# A STOCHASTIC APPROACH TO SIMULATE AND OPTIMIZE THE COATING UNIFORMITY OF ROTATIONAL MOLDING FOR MICROALGAE FACADES

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**ABSTRACT**

Microalgae facades have been positioned as a potential solution to improve building energy efficiency, indoor air quality, and carbon sequestration. We investigated rotational molding as a method to fabricate freeform photobioreactors for microalgae facade integration. The challenge is that the optimal speed ratio for biaxial rotational molding is dependent on geometry, and there is no known method to determine the optimal speed ratio for any given geometry. We proposed a model with a stochastic approach to simulate the optimal speed ratio of a rotational molding machine given any specific geometry. The model is implemented in Grasshopper for simulating an intertwined geometry. As a validation process, we designed and built a biaxial rotational molding machine and tested various parameters for casting evenly coated photobioreactors. The experiment results showed that the speed ratio of the rotational molding machine, determined by the model, was well fitted to create uniformly coated photobioreactors.

**Keywords:** Rotational molding, speed ratio optimization, stochastic approach, microalgae facades

## 1 INTRODUCTION

### 1.1 Background

Fossil fuel dependence in our society has resulted in continuous greenhouse gas emissions to the atmosphere which subsequently leads to global warming. To combat global warming, renewable energy has been identified as one of the most effective ways to cut down greenhouse gas emissions. As a source of renewable biofuel source, microalgae can produce 10-20 times higher biofuel yield than the best yield crop (Mandal and Mallick 2014). There are two primary ways to grow microalgae, in raceway ponds or photobioreactors. The most pronounced benefit of growing microalgae in photobioreactors compared to open raceway ponds is that microalgae are better protected from exterior contaminants. Given the vast surface area of buildings, there have been efforts to grow microalgae as part of building facades (Arup 2013). Additional benefits of installing photobioreactors as a building facade are that it can sequester carbon dioxide from the indoor air that is supplied to the façades through inlet air tubes, and release fresher air with more oxygen back into the room through outlet air tubes. However, these efforts to incorporate microalgae into building facades are so far limited to growing microalgae in between two panes of glasses. In this research, we investigated methods to fabricate freeform photobioreactors that can be installed as building facades. This is expected to provide architects with more freedom in creative designs.

### 1.2 Microalgae Facades:

The microalgae façade system integrates biological cells with building materials to enhance building energy efficiency, good indoor air quality, and real-time carbon uptake. The system is made of a network of customizable, scalable matrix and is coupled with an intelligent control system to enhance shading efficacy and daylight transmission depending on site locations, building orientations, and the time of use.

Capitalizing on the symbiotic relationship between users and nature, another technical innovation enables the technology to reduce occupant-generated CO2 inside the room and in return generate oxygen-rich air for user wellbeing. While CO2 is not often considered a pollutant, with high concentration, it can reduce work productivity (Satish et al. 2012). The superior photosynthetic process of the microalgae system actively sequesters CO2 and improves indoor air quality that enhances occupant productivity and satisfaction.

With the worldwide pandemic, people have even fewer chances or little accessibility to nature. Potential advantages of interacting with nature have been well researched, including stress reduction, psychological restoration, the promotion of physical activity, mental health, and social cohesion. The proximity to nature and green light quality is expected to provide positive health effects and wellbeing.

### 1.3 Essential Material Properties

The materials for photobioreactors need to meet strict requirements to grow microalgae and function as part of a building facade. The critical factors when selecting photobioreactor materials include transparency, toxicity, water tightness, and structural integrity.

1. Transparency: Microalgae utilize the visible light spectrum of sunlight as the energy source to synthesize biomass with the existence of carbon dioxide. The optimal material for photobioreactors should have high visible light transmittance.
2. Devoid of toxicity: Since microalgae are living organisms, it is obvious that the material used for a photobioreactor should not be toxic to microalgae.
3. Acid/base resistance: Different microalgae strains require different acidity for optimal growth. Some strains require an acidic environment, while some may prefer a base solution. The material for a photobioreactor is preferred to have the ability to resist different pH levels.
4. Watertightness: All strains of microalgae require water to stay alive and grow. It is essential for a photobioreactor to be watertight, especially when it is applied to a building facade.
5. UV-resistance: While the visible light in the sunlight is essential to microalgae growth, the UV spectrum may potentially cause degradation to photobioreactors depending on its material. Given that longevity is crucial for building facades, the optimal material choice for a photobioreactor should resist UV light.
6. Structural strength: The material for photobioreactors should be strong enough to hold the self-weight of the photobioreactors and the hydrostatic pressure from the water inside them. The material should also be resistant to creep and fatigue.

