process. Understanding the sustainable advantages of AM, this paper moves forward to the optimization of geometrical forms that cater to both cyanobacterial and fabrication requirements, focusing mainly on light exposure as a critical factor for enhanced *Synechocystis* PCC 6803 performance within the co-fabrication process.

3 Biologically Informed Computational Design

Computational design to manufacturing (CAD to CAM) processes within architecture has accompanied various biodesign processes such as the 3D printing of mycelium-based composites and the fabrication of bioluminescence micro-architectures [18, 25]. With that, to the best of our knowledge, 3D printing of an architectural mixture containing living cells of cyanobacteria has yet to be introduced and still requires further investigation. Utilizing CAD as an investigative tool for designing with and for cyanobacteria, enables a better understanding of the organism's connection to geometry at the architectural scale and within a co-fabrication process [3]. Through CAD techniques we are able to design for increased surface area and light exposure for enhanced cyanobacterial photosynthesis and MICP. As the generated forms of the printed components aim to cater to both biological and architectural requirements, the design process will take into consideration biological constraints such as the motility of the cells, biomass production and $CaCO_3$ precipitation, and architectural performance such as stability through different design parameters including the printing tool path, dimensions of the printed components (width, height), and geometrical properties.

3.1 Incubation and Light Constraints

In our recently founded design biolab, the photosynthetic cyanobacteria are grown within a growth chamber (incubator) with regulated environmental conditions. Therefore, to maintain growth post-fabrication, the printed components will be incubated and kept at the same pre-defined environmental conditions to which the cyanobacteria are accustomed. Consequently, we currently aim to design modular construction components, such as bricks, blocks, and panels within the size constraints (maximum 40 × 40 × 40 cm) of the incubator.

As light is a main factor in cyanobacterial activity, suitable light intensity was also defined to encourage cell growth [3]. Therefore, when studying the designed geometries for increased light exposure we must take into consideration the light direction and distribution within the incubator (See Fig. 3). In incubators, as in the case of our Biochemical Oxygen Demand (BOD) incubator (MRC), lights are positioned above the shelves. While the inner chamber is made of stainless steel which could aid in light distribution, to ensure maximum light exposure, we defined that the main light source origin for the geometrical design process of the printed components is set from above and perpendicular to the incubator shelves.

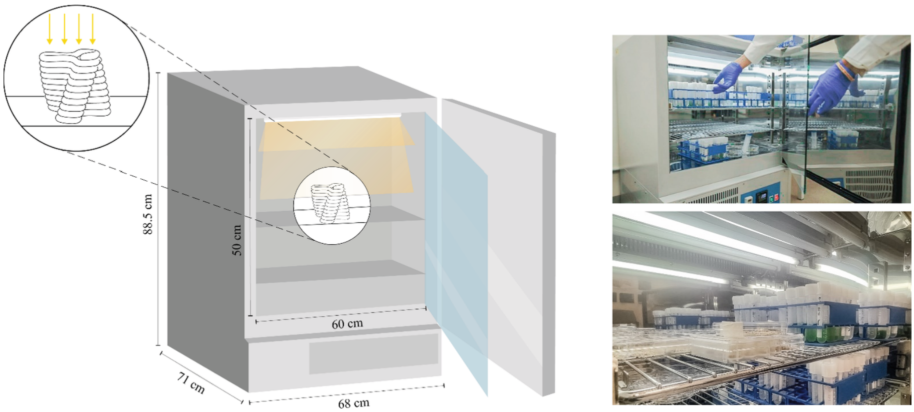

Fig. 3. (Left) Diagram, Post-fabrication incubation of the printed components. The diagram demonstrates the light direction within the BOD incubator. (Right) Images, BOD incubator in the design Biolab containing cyanobacteria cultures (Top) and samples of the biomixture (Bottom), D.D Lab.

3.2 Material-Driven Geometrical Design

Tool Path Design. Tool paths development, many times, is considered a technical process that advances the realization of the modeled design [6]. When fabricating for a specific performance, it becomes a leading factor that alters not only the fabrication process but also the final structural and aesthetic performance of the printed component. For example, in 3D concrete printing, tool paths are designed for minimizing material use, carbon-efficient production and increased strength [6]. While such factors are of relevance also in the case of printing sand-based architectural components, when designing with living cells additional considerations are introduced. Bacterial and fungal growth in angled channels has demonstrated that sharp angles reduce the biomass production of both bacteria and fungi. In the case of bacterial growth, the amount of biomass differed significantly as the sharp angles required movement that was not natural to the bacteria [2].

Knowing that cyanobacteria move towards the light in order to perform viable metabolic activities [19], constraints in motility could risk cell viability in addition to reducing the production of biomass. In order to increase MICP within the architectural components, designing tool paths that encourage cyanobacteria motility needs is of great significance. Therefore, in the tool path design, in addition to increasing light exposure, properties of the habitat geometry are considered to encourage bacterial motility and reduce sharp angles.

