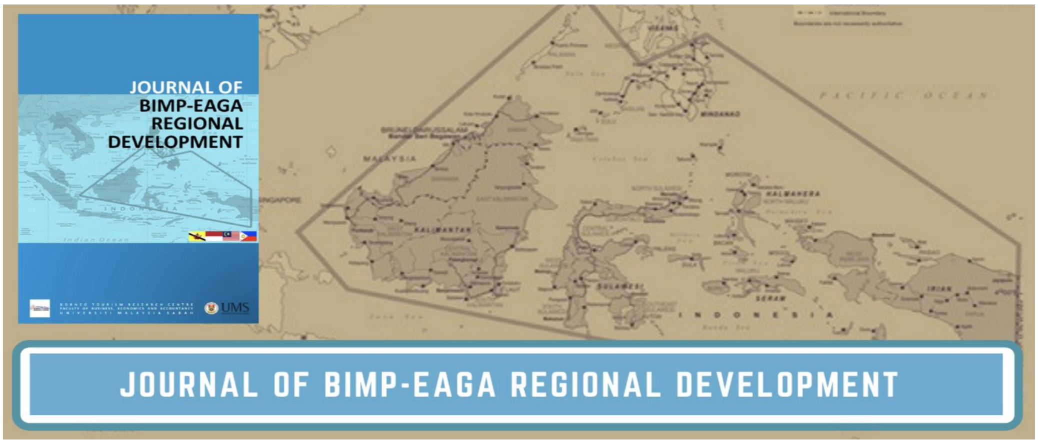
JOURNAL OF BIMP-EAGA REGIONAL DEVELOPMENT

DESIGN AND SIMULATION ANALYSIS OF 3D-PRINTED ARTIFICIAL CORAL REEFS

Eisley John S. Tiongson[a]*, Lester Alfred M. Olasiman[a]

[a]*Adamson University, 900 San Marcelino St. Ermita, 1000 Manila, Philippines*

Abstract

This study addresses the need to understand the hydrodynamic behavior of artificial coral reefs, inspired by natural coral formations such as brain, cauliflower, lace, dome, digitate, and organ pipe corals, which are found in our oceans. The selected natural coral reef designs underwent computational fluid dynamics (CFD) simulations to replicate their behavior. These designs were then recreated through a 3D printing process to develop artificial coral reefs. Simulation analyses were conducted to assess water flow coverage and velocity. The analysis revealed that the brain and cauliflower coral design exhibited limited water flow coverage. In contrast, the digitate and organ pipe coral design demonstrated more favorable simulation outcomes, showing efficiency in mimicking the natural fluid dynamics of coral reefs. This was evidenced by the lowest velocity and more extensive water flow coverage in the digitate design. The results contribute to a better understanding of artificial coral reef design, highlighting the digitate and organ pipe coral's potential for more efficient integration into marine ecosystems. This study underscores the ecological relevance and practical benefits of using specific coral designs to enhance artificial reef performance.

Keywords: Coral Reefs; Flow Simulation; 3D Printing; Fluid Dynamics

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1. Introduction

Coral reefs represent complex, biodiverse marine ecosystems characterized by the symbiotic relationship between coral polyps and algae (Jackson, et.al, 2001). These structures are formed through the deposition of calcium carbonate by coral polyps, resulting in the development of diverse coral species, including Stony Corals (Scleractinia) and Soft Corals (Alcyonacea), each with distinct morphologies and ecological roles. (Miththapala, 2008) Despite their environmental significance, coral reefs face severe threats, primarily from anthropogenic activities such as overfishing and destructive fishing practices, which disrupt the delicate balance of these ecosystems. Coastal development and pollution further exacerbate these issues, leading to coral reef degradation and loss of biodiversity (McManus, 2001). Nutrient enrichment, particularly from nitrogen and phosphorus sources like agricultural runoff and sewage, can result in eutrophication, leading to increased algal growth and

Corresponding author. Eisley John S. Tiongson
Received: 01.11.2024
Accepted: 12.12.2024
Revised: 12.19.2024
Published: 31.12.2024
DOI: https://doi.org/10.51200/jberd.v10i1

coral smothering (Smith, 2009; Göltenboth, et.al, 2006). These environmental stressors and climate change-induced phenomena like ocean acidification and coral bleaching pose significant challenges to coral reef conservation and restoration efforts (New Heaven Reef Conservation, 2016). To mitigate these threats, artificial reef structures have emerged as a viable solution for rehabilitating degraded coral reef ecosystems. Modern technologies, including 3D printing, allow for the creation of complex, durable artificial reef structures that mimic natural coral formations. These structures not only provide habitat for marine organisms but also serve to raise awareness and promote sustainable marine conservation practices (Dizon, et.al, 2018).

