BIOINSPIRED STRUCTURES IN LIGHTWEIGHT PRODUCT DESIGN WITH ADDITIVE MANUFACTURING

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ABSTRACT

Bioinspired lightweight product design involves complex geometries that are difficult to be made with traditional manufacturing processes. A unique way to create such complex geometries is through additive manufacturing. The overall objective of this research is to take a systems approach for the design of lightweight structure material systems. The system approach consists of four dimensions including unit structures, functionality, material layers, and physical properties. A case study is conducted based on aux, balsa wood, and auxetic structures for the lightweight material design. 3D model tests (e.g. finite element analysis and sustainability analysis) and physical tests are conducted on the developed materials and served for target purposes. The results of this research offers new insights into the design, manufacture and application of smart lightweight structures in engineering fields and contributes to the engineering management by providing a systems engineering approach to the lightweight material structure design realm.

Key Words: Bioinspired design, sustainable manufacturing, green design, additive manufacturing

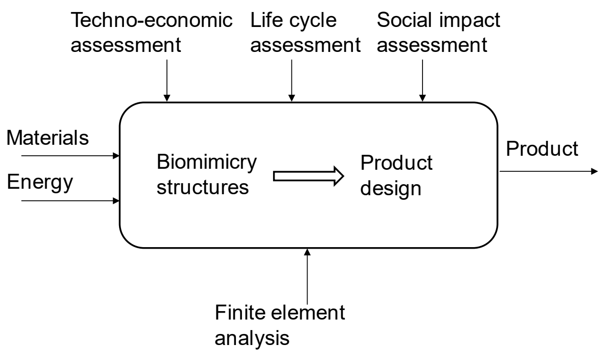
1. INTRODUCTION

The worldwide climate change imposes collaborative efforts from government, industry, and academia. In advanced manufacturing industry, efforts have been focused on reducing materials, energy, and enhance circular economy of final products. The Chinese government has released plans for “China Manufacturing 2025” including “The Development of Additive Manufacturing Industries”, “Industrial Green Development Plan”, and “Guidelines for Green Manufacturing Engineering Practices” (European Union Chamber of Commerce in China, 2017). Throughout a product’s life cycle, design is the most influential activity to determine the environmental impact and carbon footprint over the manufacturing, transportation, use, and end of life stages. Among many design theories and methods, bioinspired design learns from nature or biology to stimulate design ideas for various product purposes such as light weight, high strength, and resilience. The complex structures from bioinspired design are usually not able to be created with traditional manufacturing processes. A unique way of making these geometries is through additive manufacturing which creates complex structures layer by layer.

Research in bioinspired sustainable product design has created light weight structures (Zhang, Nagel, Al-Qas, Gibbons, & Lee, 2018), biomaterials (Zadpoor, 2017), as well as function based (Nagel, Stone, & McAdams, 2014) products. The complex structures that additive manufacturing is capable of implementing could increase the product’s overall functionality as a whole, while reducing the amount of energy and natural resources consumed during the production process. But of the few rigorous environmental assessments that have been completed, one study compared the different technologies used throughout additive manufacturing and discovered that laser-based methods had the greatest potential to reduce the environmental impact (Morrow, Qi, Kim, Mazumder, & Skerlos, 2007). Among the laser-based additive manufacturing methods Selective Laser Sintering (SLS) was found to be the most appealing when considering the environmental impact due to its low energy consumption, minimal waste products, and a favorable total energy indicator (Frazier, 2014). Overall additive manufacturing is considered more environmentally friendly than conventional manufacturing due to the reduce in material consumption, energy consumption, and water usage (Huang, Liu, Mokasdar, & Hou, 2013). Additive manufacturing also does not require near the amount of coolant/ auxiliary inputs nor does it generate the amount of material that enters a landfill compared to conventional manufacturing (Huang et al., 2013). Therefore, additive manufacturing is expected to become the preferred method of manufacturing due to its flexibility and long-term sustainability. Sustainability assessment research have been primarily focused on traditional manufacturing processes (Epping, Zhang, Epping, & Zhang, 2018), work cells (Zhang & Haapala, 2015), and systems (Zhang, Calvo-Amodio, & Haapala, 2013). While research have been conducted on separate areas of bioinspired design, additive manufacturing, and sustainability, the literature on bioinspired design and sustainable additive manufacturing is limited. Therefore, the objective of this research is to identify biomimicry geometric structures for product applications, assess the functionality, economic, and environmental impacts of the selected biomimicry geometric structures, and implement the biomimicry geometries through an additive manufacturing process.