## 1.4 Comparison of Fabrication Methods

A photobioreactor is essentially a hollow object that can contain medium (water and nutrients) and microalgae. There are various fabrication methods that can create hollow photobioreactors. In this research we investigated and compared the following fabrication methods: rotational molding, 3D printing, blow molding, injection molding, stamping, vacuum forming, CNC milling, and slumping. The latter five fabrication methods require a photobioreactor to be fabricated in two halves and be sealed together afterward. Figure 1 shows a hollow object made from two halves with vacuum forming. The primary challenge of this category of fabrication methods is that the seams where the two halves meet need greater attention to eliminate potential water leakage.

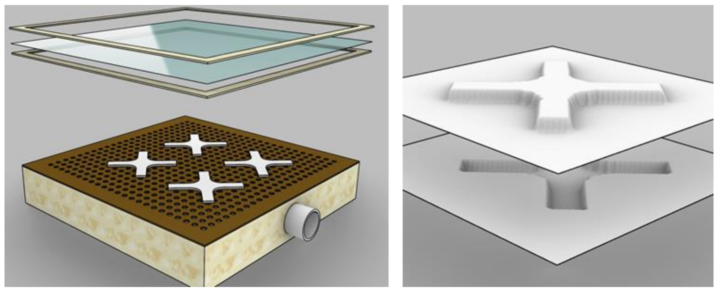

Figure 1: Fabrication methods, e.g. vacuum forming (left), that create two halves (right) and the seam needs to be sealed afterward.

Unlike the latter five fabrication methods, rotational molding, 3D printing, and blow molding can create hollow objects without a seam. Here is a brief three-way comparison of these three fabrication methods. 3D printing is limited to the physical size of the printer, which is typically under 1’ x 1’. Blow molding creates weaker corners because the material gets thinner while it is stretched to reach the corners. Rotational molding can be used for larger hollow objects, such as a full-scale plastic canoe, while reinforcing corners by depositing more material at corners. However, rotational molding does take longer compared to blow molding.

Given the qualitative analyses above, rotational molding was chosen as the optimal method for fabricating photobioreactors in this research. We also chose resin as the material of the photobioreactors. Although resin is harmful to microalgae when in its original form, it is not toxic when fully cured.

## 1.5 Problem Definition

Rotational molding is a well-studied fabrication method and is commonly used in the industry. The actual speeds of rotation and the speed ratio are the two most important factors in fabricating uniformly coated hollow objects. Speed ratio refers to the ratio of the speed rotating along the major axis and the minor axis. For two-axis rotational molding machines, it is well known that the speed ratio between the two axes can greatly affect the uniformity of the material distribution on the interior surfaces of the mold. For example, if the speed ratio between the major axis and the minor axis is set to 1:1, the top surface of the mold is unable to be coated. Some speed ratios work better than others to achieve even coating. In addition, the optimal speed ratio depends on the geometry of the mold. In other words, for the best coating results, the rotational machine has to be modified according to the shape of the mold. Table 1 shows a rough guideline of recommended speed ratios for certain geometries (Crawford and Throne 2001).

Although this guideline provides a good starting point for deciding on a working speed ratio, it is not comprehensive enough for many geometries. The X-shaped module used in this research does not fit into any of the categories. So do C-shape, L-shape, and many others. In addition, the vague terms also pose challenges to decide which speed ratio to use. For example, a 4:1 ratio is recommended for rectangular boxes and a 1:3 ratio is recommended for flat rectangles. How flat is flat is not well defined and causes ambiguity. Different flatness calls for a different speed ratio for the optimal distribution of the material.

Table 1: Recommended Speed Ratios for Various Geometries.

| **Speed Ratio** | **Geometries** |
|---|---|
| 8:1 | Oblongs, straight tubes (mounted horizontally) |
| 5:1 | Ducts |
| 4:1 | Cubes, balls, rectangular boxes, and most regular 3-D shapes |
| 2:1 | Rings, tires, mannequins, flat shapes |
| 1:2 | Parts that show thinning when run at 2:1 |
| 1:3 | Flat rectangles, suitcase shapes |
| 1:4 | Curved ducts, pipe angles, parts that show thinning at 4:1 |
| 1:5 | Vertically mounted cylinder |

### 1.6 Research Goals

The goals of this research are to develop an analytical model for simulating the optimal speed ratio for any geometry and build a rotational molding machine based on the optimal speed ratio to assess the coating uniformity of the final products.