2. Literature Review

3D printing is gaining popularity due to its cost-effectiveness compared to conventional manufacturing methods and its versatility in various fields such as medicine, architecture, and mechanical engineering. Different filaments are used for 3D printing, including PETG, ABS, and PLA, each with its own advantages and disadvantages. Understanding the properties of these filaments is crucial for selecting the most suitable one for a specific application. (Dizon, Espera Jr, Chen, & Advincula, 2018)

This study focuses on designing artificial coral reefs to provide habitats for fish and protect them from predators, aiming to mitigate coral bleaching. UNESCO warns that without significant reductions in carbon emissions, coral reefs worldwide, including iconic sites like the Great Barrier Reef and the Seychelles, could disappear within 30 years due to ocean warming. (Parker, 2017)

2.1. Coral Bleaching and Ocean Acidification

Coral bleaching is a significant threat to coral reefs worldwide, including those in the Philippines. When corals are stressed by changes in environmental conditions such as temperature, light, or nutrient levels, they expel the symbiotic algae living in their tissues, causing them to turn completely white. (National Ocean Service, 2021) This process can have devastating effects on coral reefs, as the algae provide the corals with energy through photosynthesis and give them their vibrant colors.

The Philippines has experienced severe coral bleaching events in the past. For example, between 2009 and 2010, a massive bleaching incident caused by a severe El Niño ocean-warming event led to the estimated death of 95% of corals in the country. (Chan, J., 2020) This event highlighted the urgent need for conservation efforts and innovative solutions to protect coral reefs and the marine ecosystems that depend on them.

By designing artificial coral reefs that provide habitats for fish and protect them from predators, researchers aim to create resilient ecosystems that can help mitigate the impacts of coral bleaching. These artificial reefs can serve as refuges for marine life and contribute to the restoration of damaged coral reefs, helping to preserve these valuable ecosystems for future generations.

2.2. Artificial Reef Projects

In Barangay Talavera, Hinatuan Island, Surigao del Norte, Hinatuan Mining Corp. installed an artificial reef in an area where less than 1% of the country's corals are in excellent condition. The Philippines, known as one of the world's top fish producers, is facing a decline in fish catch, leading the Department of Agriculture (DA) to declare fishing moratoriums to allow fish stocks to replenish. Destructive fishing methods such as trawling, dynamite, and cyanide use have been identified as major causes of coral reef destruction. To address the deteriorating state of the country's corals, a budget of P500 million was allocated for coral reef rehabilitation, prompting the Department of Environment and Natural Resources (DENR) to revisit its ongoing program on the rehabilitation of damaged marine ecosystems. Artificial reefs, defined as structures placed in bodies of water to serve as shelter, habitat, food sources, breeding areas, and shoreline protection, have been installed in the Philippines since the

1970s. These reefs provide ecological functions lost due to coral reef destruction and have been successful in increasing fish catch in fishing communities. Experts suggest that artificial reefs can help mitigate the effects of depleting fish caught by providing ecological functions for young fish and attracting bigger fish that prey on smaller fish. However, proper implementation of artificial reef projects is crucial, as there have been reports of negative effects from some projects. (Mayuga, J., 2017)

2.3. Additive Manufacturing (3D Printing Process)

Additive manufacturing, utilized in 3D printers, offers numerous advantages compared to traditional manufacturing methods. These include the ability to create intricate geometries, optimal material usage, and the elimination of expensive tooling (Rafi et al., 2013). Factors favoring additive manufacturing over conventional methods include low production volumes, high material and machining costs, capital and logistics expenses, transportation costs, and prototyping needs. (Frazier, 2014)

The process begins with the virtual design of the object, serving as a blueprint for the 3D printer. Various software such as AutoCAD, MeshLab, and SolidWorks are used for this purpose, enabling the creation of precise drawings and technical illustrations. Alternatively, a 3D scanner can be used to create a virtual design by capturing images of an existing object from different angles.

Subsequently, the 3D printer starts printing the object's layers through material extrusion. This process involves the nozzle of the 3D printer ejecting a semi-liquid material, such as molten plastic, metal, or cement, following the blueprint of the digital model layer by layer. The extrusion nozzle can move both horizontally and vertically, precisely placing the material to form the object. (GCFGlobal, 2021)

3. Methodology

This paper aims to provide additional alternative artificial reef structures for marine life through 3-dimensional modeling and flow simulations. As shown in Figure 1, the proposed process contains seven steps elaborated in the following procedures.

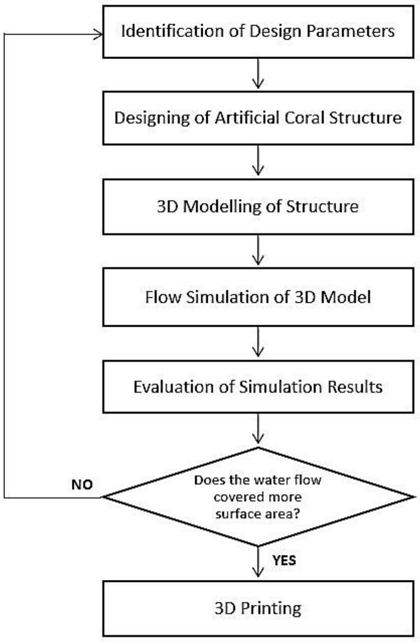

Figure 1.Methodology Flowchart

3.1. Identification of Design Parameters

The initial stage involves the identification of key design parameters essential for creating a new artificial coral reef structure. These parameters include factors like local weather conditions, underwater water flow velocities, the size of fish species, water depth, coral height, and the natural structure of existing coral reefs.