2. Method

In this study we will be following the outline seen in Figure 1. This study begun with in depth research into the various additive manufacturing techniques (Deposit Energy Deposition, Selective Laser Sintering, Material Jetting, Sheet Lamination, etc.) and the associated materials that those techniques can utilize (Titanium, Aluminum, Polymers, Alloys). An additive manufacturing technique was selected based upon the conducted research that presented thorough information in the following areas, but not restricted to, material processing capability, precision and accuracy of the technique, projected environmental impact, machine purchase cost and local availability to the technique. Once a technique was decided upon, then research into biomimicry structures was conducted; focusing on: the most commonly used in industry, most commonly used in laser-based additive manufacturing methods, structure applications in different facets of industry, structure application to product needs.



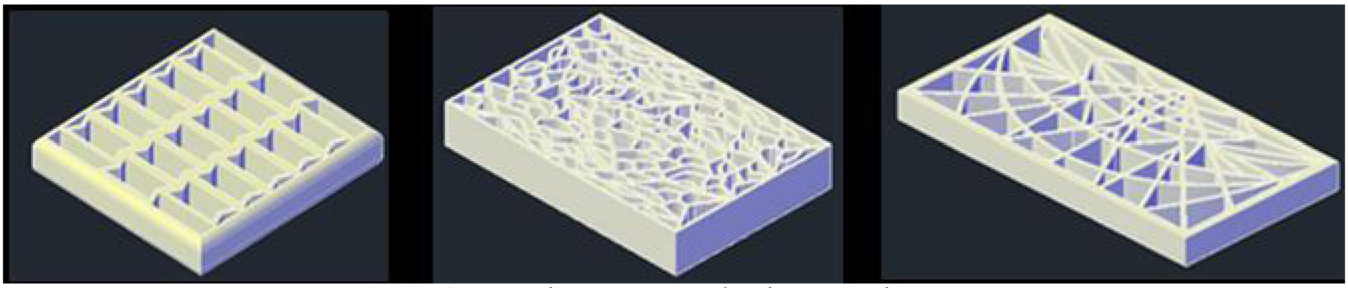
[Figure 1] Research Methodology

With an additive manufacturing technique, selected material of interest, and decided upon structures were discovered; came the need to develop multiple 3-D computer aided design (CAD) models. The models were designed to allow for each of the selected structures (diamond, honeycomb, lattice) to be applied to and in such a way to reduce variation (or structure favorability) during the assessment of the structures. With completed 3-D CAD models, the techno-economical assessment (Life Cycle Cost Analysis), Life Cycle Assessment (LCA), and Finite Element Analysis (FEA) could be completed (by basing assessments off of the generated 3D CAD models). From these assessment results, there will be the identification of the best performing structure, with respect to economic feasibility and environmental impact.

Life Cycle Cost Analysis is a tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain and, finally, dispose of an object or process, when each is equally appropriate to be implemented on technical grounds (Cole & Sterner, 2000). Finite element analysis (FEA) is a computer simulation to predict how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects (Hughes, 2012). Finite element analysis shows whether a product will break, wear out, or behave the way it was designed. In a general sense, it is used as a prediction method for what is or might happen to the product once the product is used. Life cycle assessment is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use (ISO, 2006). The methods are integrated into the framework above to systematically evaluate the function and sustainability of the designs.

3. ANALYSIS AND RESULTS

The biomimicry structures that were chosen to create and test on were auxetic, bone tissue, and lily pad structures. To understand each of these structures, 3D models of the structures were created within AutoCAD. Multiple tests were conducted on each structure with finite element analysis, static analysis, and fatigue analysis as mentioned above. Figure 2 shows the cross section of the three structures selected in their 3-dimensional form. The tested structures have the geometries fill the entire 3 x 3 x 1 block in order to obtain accurate data on how they react under various forces and pressures. These models also more accurately represent how these geometries can be used in various parts and tools through various industries.



[Figure 2] Bioinspired structures: Giant Lily pad, Auxetic, and Bone tissue

FEA was conducted using Solidworks to test how different designs would react to minimal force all the way up to major forces to better understand how each structures properties are exhibited. For the static analysis 10lbs, 100lbs, 500lbs, 1000lbs, and 1500lbs force were applied from both the top and side of the model, as seen in the figure. As for the fatigue analysis the model was subjected to the same sources over 10,000,000 cycles in order to analyze the damage done to the part.

It was clear across all models that the 500lbs force showed significant change in the model. From the testing results, the auxetic structure experienced the greatest deformation and stress compared to the bone and lily pad structure. This can be due to the fact that the auxetic structure has the ability to expand perpendicular to side where the force was applied, which within the closed model cause too much stress throughout the entire structure especially under high forces. Where the properties of the lily pad and bone have high strength and stiffness which allow it to withstand high external loads.

Overall, it can be concluded that the bone withstood the lowest amount of damage over the 10,000,000 cycles at 9.31679E-014. The lily pad took the largest amount of damage at 1.56735E-012 which was expected due to the fact that it had the highest porosity and vascular nature making it more likely to break under high sustained pressure. It should also be noted that the bone structure had highest life cycle meaning it is expected to fail later then the other two structures on both the side and top force results. In general the bone held up the best over time likely due to its high stiffness and strength allowing sustain high pressure.