### 1.7 Research Scope

There are many types of rotational molding machines, such as rock-and-roll, shuttle, etc. (Kearns and Crawford 2003). In this research, we focused on developing a simulation model for a full biaxial rotational machine as shown in figure 2.

Figure 2: A biaxial rotational machine with an X-shaped mold at the center.

## 2 METHODOLOGY

Rotational molding creates hollow objects by coating a thin layer of material(e.g. thermoplastic, resin, etc.), typically in the form of viscous fluid, along the interior surfaces of a hollow mold. The material solidifies either with chemical reactions or temperature drop. When a greater shell thickness is desired, the coating process is repeated after the previous layer solidifies. For the vast majority of hollow objects created by rotational molding, the volume of the material that is used to create the hollow objects is far less than the volume of the void space of the mold. In other words, when filling material in the mold, the material will settle at the bottom of the mold and typically fills only a small portion of the volume of the mold. The majority of the mold volume remains empty. When the machine rotates, the material in fluid form flows along the surface toward the lowest position of the mold due to gravity, assuming that the rotating speed is slow enough so that the effect of centrifugal force is negligible. This means that for the interior surface of the mold to be evenly coated, all surfaces should rotate toward the bottom of the geometry with a similar probability.

## 2.1 A Stochastic Prediction

As mentioned earlier, the geometry of a hollow object and the speed ratio of the two rotational axes are interdependent. Given a specific geometry, different speed ratios cause the machine to rotate differently, and subsequently the probability of each surface rotating toward the bottom of the geometry is different, i.e. the coating uniformity would be different. In this research, we propose a stochastic approach to simulate how evenly a mold can be coated given a specific geometry. This model is based on the following rules:

1. Rule 1: Surfaces with normal vectors pointing downwards have a probability of 0 to be coated.
2. Rule 2: Any portion of a surface above the center of rotation has a probability of 0 to be coated.
3. Rule 3: Vertical surfaces and surfaces with their normal vectors pointing upwards have a probability of 1 at the lowest point of the geometry and a probability of 0 at the center of rotation. The probability of any portion in-between is interpolated linearly by its Z value.
4. Rule 4: After the simulation finishes, the average probability of each surface getting coated is calculated based on the three rules described above. The speed ratio with the least standard deviation of the probability can coat the surface with the most uniformity.

To explain the premises of the rules in detail, a hypothetical 2D scenario (in section) is used as shown in figure 3: a rectangle, the section of the interior of the mold, rotating about center O in a clockwise direction. For biaxial rotation, the rules apply to both axes in the same manner. The triangular area with a dotted pattern represents the liquid material settled at the bottom of the geometry. The arrows denote the normals of the interior surfaces of the mold. Point A denotes the lowest point. Point D denotes the intersection of the surface and the horizontal plane passing center O. Point B denotes the midpoint between A and D. Point C denotes the midpoint between B and D. Point E denotes a point that is above the center of the geometry.

1. Premise for rule 1: The normal vectors of surface S1 and S2 are pointing downwards and thus have a probability of 0 to be coated according to rule 1. Because the liquid material only takes a small portion of the volume and settles at the bottom, surface S1 cannot have contact with the material at this point of time. Surface S2 is also unlikely to have contact with the material since we are assuming that it rotates clockwise. Had we assumed counterclockwise rotation, surface S2 would satisfy rule 3 by the time it has contact with the liquid material.
2. Premise for rule 2: Point E has a probability of 0 because the liquid material only takes a small portion of the volume and settles at the bottom so it is unlikely that the material will have contact with point E at this point of time. Since we are assuming that the machine is rotating clockwise, the material will coat point E as it further rotates, but by the time the material coats point E, point E will be below the center of rotation O (and axis X) and does not satisfy rule 2 anymore.
3. Premise for rule 3: $P_A$ denotes the probability of point A getting coated at this point in time, $P_B$ denotes point B getting coated, and so on. It is obvious that $P_A = 1$ because point A is the lowest point and is already submerged in the liquid material. Point B and C look as if they will certainly be coated since the geometry is rotating clockwise. However, in reality the rotational molding machine always rotates about two axes simultaneously, i.e., it rotates clockwise about center O with some degree of rotation about X axis at the same time. Therefore, it is possible that the liquid material can run over point B and coat it, but it is also possible that it runs past point B without coating it because the geometry is also rotating about axis X. The further away from the bottom of the geometry, the more likely the material runs past the point and the less probability of getting coated.
4. Premise for rule 4: If the standard deviation of the probability of each point getting coated is 0, it means that every point has the same probability of getting coated resulting in the interior

surface of the mold being coated evenly. The greater the standard deviation, the greater the likelihood that certain points on the surface will not be coated or coated with thinner material.