3.2. Designing of Artificial Coral Structure

The design will use the identified parameters to construct three distinct artificial coral formations inspired by two natural coral reef structures. The proposed designs include a fusion of brain and cauliflower coral features, a blend of lace coral with dome coral characteristics, and a composition merging digitate coral attributes with organ pipe coral.

3.3. 3D Modelling of Structure

Once the proposed designs are finalized, a solid modeling computer-aided engineering software, SOLIDWORKS Application, will build the three-dimensional model and assembly for each structure combination. With the help of computer-aided engineering software, the three proposed artificial coral reef models will undergo a computational fluid dynamics (CFD) analysis, enabling us to quickly identify the behavior of the flow of water around the modeled designs.

3.4. Flow Simulation of 3D Model

The three proposed artificial coral reef models will undergo three simulations using the SOLIDWORKS application: stress analysis, flow trajectory, and surface plot vector. These simulations will help evaluate the structural integrity, water flow dynamics, and interaction of water vectors with the coral surfaces, respectively.

3.5. Evaluation of Simulation Result

Following the Computational Fluid Dynamics (CFD) analysis, the study will assess each model based on its ability to cover a significant surface area for water flow effectively. The study will advance to the structure's three-dimensional (3D) printing phase if the simulation demonstrates sufficient coverage. Subsequently, the model will undergo iterative redesign, remodeling, simulation, and evaluation processes to optimize its performance.

3.6. 3D Printing

After achieving the desired results, the three simulated artificial coral reef structures will be simulated using an open-source slicing application for 3D printing before fabrication to identify the printing timeline and proper orientation. Once simulated, fabrication will be done by printing a small-scale model to determine the difficulty of printing the models.

4. Findings

4.1. Design Parameters

The study considered standard weather conditions, ensuring that the results are not affected by unexpected and extreme conditions caused by natural phenomena and human activities. By eliminating the possibility of strong waves, the simulation results may focus on the behavior of the water stream flowing toward the proposed models based on the determined water depth. The velocity of water flow underwater may vary concerning habitat exposure and depth of water. Most common current velocities range from 1.3 to 36.4 cm/s. In this paper, the velocity used in the simulations of three proposed artificial coral reef structures is 36.4 cm/s. The size of fish adapted in the study ranges from 7 centimeters or approximately 2.8 inches for the tiniest individuals up to 17 centimeters or about 6.7 inches for the largest ones.

4.2. Structural Design

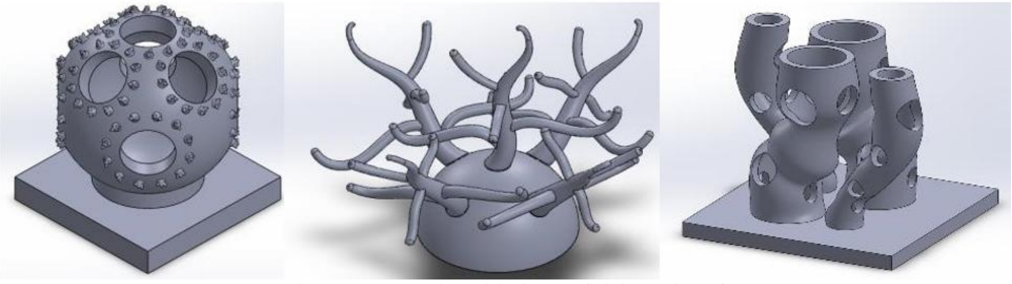

Figure 2.Proposed Models for Artificial Coral Reef

Figure 2 presents the three proposed alternative models for artificial coral reef structures. The first model comprises two main components: the body and small bumps. The body emulates the spherical shape of brain coral, while the small bumps replicate the symmetrical head formation of cauliflower coral. The design includes nine equally spaced 30-cm holes surrounded by 3.30-cm high small bumps on the spherical body's surface. This configuration allows small species to navigate the structure while protecting larger species. The proposed structure is hollow and spherical, standing at 112.70 cm. The second proposed model contains two parts: the base and the stems.

The base was designed according to the relatively flat and circular shape of dome coral, while the branching formation of lace coral inspired the stems. The total assembly height of the design is 96.08 cm with a span of 137.68 cm. There are five stems with a height of 68.61 cm and a span of 87.79 cm each, which are notched on the surface of the base which is a combination of Digitate and Organ Pipe Coral. The last proposed model is designed with four branching projection structures based on the digitated coral and covered with holes adapted from the organ pipe coral. The total height of the design is 122.56 cm with a span of 150 cm.