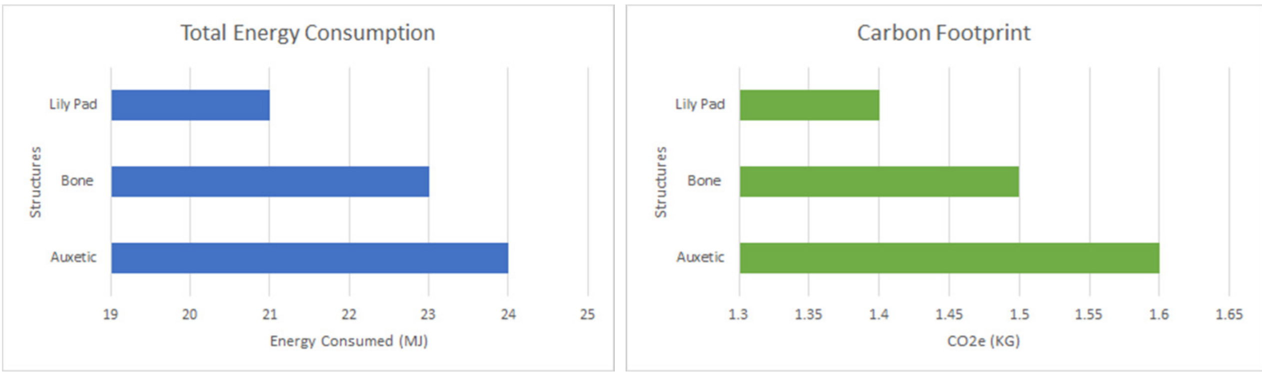
Figure 3 shows the life cycle environmental impact results on energy consumption and carbon emissions. For the auxetic structure the total amount of energy consumed for material, manufacturing, transportation, and end of life was 24MJ with the majority of the energy consumed being in materials. Across all categories excluding air acidification materials had the greatest overall impact. This is due to the material consumption and energy use during material preparation for the additive manufacturing process.

For the bone structure the material has the greatest contribution to carbon footprint at 1 kg and the manufacturing of the part at .445 kg. This number is much less when comparing to the carbon dioxide emissions from subtractive manufacturing. The total energy consumed is 23MJ with the greatest contributor being the material. The greatest air acidification factor can be attributed to the manufacturing at 2E-3 kg of sulfur dioxide.

Similar results were shown among the lily pad structure for the sustainability analysis with total energy consumed being a total of 21MJ which is the lowest across all three structures. The material can be attributed as the greatest contributor among the carbon footprint, total energy consumption, and water eutrophication. Similarly to auxetic and bone the greatest contributor to air acidification is the manufacturing process. This lily pad structure is the most sustainable across all categories of our analysis.

Overall, the lilypad structure consumed both the lowest amount of energy and had the smallest carbon footprint. This is due to its high porosity and vascular structure which requires less materials than the rest of the structures.

[Figure 3] Energy consumption and carbon footprint from the three structures



4. CONCLUSION

Additive manufacturing has tremendous capabilities across various fields of industry including automotive, aerospace, architecture, and medical fields. The major bottleneck seen in AM is the timely process design limitations. Through the introduction of bioinspired design presents solutions to structural integrity and material reduction. This paper aims to develop a systematic methodology to identify biomimicry geometries for product applications. The systematic methodology is intended for design engineers by providing a systems engineering approach to the lightweight material structure design realm. Furthermore, the end goal is to assess the functionality, economic, environmental, and social consequences from production with AM processes.

The method integrates concurrent considerations of multiple additive manufacturing design and bioinspired design factors including raw material quality (e.g., size, shape, internal porosity), processing parameters (e.g., laser power, roller speed), and functionality of the product (e.g., stress, strain, displacement). Sustainability assessment methods (e.g. life cycle costing, life cycle assessment) have been used for evaluating cost and environmental impact for processing different geometries. Finite element analysis is used for product functionality testing. A case study is conducted on making a unit Titanium product with selective laser sintering process. Three structures were examined: lily pad structure, bone structure, and auxetic structure. Cost assessment considered material, labor, energy, and equipment components. A cradle to grave life cycle assessment was conducted to assess environmental impact, including material, manufacturing, transportation, end of life plan. The results show that lily pad structure yields lowest cost and environmental impact. This study reveals that the model can be applied in additive manufacturing early product design and it assists researchers and engineers in their exploration of new bioinspired geometries that could be applied to industrial products. Future research will be focused more on physical testing of these geometries as well as modified versions and new designs. Some physical tests to be conducted include stress, strain, displacement, and different temperatures and environments. Topology of the product also needs to be studied with physical prototypes.

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