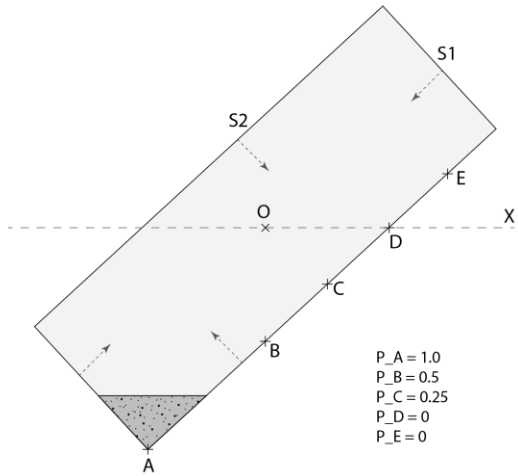


Figure 3: A hypothetical scenario that liquid material coats a rectangular geometry using a rotational molding machine.

## 2.2 Programming in Grasshopper

The above-mentioned model is implemented in Grasshopper for simulating the coating uniformity of a given geometry. Here are the steps how the Grasshopper definition is set up:

1. Step 1: Each surface of the geometry is discretized into small cells and the centroids (green dots in figure 4 left) of the cells are used in the simulation to calculate probabilities.
2. Step 2: A full rotation is divided into a certain number of discrete steps (360 steps is used in this research). Figure 4 (right) shows cumulative graphics of all 360 rotations of an X-shaped mold.
3. Step 3: All 360 steps are simultaneously sent to the model with parallel processing to calculate the probabilities of each point getting coated (figure 5), and the standard deviation of the probabilities is calculated (table 2).

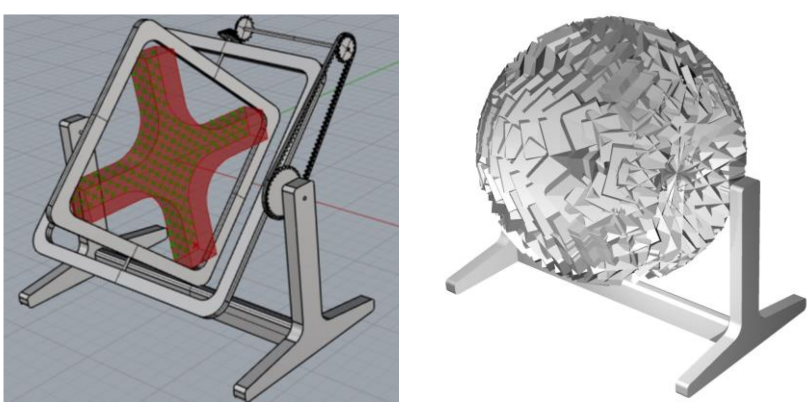

Figure 4: Discretization of the interior surfaces of the mold (left) and the cumulative rotation of the X-shaped mold (right). The two rectangular frames on the right image are hidden.

This process is repeated for different speed ratios, such as 1:1, 1:2, 1:3, and so on. Figure 5 shows the probabilities of each cell getting coated for different speed ratios. The X axis represents each cell of the discretized surfaces, and the Y axis represents the average probability of the 180 rotational steps of each cell. Less fluctuation in the graphs means greater uniformity. As expected, the speed ratio of 1:1 shows a probability of 0 for the top surface (the first half on the X axis). Table 2 shows the standard deviation of the probability for different speed ratios.

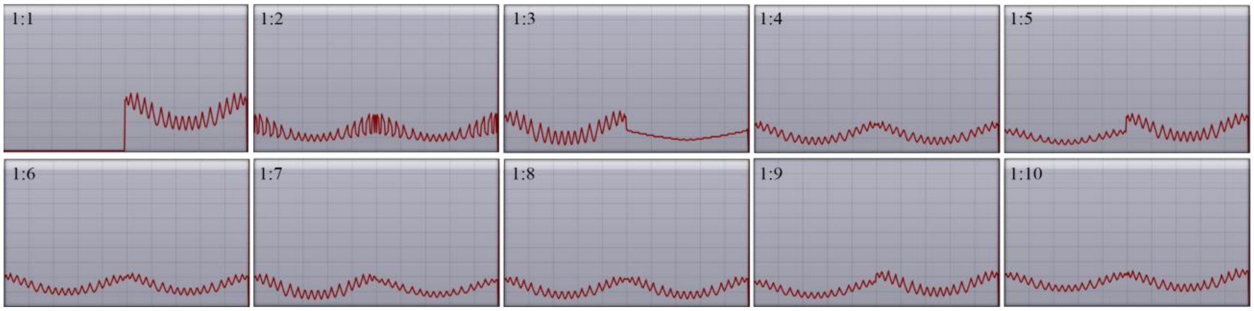


Figure 5: Coating probabilities for different speed ratios.