4.3. Simulation Results

This section presents the results of various tests conducted in the study, each depicted in separate figures. One set of figures illustrates stress analysis, highlighting areas of potential stress concentration in the model. Another set displays the flow trajectory from the inlet valve as it passes through the specimen, indicating how the water flows around and interacts with the structure. Additional figures present surface plots showing water vectors on the specimen's surfaces, providing insight into water behavior upon contact with the structure. Furthermore, goal plots are included to show the numerical values of selected study goals. These results help identify areas of high stress and displacement in the model, aiding in design optimization for real-world applications.

4.3.1. Stress Analysis

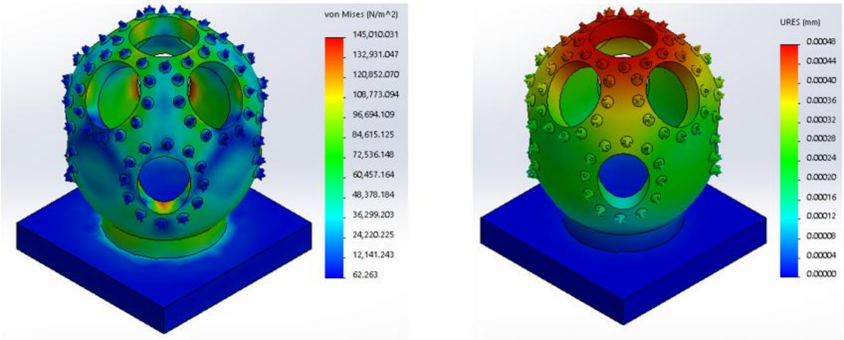

Figure 3.Stress & Displacement Analysis of Brain and Cauliflower Coral

Figures 3 shows the hydrostatic pressure analysis of this specimen. This model couldn’t withstand the pressure of 10 feet and deformed into an oval-shaped object. The study shows that there is a high displacement value, which is shown as the red color at the top of the specimen, which pulls the specimen upward.

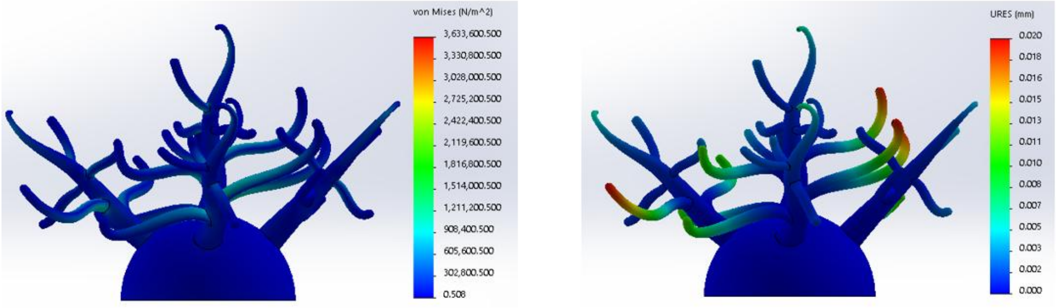

Figure 4.Stress and Displacement Analysis of Lace and Dome Coral

Using ceramic as the material and applying it with a 4.33 psi pressure, the study could observe the data in Figure 4. Stress analysis of the lace and dome coral, where the whole area of the specimen has a low amount of stress. The only noticeable part was the foot of the branches, which showed a little bit of stress compared to other parts of the specimen.

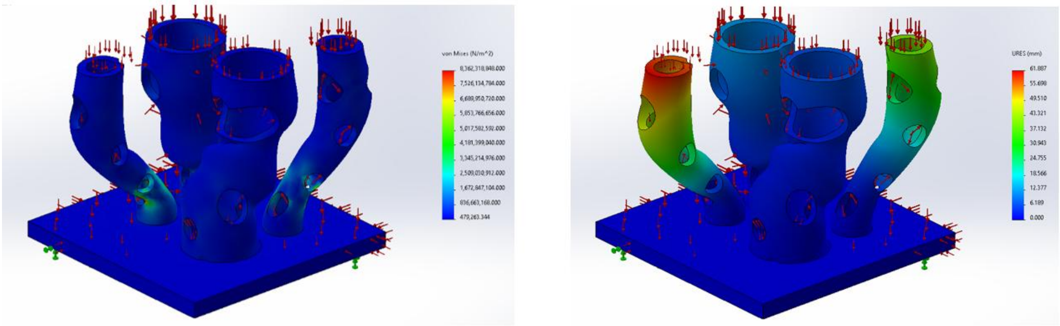

Figure 5.Stress and Displacement Analysis of Digitate and Organ Pipe Coral

Figure 5 provides a visual representation of the specimens' response upon exposure to a pressure of 10 feet. Notably, the model illustrates a remarkable absence of stress, except for the lower body of the thin coral, which exhibits noticeable strain. This observation suggests that the thin coral structure is more susceptible to deformation or damage under the applied pressure. Understanding such stress distributions is crucial for assessing materials' structural integrity and resilience in various underwater environments. The findings from this figure contribute to our knowledge of how different specimens react to specific pressure levels, aiding in the design and engineering of resilient structures.

