DE GRADUS

Programming heterogeneous performance of functionally graded bio-polymers for degradable agricultural shading structures.

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Abstract. This paper presents an holistic approach to the digital design and fabrication of fungi- and algae-based biopolymers, based on studies and simulations of material properties and post-fabrication behavior. The research is motivated by the problem of plastic waste, the need to create more sustainable manufacturing processes, and the opportunity for material composition and organization to be informed by performance, leading to homogenous, complex and integral architectural elements for temporary architecture of agricultural shading systems. The paper details design and specification methods for functionally graded biopolymer panels, as well as fabrication methods through the making of prototypical built elements. The research details parallel trajectories of: material exploration made out of renewable and biodegradable resources available and abundant in every habitat on the earth; advancement in tools and methods for in-situ robotic additive manufacturing of viscous bio-polymers; development of the strategy for functional grading of the material properties to optimize site specificity and material distribution, and to reduce building material waste. It presents comparative material characterizations, an integrated simulation-based approach to support the process of programming localized performance, and architectural application tested via full-scale prototypes.

Keywords. Functionally graded material; bio-polymer; programmable matter; robotic farbication; multiscale modeling.

1. Introduction

Architecture and building materials are often assumed to be everlasting, while temporary architecture is most often associated with ease of disassembly and transportation - the use of prefabricated and standardized modular components determines the principles of architectural design. Prefabricated elements are built off-site and assembled on-site. Materials and architectural components intend to be disassembled and reused, following the circular economy and sustainable concept of the closed life cycle. Nonetheless, waste management is a large concern

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in the construction industry. The United States generates 160 million tons of construction and demolition waste annually, where demolition was responsible for 90% of the total waste in the year 2000 (Cruz Rios, 2018). Furthermore, building construction and manufacturing industry consume 40% of the total amount of raw materials needed in the global economy (Akbiyikli et al, 2012). And those materials such as sand and minerals are finite. Moreover, the industry is accounted for 36% of global final energy use and represents the largest share of total global energy-related carbon dioxide emissions, which in 2017 achieved nearly 40% (IEA/UNEP, 2018). The implications of this contemporary practice challenge architects and engineers to rethink their approach to materials, design and fabrication processes.

Modern human-made structures are inefficient when compared to nature, which creates complex, dynamic structures, with functionally graded material properties, able to adapt to changes in environment and reuse the biomass. Mass production and industrial automation contributed to generalization of the architectural elements and compartmentalization of form-making as a process independent of its sources in material knowledge. The complexity of biological organisms is based on matter and it results in multi-functionality of the body, having structural hierarchies and customized dynamic functionalities (Keating, 2016). The gradient of material properties allows complex functionality and benefits, such as the improvement of the weight vs bending strength ratio generated by the radial density in bones (Michalatos and Payne, 2013). With current computational design tools and possibility of use new technologies in fabrication, architects and engineers are able to advance complex structures and material optimization.

Functionally graded materials (FGM) are a relatively new generation of materials characterized by gradient variation of micro-structure and mechanical properties - according to prefixed requirements. They consist of two or more constituent phases with a continuously variable composition creating properties that change spatially within the structure, for instance in order to design components optimized for specific applications (Maalawi, 2018). Human-made FGM was first introduced in 1984 in Japan during the Spaceplane project in order to develop a thermal barrier capable of withstanding surface of high temperature gradients.

An environmental crisis and a problem of white pollution encourage numerous investigations focusing on novel, sustainable materials such as bio-polymers - an alternative for non-bio-degradable plastics based on fossil raw materials. Polysaccharides, proteins and lipids are degradable polymers from renewable, cheap available, bio-compatible and environmentally friendly ingredients - these include recently extensively investigated: cellulose, starch, chitosan, seaweed such as alginate, carrageenan, agar (Abdul Khalil et al., 2016). **Bio-polymers (BP)** can be reproduced anywhere without special facilities.

2. Background

In 2011 researchers at Harvard's Wyss Institute have developed *Shrilk*-**chitosan-based bio-polymer (CBBP)** isolated from shrimp, which exhibits the strength of an aluminum alloy, being at the same time twice lighter (Fernandez and Ingber, 2011). Chitin is a BP which occurs naturally as a major component in the skeletal or exoskeletal structures of lower animals, arthropods and fungi. It has structure similar to cellulose, however, it provides more rigidity to the structures. (Fernandez et al., 2014) have advanced a method to fabricate 3D objects out of this BP, with complex shapes using traditional casting or injection molding manufacturing techniques.