Table 2: Standard Deviation of Probabilities for Different Speed Ratios.

| **Speed Ratio** | **Standard Deviation** | **Speed Ratio** | **Standard Deviation** |
|---|---|---|---|
| 1:1 | 0.139778 | 1:6 | 0.101944 |
| 1:2 | 0.116126 | 1:7 | 0.101294 |
| 1:3 | 0.331545 | 1:8 | 0.102181 |
| 1:4 | 0.098151 | 1:9 | 0.103551 |
| 1:5 | 0.099791 | 1:10 | 0.109039 |

In this research, we designed an intertwined geometry as an example of a freeform photobioreactor (figure 6 left). To build the photobioreactor as a real-size building facade application, we conducted studies on how to break down the facade into modular assembly with manageable sizes. In the end, we split the facade into full X-shaped modules, half modules, and quarter modules (figure 6 right).

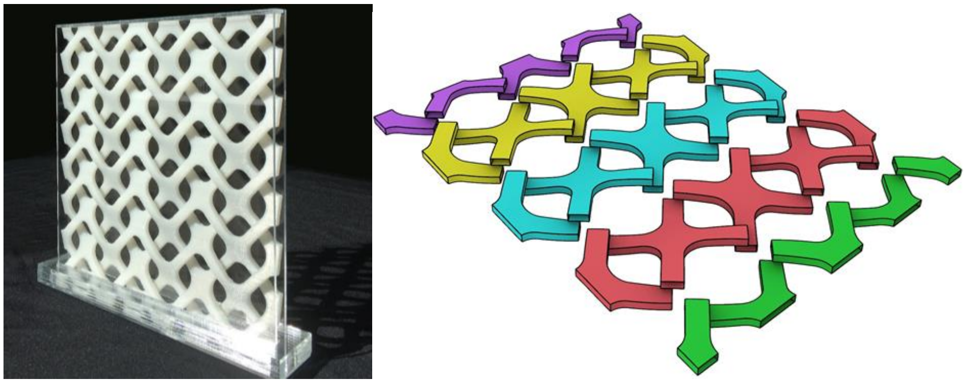

Figure 6: Intertwined photobioreactors as a building façade (left) and the Modular break-up of the facade to fit the size of a rotational molding machine (right).

We used an X-shaped module to simulate the optimal speed ratio using the proposed model. We simulated speed ratios of 1:1, 1:2, 1:3, …, and 1:10. The simulation results showed that a speed ratio of 1:4 would coat the X-shaped geometry most evenly. We further simulated with more granular speed ratios of 1:3.2, 1:3.4, 1:3.6, … 1:4.6, 1:4.8 to see if any fractional speed ratio would perform better than the whole number ratios. The results showed negligible differences between the fractional speed ratios. The final simulation results show that a speed ratio of 1:3.8 ~ 1:4.4 would result in the best coating uniformity. As speculation, whole number ratios, such as 1:2, 1:5, etc., make the machine repeat its position after a full rotation of the primary gear. A fractional ratio will not repeat its position and potentially can coat the mold with greater uniformity.

## 3 DESIGN AND FABRICATION OF ROTATIONAL MOLDING MACHINE

We designed and built a rotational molding machine to demonstrate how evenly the geometries can be coated (figure 7). In building a rotational molding machine, speed ratio can be translated into gear ratio, i.e. the ratio between the number of teeth of the primary sprocket and the secondary sprocket. Two parameters of the machine were required to be set with which the machine would be designed around. The first parameter was acquiring a set of gears that would achieve the closest ratio for optimal coating uniformity between 1:3.8 and 1:4.4. With a higher tooth gear being desired for less strain on the motor, a 9-tooth and a 38-tooth steel sprockets were sourced along with a size 40 roller chain to achieve a ratio of 1:4.22. With the gears selected, the second parameter was the dimensions required for the mold that the machine needed to accommodate. With the X-shaped module being set at approximately 12”x12”x4”, a maximum mold boundary was determined at 18”x18”x6”. A full digital model utilizing Rhinoceros 3D was then created to develop the rest of the frame, stand, and rotational mechanisms for the machine to run from.