4.3.2. Flow Simulation Trajectory Results

Computational simulations are conducted to analyze the flow trajectories surrounding these designs, providing insights into water flow patterns. Velocity is measured in centimeters per second (cm/s) during these simulations.

The flow simulation incorporates the visualization of streamlines, enabling a detailed analysis of flow conditions inside and outside the coral structures. This approach allows for a comprehensive understanding of the hydrodynamics affecting each design, aiding in evaluating their efficacy in mimicking natural coral formations.

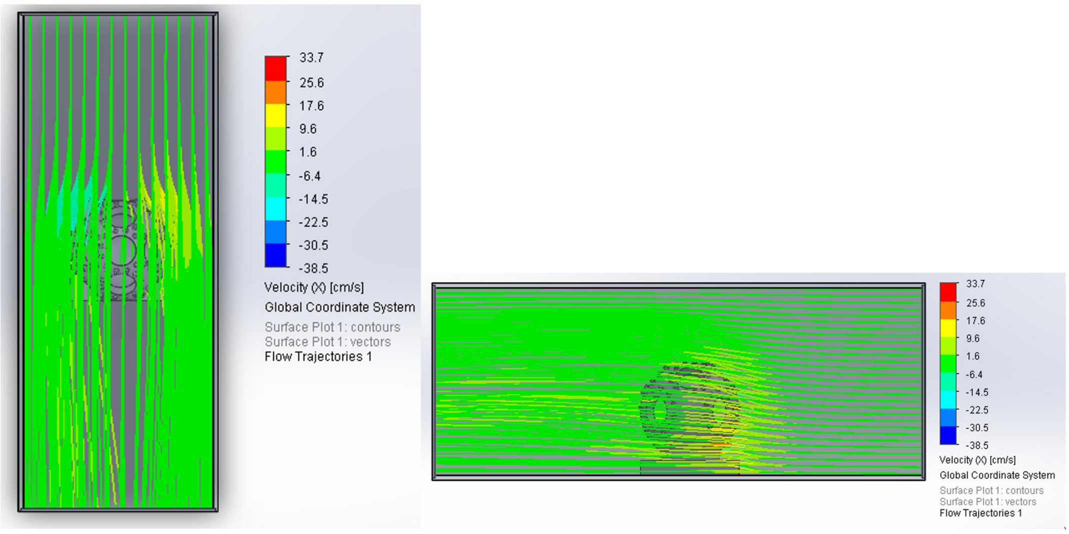

Figure 6.Trajectory Flow Simulation for Brain and Cauliflower Coral

Figure 6 illustrates the flow trajectory outcomes for Brain and Cauliflower corals. Upon impact with the Brain and Cauliflower coral's surface, the flow disperses in various directions and velocities, as depicted by the color spectrum. Red signifies the highest velocity, while blue indicates the lowest. The lower area of the Brain and Cauliflower coral shows the fastest velocity, ranging from 25.6 to 33.7 cm/s (red), and the slowest velocity, approximately -14.5 to -22.5 cm/s (blue).

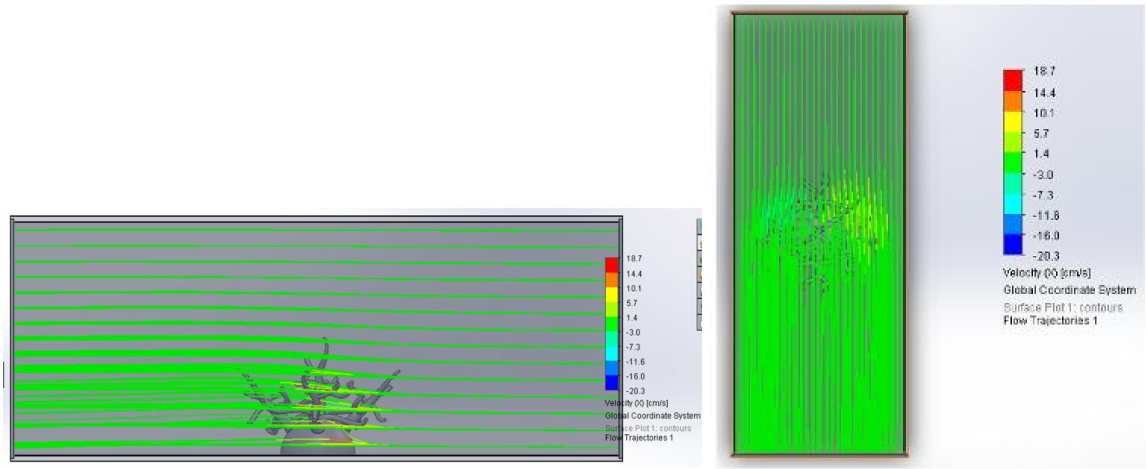

Figure 7.Trajectory Flow Simulation for Lace and Dome Coral

Figure 7 presents the trajectory outcomes for lace and dome coral designs. Similar to the previous model, the flow pattern includes red and yellow markings in the lower section, indicating fast velocities ranging from 14.4 to 18.7 cm/s and 5.7 to 10.1 cm/s, respectively. In contrast, one side of the model features a blue line, representing a lower velocity ranging from -7.6 to -11.3 cm/s. The design is predominantly shaded green, signifying an average speed ranging from -3.4 to 1.4 cm/s.