Similar to tool paths usually 3D printed with concrete and clay [5, 6, 8, 17], geometrical properties such as component curvature and printing radius are important for the stability of the component throughout the printing process. Through parametric control of such geometrical properties, we developed a tool path design process in order to correlate the thresholds and range of motility for our specific cyanobacterial strain with the geometry of the printing properties. At this point, we examined the link between geometrical form and potential bacterial motility through simple curvature tool paths (See Fig. 4). When establishing the cyanobacterial motility, we can further develop the tool path to examine the motility range by altering the angles and the curvature of the tool path.

Fig. 4. (Left) Diagram, Development of a potential curvature tool path for encouraging cyanobacterial motility using CAD tools such as Rhinoceros and Grasshopper. (Right) Images, Robotic printing of the developed tool path with non-living sand-based mixtures towards printing with cyanobacteria.

Geometrical Analysis. The examination of the components' geometrical design is determined also in relation to microenvironmental conditions that affect cyanobacterial performance. The first step towards designing geometries for photosynthetic activity is to design for light exposure through increased surface area. As a case study, we tested two geometrical principles, rotation and offsetting of the printed layers, in relation to the previously developed extruded tool paths aiming to quantify the increase in surface area and analyze light exposure (See Fig. 5). To maintain a set of base constraints, all geometrical iterations are in the same height and base area. In addition to light exposure these initial geometrical forms, as part of an architectural fabrication process, cater to printing constraints. Therefore, a range was defined to evaluate the structural stability of the overall geometry and resulting overhangs. The rotation of layers was examined in a range of 3–7° and the offsetting of layers was examined in a range of 1–5 mm.

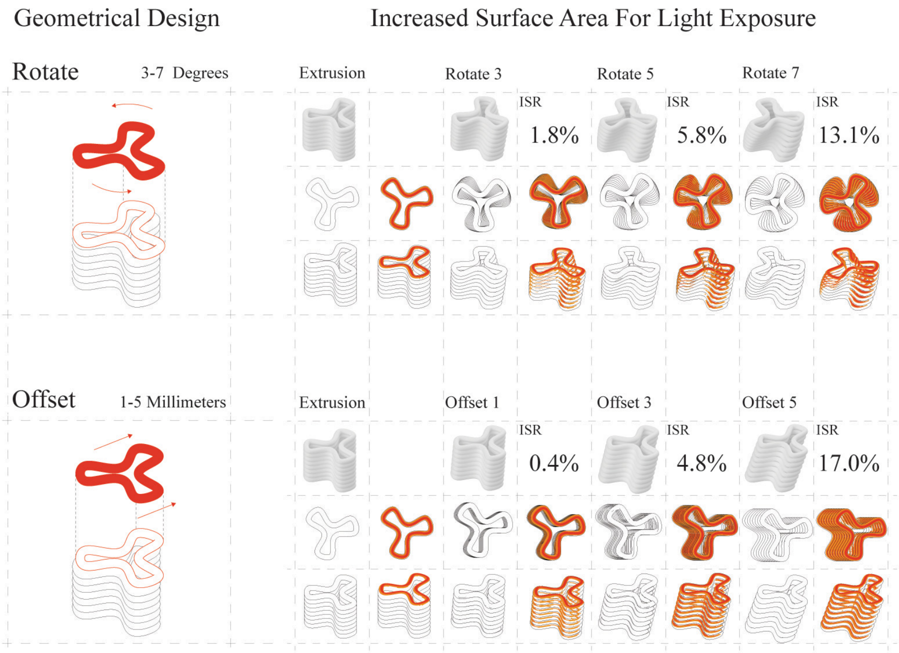

Fig. 5. Geometrical analysis for increased surface area and light exposure. (Left) Applied design principles. (Right) Geometrical variations in the defined ranges for each design princple.

Using Rhinoceros, Grasshopper and its associated plugins Ladybug and Honeybee, the toolpath geometries were calculated for surface area visualizing the areas that are exposed to direct light and simulating the potential lighting conditions in the incubator. The offsetting of layers resulted in a greater increase of surface area; variation "Offset 5" holds the highest surface area of 17% after variation "Rotate 7" with an increase of 13.1% (See Fig. 6). With that, the feasibility of printing such geometries will be tested and optimized before implementing the process with living cyanobacteria cells. This geometrical investigation demonstrates potential guidelines linking biological and geometrical properties to tool path design. This will also guide the optimization of the printed cyanobacteria-based components and increase biological performance.