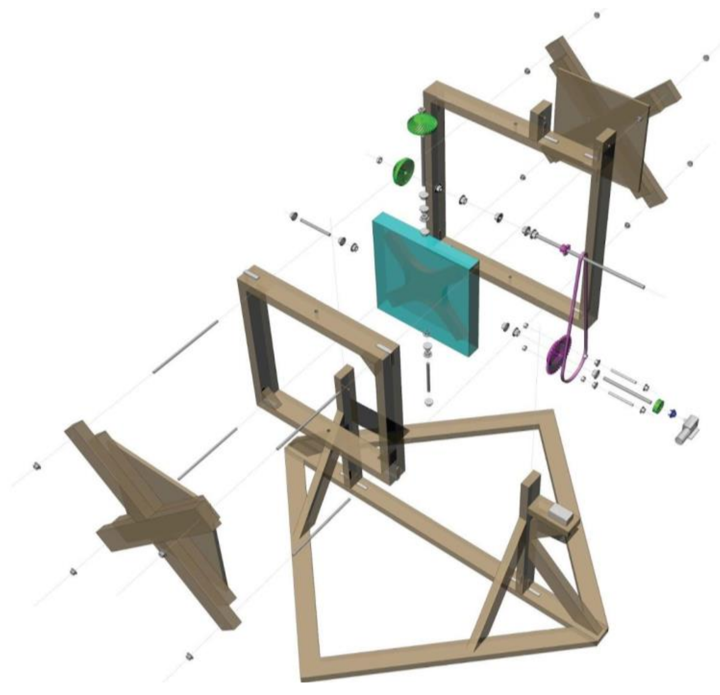

Figure 7: Digital fabrication model of the rotational casting machine.

In its first iteration, the frame of the rotational molding machine utilized wood studs along with steel brackets providing a lightweight and high tensile strength solution while simultaneously allowing for easy alterations and adaptability. This proved to be extremely beneficial as numerous modifications were required during assembly and throughout the early casting process; allowing for several adaptations of motors, fine-tuning of axial and rotational tolerances, as well as adaptations for different molds. A second iteration of the machine was later built utilizing aluminum in lieu of wood to provide an even higher strength-to-weight frame and allow for slightly larger and heavier molds to be cast.

Several elements were implemented within the rotational molding machine to achieve and/or improve its rotational motion. To transfer the rotational axis from the exterior to the interior frame, bevel gears were designed and 3D printed to accommodate the dimensional requirements of the machine. The parts were first printed with a polylactic acid filament with polycarbonate filament being chosen later for its higher strength capacity. Within the initial wood frame, steel sleeves were embedded into the studs for the threaded steel rods acting as the axles to insert into. This provided a lower frictional resistance between the pieces and allowed for PTFE lubrication to be utilized in an optimal application, allowing the machine to rotate freely and reducing wear on the axles, frame, as well as the motor. Bearings were later added at each of the main axes which further reduced frictional stresses as well as provided additional stability to the shafts and frames.

While manual rotations by hand are common in rotational molding, a motor was used for automation due to the set time of the selected resin and the required consistency for accurate testing. This allowed smooth rotational molding for extended periods of time allowing researchers the freedom to prepare the next mold for increased efficiency in production. A 24V, 300 RPM DC motor was used in this machine. The higher RPM was mitigated with a 80:1 worm gear speed reducer which allowed the machine to slow to approximately 0.5-4.5 rotations per minute. The slower speed is well suited for the casting process, allowing the resin to slowly and evenly coat the entirety of the mold. The worm gear speed reducer also increases torque significantly, extending the motor's life and allowing much heavier casts (figure 8).