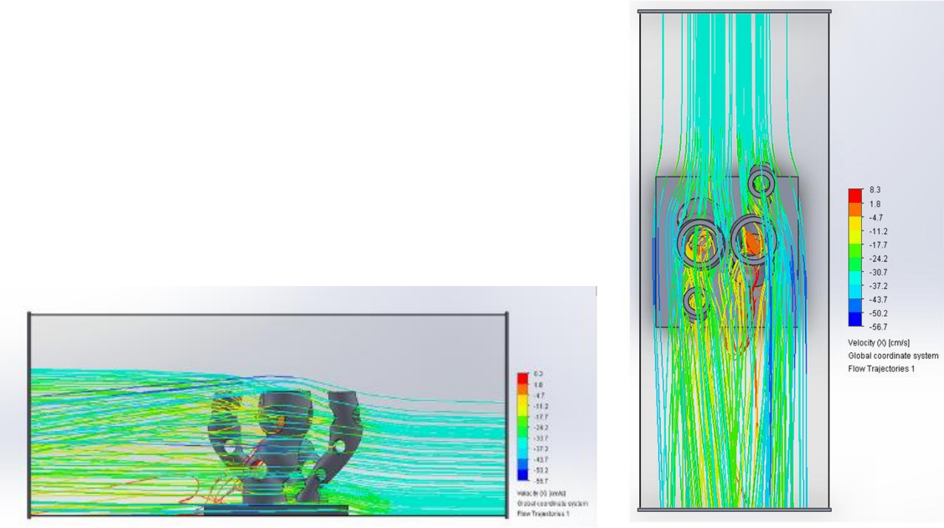

Figure 8.Trajectory Flow Simulation for Digitate and Organ Pipe Coral

Figure 8 depicts the trajectory simulation results for Digitate and Organ Pipe coral designs. Upon impact with the surface of the Digitate and Organ Pipe coral, the flow disperses in various directions and velocities, as indicated by the color spectrum of the lines. Red denotes the highest velocity, while blue represents the lowest. Upon closer examination, it is evident that one side of the Digitate and Organ Pipe coral exhibits a moderate velocity. The study further analyzed the flow and current of water upon impact with the Digitate and Organ Pipe coral. Yellow vectors indicate a faster flow speed, while light blue vectors indicate a slower flow speed.

4.3.3. Surface Plot Vector Simulation Results

The study employs Surface plots with contours and vectors to simulate and analyze Brain coral, Lace coral, and Digitate coral designs. These plots visually depict water surface properties and highlight areas of interest within the designs, such as regions characterized by high velocity and turbulence.

By displaying vectors on the surface of the designs, the study identifies the flow direction in each part of the coral structures. Various angles are examined to understand the flow behavior and distribution throughout the designs comprehensively.

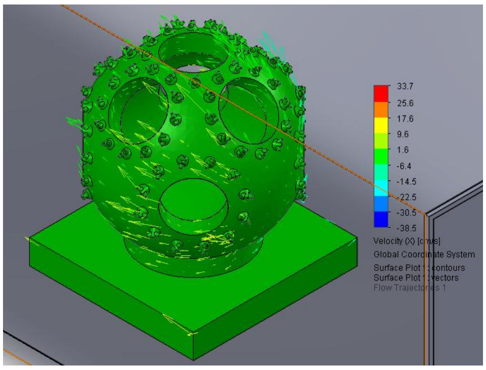

Figure 9. Surface Plot (Vector) for Brain and Cauliflower Coral

Figure 9 depicts the simulation results for Lace and Dome Coral. The study focuses on the water flow behavior upon impacting the coral's surface. The yellow vectors indicate areas with faster flow speeds, ranging from 5.7 to 18.7 cm/s and 14.4 to 18.7 cm/s. Conversely, the blue line represents a lower velocity, ranging from -7.6 to -11.3 cm/s. The predominant green color signifies an average speed ranging from -3.4 to 1.4 cm/s, the overall average speed observed in this design.