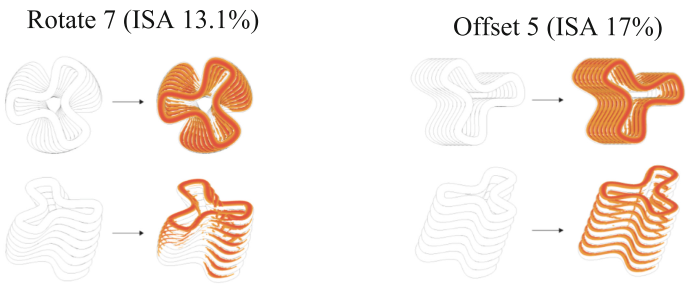

Fig. 6. Top view and isometric view of the light exposure analysis for both variations with the highest increase in surface area, “Rotate 7” and “Offset 5”.

4 Prototyping an Additive Co-fabrication Process with Cyanobacteria

Constructing a systematic CAD to CAM setup is essential for the proper implementation of the developed co-fabrication workflow. While this paper demonstrated computational design methods for the optimization of cyanobacteria performance, a corresponding automation workflow has been developed utilizing a UR5e robotic arm for the deposition of a biomixture with cyanobacteria. As printing with living cells presents new obstacles to the architectural world, we aim to expand and upscale biofabrication processes within relatively large-scale architectural additive manufacturing (See Fig. 7).

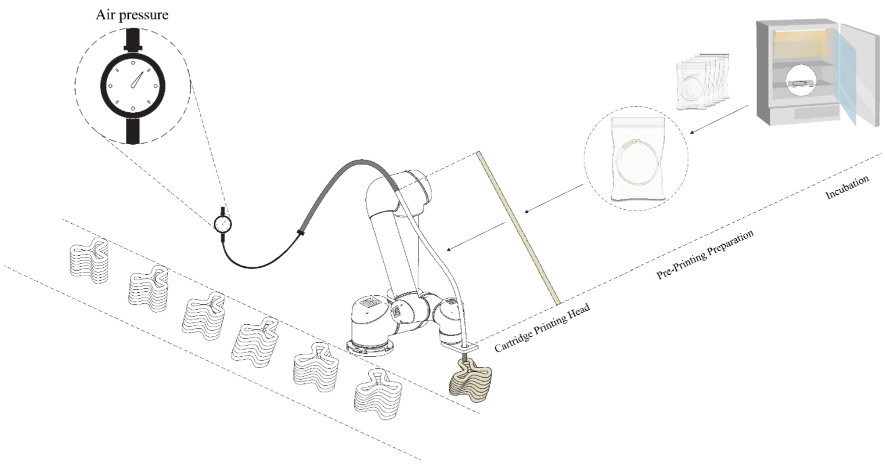

Fig. 7. Diagram. Automation workflow of the upscaled biofabrication process within relatively large-scale architectural production with living cyanobacteria cells.

Currently, based on the geometrical analysis, we have gone on to prototype potential habitat geometries to further understand the fabrication constraints with the selected sand-based mixture using the sand-agar ratios that we developed for our bacterial strain

(See Fig. 8). Expanding on the outlined method for biologically informed computational design, we have drawn inspiration from and for architecture to further design geometrical forms that perform architecturally in terms of stability and function. These architectural components could potentially offer an alternative to common printed concrete blocks and products. Moreover, on the biological level, knowing that cyanobacterial performance will decrease as the rate of cell death naturally increases, we will aim to enhance the cells' activity throughout their lifespan by optimizing biological procedures. In addition, we aim to examine the natural behavior and production of cyanobacteria by identifying the cyanobacterial growth phases, quantifying the fixation of CO_2 and the production of $CaCO_3$.

Fig. 8. Non-living sand-based printing using robotic deposition towards developing architecturally performing components.

5 Conclusion

As the AEC industry is taking a necessary shift towards sustainable design due to rising ecological and environmental concerns, this ongoing research proposes to utilize cyanobacterial performance within a co-fabrication workflow to produce architecturally performing components. Integrating cyanobacteria within a design process can be of great significance as it has the potential to substitute cement concrete with a carbon-efficient biomixture.

As cyanobacteria are active participants throughout the co-fabrication process, the printed geometries should allow the bacteria to maintain its functionality and even encourage its biological performance throughout and post-fabrication. Therefore, in this paper we outlined design guidelines for enhanced cyanobacterial photosynthesis and MICP that can result in the solidification of sand-based biomixtures. Recognizing the importance of light in the mechanisms of cyanobacteria, we leverage CAD tools to design custom tool paths that encourage cyanobacterial motility towards the light in order to quantify and analyze increased light exposure through increased surface area. In addition, future steps will analyze the effect of light penetration on the printed components in relation to geometrical porosity in order to encourage 3D cell spatial distribution and increased biomass production.

Through a CAD to CAM workflow that caters to the three main cyanobacterial performances; photosynthesis, MICP and CO_2 fixation, we aim to enable decision-making in a design process that is informed by cyanobacterial behavior. Such a design process presents new sustainable opportunities to minimize the harmful effects of current production processes in the AEC industry and encourage a positive impact that is harnessed from natural processes.

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