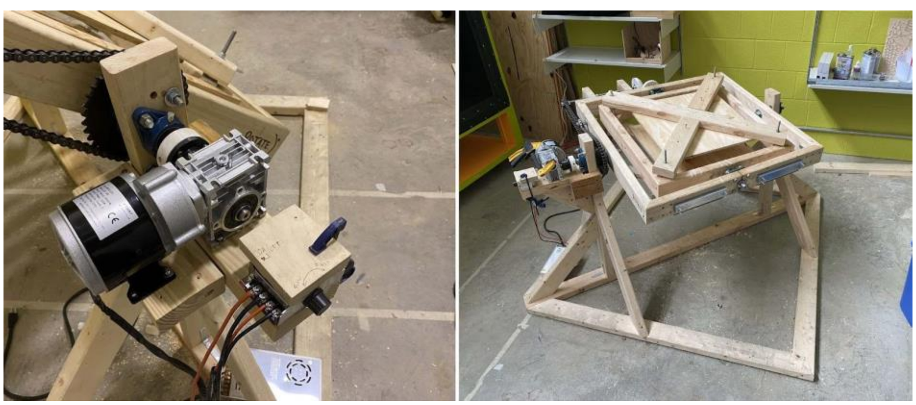

Figure 8: Highlighted modifications and improvements of rotational molding machine.

## 4 EXPERIMENTS ON MOLDING PARAMETERS

There are many parameters other than speed ratio (gear ratio) that affect coating uniformity. To test the parameters and the coating uniformity, we cast a rubber mold and used it for molding clear photobioreactors using different types of resin.

### 4.1 Mold Casting

We used a two-part mold technique with Smooth-On Mold Max 30, an optimal silicone for clear resin. The process begins with 3D printing the object and sanding the surfaces to be as smooth as possible. Then the 3D printed model is clayed at the bottom half to make sure it has an even seam for the two halves (figure 9 left). Then a wall is built around the clay, as well as registration keys, before pouring the silicone. The keys are crucial since these help line up the two halves together to ensure a tight seal. To cast one of the halves, 400 grams of A and 400 grams of B were used at a 1:1 ratio. After mixing the two, the air trapped inside the silicone mixture is removed with a vacuum chamber. This machine removes all air particles leaving a clean silicone mold without bubbles on the surface. After letting the silicone rest overnight, the mold half is flipped over and all clay is removed from the other side (figure 9 middle). The side with registered keys is then sprayed with mold release for easier separation of the two halves (figure 9 right).

Figure 9: Mold making process. Claying the 3D printed object (left), casting one side of the mold with Mold Max 30 ( middle), and the cast two halves of the rubber mold (right).

### 4.2 Rotational Molding Parameters

The outcomes of the rotational molding process were derived from a few different parameters: the types of resin, volume to weight ratio, rotational speed, total duration, and ambient temperature. The first factor is the products being utilized to find desired transparency. The three products utilized for experimentation were Smooth-On Crystal Clear 202, Smooth Cast 325 urethane resins, and Innothane IE-3025 rigid polyurethane. The main reason for using these three products for testing was due to their short "pot-life" for the efficient production of modules. Surface Area to Weight ratio is used as a parameter due to the fact that most mixing operations are done using a weight split into part A and part B. The surface areas for the four different modular parts became a crucial part of finding the consistent thickness as a layering process. Figure 10 shows the four different types of modules. The surface area of the full X-shaped module is 233.4 $in^2$, the surface area for the half modules is 124.8 $in^2$, and the surface area for the quarter module is 66.6 $in^2$.

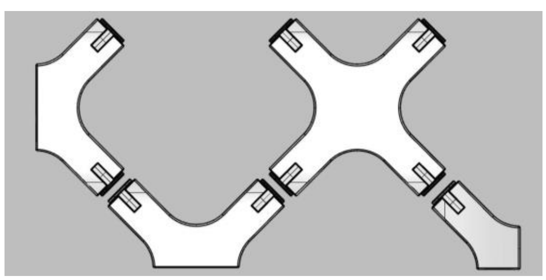

Figure 10: All four types of the module pieces

Figure 11 shows the final models cast from three different types of resin: Crystal Clear 202, Smooth Cast 325, and Innothane IE-3025. As shown in the images, Crystal Clear 202 showed a high degree of transparency and Innothane IE-3025 was not able to produce a transparent enough photobioreactor for microalgae growth. After numerous tests, we identified the optimal parameters, as listed below, for casting a transparent resin photobioreactor with a biaxial rotational molding machine. The cast modules were then baked in a thermal chamber for an hour to add additional strength.