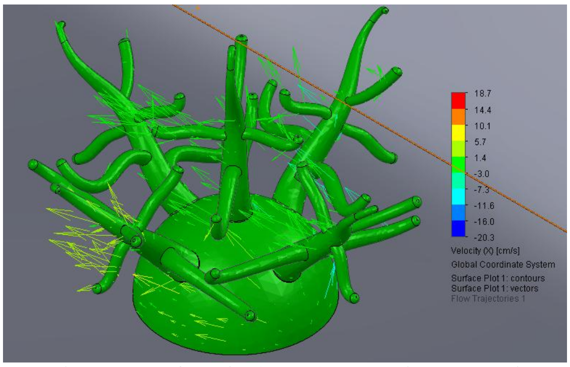

Figure 10. Surface Plot (Vector) Lace and Dome Coral

Figure 10 presents the surface plot vector simulation result for Lace and Dome Coral, analyzing the water flow pattern upon impact with the coral structure. The simulation reveals that the water flow splits into two parts, with one part flowing in one direction and the other in the opposite direction. One side of the coral experiences a faster flow speed, ranging from 14.4 to 18.7 cm/s and 5.7 to 10.1 cm/s, while the opposite side exhibits a slower flow speed, indicated by light blue vectors ranging from -7.6 to -11.3 cm/s. This design demonstrates a balanced flow distribution, with both sides of the coral receiving adequate water flow coverage.

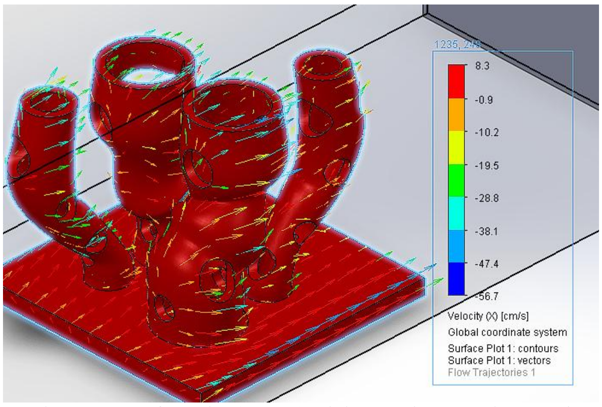

Figure 11. Surface Plot (Vector) Digitate and Organ Pipe Coral

Figure 11 illustrates the surface plot vector simulation results for the Digitate coral. The study examines the water flow dynamics upon impact with the coral's surface in this segment. The yellow vectors indicate areas with faster flow speeds, ranging from -19.5 to 10.2 cm/s, while the light blue vector represents a slower flow speed, approximately -28.8 to -47.4 cm/s. The predominant green color signifies an average speed ranging from -9.5 to -47.4 cm/s, the overall average speed observed in this design.

Table 1. Flow Trajectory Summary

Coral	Minimum Velocity (cm/s)	Average Velocity (cm/s)	Maximum Velocity (cm/s)
Brain and Cauliflower Coral	-40.1349	-0.073657	34.6553
Lace and Dome Coral	-20.9681	0.000561129	19.1094
Digitate and Organ Pipe	-62.0943	-37.2216	8.68965

Table 1 outlines the minimum, average, and maximum velocity values, along with turbulence characteristics, for three coral reef designs: Brain and Cauliflower Coral, Lace and Dome Coral, and Digitate and Organ Pipe Coral. Velocity is measured in centimeters per second (cm/s), and turbulence is represented as a percentage. These values provide insights into the water flow required to sustain a healthy coral ecosystem.

Brain and Cauliflower Coral's minimum velocity is -40.1349 cm/s, indicating the water flow must not fall below this level to maintain a healthy ecosystem. The average velocity is -0.073657 cm/s, suggesting a minor backflow on average, while the maximum velocity of 34.6553 cm/s represents the highest flow speed around this coral design.

Lace and Dome Coral's minimum velocity is -20.9681 cm/s, the threshold below which water flow must not drop to support a healthy ecosystem. The average velocity is 0.000561129 cm/s, showing a near-stagnant average flow, with a maximum velocity of 19.1094 cm/s marking the peak flow observed around this coral type.

Digitate and Organ Pipe Coral's minimum velocity is -62.0943 cm/s, highlighting the necessity of maintaining water flow above this level for a healthy coral ecosystem. The average velocity is -37.2216 cm/s, reflecting a consistent backflow around this design. The maximum velocity, at 8.68965 cm/s, denotes the highest flow speed recorded around this coral.

4.4. 3D Printing Process (Additive Manufacturing)

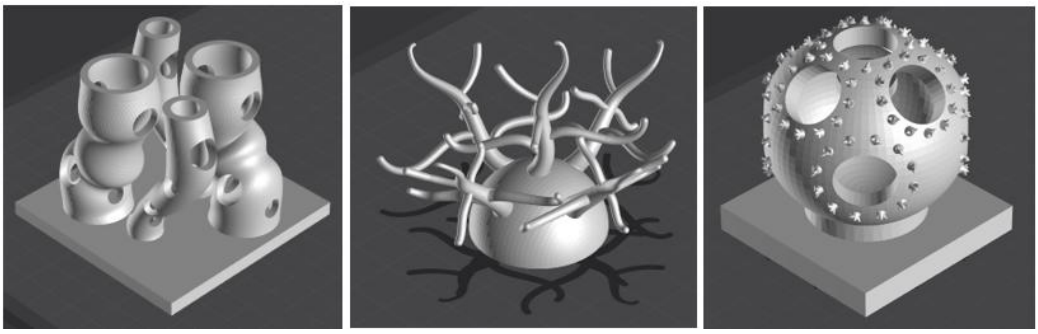

Figure 12.3D Model of Artificial Coral

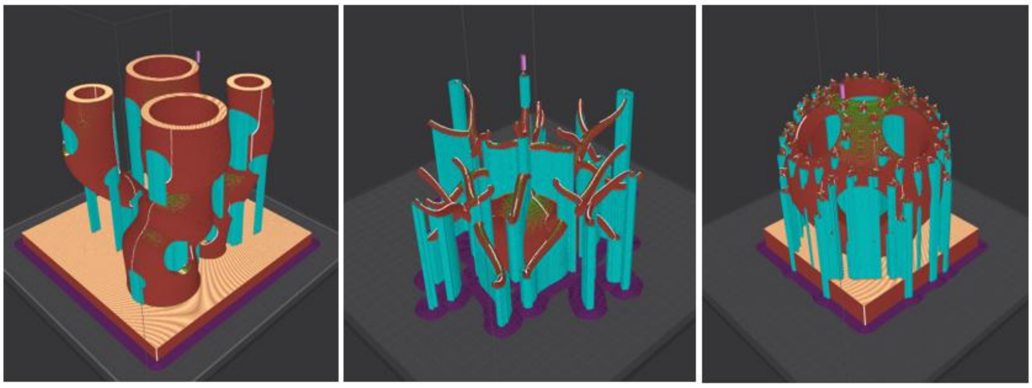

Figure 13.3D Printing Simulation of Proposed Models for Artificial Coral Reef

Table 2: 3D printing time and completion

Coral Structure	Printing Time	Dimension
Digitate and Organ Pipe	43 hours and 26 minutes	x – 225 mm y – 225 mm z – 183.85 mm
Lace and Dome Coral	11 hours and 58 minutes	x – 208.34 mm y – 200.2 mm z – 144.28 mm
Brain and Cauliflower Coral	32 hours and 10 minutes	x – 154.32 mm y – 154.32 mm z – 171.60 mm

Figure 12 represents the 3D printing simulation of the three proposed artificial coral reef structures with the help of Creality to identify the proper orientation and duration time of printing. Additionally, support in printing was activated to help achieve the designed formation. Table 2 tabulates the time of completion for each proposed artificial coral reef model, which includes the main structure of the artificial coral reef and its supports.

Figure 13 shows the small-scaled 3D printed model of the proposed models. Polylactic Acid (PLA) filament was used as material for the printed models and Creality 3D Printer was used as a tool for printing.

5. Conclusions

The study sought to emulate natural coral formations in designing artificial coral structures, including brain and cauliflower corals, lace and dome corals, and digitate and organ pipe corals. Computational fluid dynamics (CFD) analysis was employed to simulate the behavior of these artificial coral structures in ocean currents.

Among the designs examined, the brain coral design exhibited a limited water flow coverage, indicating potential inefficiencies in nutrient delivery and waste removal. In contrast, the lace and dome coral design and digitate and organ pipe coral design showed more promising results.

The digitate and organ pipe coral design demonstrated the most favorable outcomes. It exhibited the lowest velocity compared to the other designs and displayed a larger coverage area of water flow. This suggests that the digitate and organ pipe coral design is more effective in mimicking natural coral structures and provides a greater surface area for planulae attachment, enhancing the likelihood of successful coral growth and reproduction.

These findings underscore the importance of design optimization in artificial coral structures to support coral reef restoration and conservation efforts.

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Engr. Eisley John Tiongson is a registered and licensed Mechanical Engineer with over five years of experience in academia. He earned his Bachelor of Science in Mechanical Engineering from Adamson University in March 2017 and completed his Master's degree in Precision Mechatronics Engineering from MingHsin University of Science and Technology in Hsinchu, Taiwan, in June 2019.

Engr. Tiongson is deeply passionate about sustainability and leverages his expertise to contribute to the United Nations Sustainable Development Goals (UNSDG) for 2030. His research focuses on innovative solutions that promote environmental sustainability and energy efficiency.

In addition to his research, Engr. Tiongson is dedicated to educating the next generation of engineers. He has been a valuable member of the academic community, where he shares his knowledge and inspires students to pursue careers in engineering and sustainability. His commitment to both teaching and research underscores his role as a leader in the field of mechanical engineering.

Engr. Tiongson's contributions to sustainability and education have positioned him as a respected figure in the engineering community. His ongoing efforts to integrate sustainable practices into engineering solutions