1. Material: Crystal Clear 202
2. Rotating speed: 4.5 RPM for the primary gear
3. Rotating time: Two 30 minute rotation (two pours) with 10 minute rest interval
4. Temperature: Approximately 68° F to 72°F

5. Surface area to weight ratio: 1:2
6. Single layer wall thickness: 1/8 inch

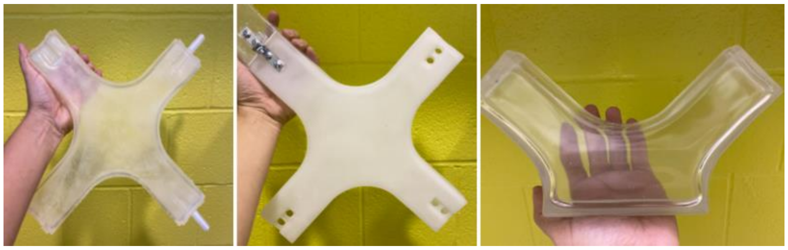

Figure 11: Cast models with three different types of resin: Smooth Cast 325 (left), Innothane IE-3025 (middle), and Crystal Clear 202 (right)

## 5 PROTOTYPING AND ASSEMBLY

With all the parameters identified, we cast 70 full, 52 half, and 6 quarter X-modules using the rotational molding machine and fabricated a 12'-0" x 7'-8" building facade as shown in figure 12. The facade consists of six different layers, one layer of water and five layers of microalgae. Each of the five layers contains different strains of microalgae, including Chlorocuccum, Chlorella, Spirulina, Scenedesmus, and Hemotococus. The facade has been in operation for approximately a year. Each strain of microalgae showed expected growth rates, and the cast modules showed no signs of degradation.

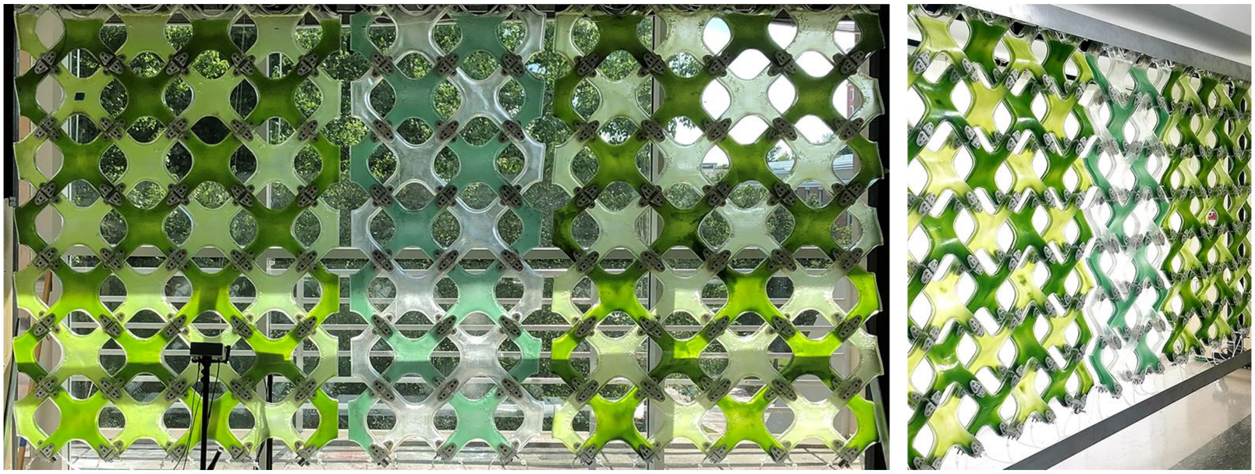

Figure 12: Final assembled microalgae façade with five different strains of microalgae.

## 6 CONCLUSION

Microalgae facades can serve as a sustainable alternative to building enclosures toward carbon-neutral, net-zero energy architecture practice. With superior photosynthetic performance, microalgae facades are expected to enhance building energy efficiency, sequester carbon, and improve occupant health and wellbeing. In this research, we investigated rotational molding as a method to fabricate freeform photobioreactors as part of building facade systems. We developed a stochastic approach for simulating the optimal speed ratio of a rotational molding machine for any given geometry. We implemented the model on the Rhinoceros/Grasshopper platform and simulated the optimal speed ratio for an intertwined microalgae facade design. We designed and built a biaxial rotational machine and tested various parameters for optimal casting quality. We were able to cast crystal clear photobioreactors with rather uniform thickness. The quality of the final cast modules suggests that the speed ratio from the simulation model functioned as expected. We do recognize that the fabrication process is not enough as a rigorous validation for the model that is proposed in this research. To validate the theoretical model, the rotational molding machine needs to be built with different gear ratios, set quantifiable metrics for uniformity, and cross-compare the photobioreactors that are cast with different speed ratios. In addition, different shapes of molds need to be tested for more comprehensive validation. Given the research grant period, we were unable to conduct such comprehensive validation. Nonetheless, our experiments demonstrate a successful application of using the model.

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