The fabrication method of crustacean-derived BP was further explored by MIT Media lab, which has developed a water-based additive manufacturing process of crustacean-derived CBBP (Mogas-Soldevila et al., 2014). Robotic fabrication based on the extrusion system allowed to produce large-scale 3D objects omitting the need of molds. Composites were premixed and extruded or mixed statically at the nozzle on-the-fly, achieving a wide range of material composition and enabling the deposition of functional material gradients. Extruded artifacts were homogeneous in form, but various proportions of the material components gave different material properties, which shaped the leaves resembling objects.

3. Aims and goals

3.1. CONCEPT OF BIO-DEGRADABLE SHELTER

If the life cycle of the products begins with the biodegradable materials, one doesn't need to concern about potential recycling - moreover, the matter of the objects could be recycled - not by saving the materials, but by commanding the objects to decompose into programmable particles or components that then can be reused to form new objects and perform new functions.

One of the significant contributor of the plastic waste production is an agricultural sector. Although it has minor contribution to the total plastic waste production (5%), it is recognized as a sector significantly able to commit to the plastic waste reduction (De Lucia and Pazienza, 2019). The plastic membranes are used to cover the soil for purposes of weed suppression, temperature enhancement, fertilizer uptake and more. This phenomenon has been defined as a "plasticulture" (Xiong et al., 2019). The long-term residue of plastic mulch in the farmland destroys the structure of the soil, causing the decline of the farmland quality. Moreover, the plastic residues turning into micro-plastics through the natural environmental degradation (Xiong et al., 2019). New bio-polymeric materials offer an alternative perspective: that of structures and systems that are programmed to disappear. Within an agricultural context, this implies structural life-cycles that after the seasonal use return to nature and enrich the soil, to grow the raw resources and use them again as a building material, and necessitates new design and fabrication perspectives that integrate structure, daylighting and color, and which can create localized and sustainable in-situ manufacturing processes.

3.2. SUSTAINABLE DESIGN TO FABRICATION PROCESS

The primary goal of the research employed an integration of the design process from the ground-up by synthesizing material creation, digital modeling, robotic fabrication and assembly in a holistic approach - based on the structural and optical demand of the agricultural shelter. Within this framework, several sub-questions have been investigated. Material-based design approach attempts to create a material which would degrade and through that - be beneficial for the farmland soil and agriculture. Likewise, this gives an opportunity to begin the process from the raw resources and make the bespoke design and construction process easy and affordable to everyone. On the other hand, this investigation undertakes a probe of decrease the overuse of material resources by the building construction sector and tests an approach of informing the digital model by the material properties data to build with minimal material and maximum performance. In this way it obtains construction and assemble of the architectural parts in the most possible sustainable process, which includes use of the local raw materials and in-situ fabrication.

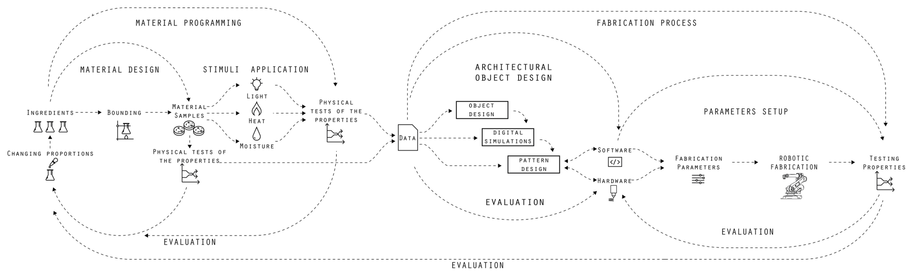

Figure 1. Workflow of the design to fabrication process integrates material design and its behavior, digital model, hardware and fabrication logic.

4. Methods

The key challenge of this investigation was to integrate the material composition and behavior, digital modeling, hardware tool with fabrication in the way that the form generation is driven by maximal performance with minimal resources through local material property variation. To obtain that, a multi-scale modeling approach was introduced. The design problem is decomposed into distinct but interdependent models according to scales and data is transferred between these models (Nicholas et al., 2015). It contains of three scales: micro, meso and macro, which are responsible for material design, pattern design and architectural design.

The investigation was based on parallel trajectories of : material exploration made out of renewable and biodegradable resources available and abundant in every habitat on earth; advancement in tools and methods for in-situ robotic additive manufacturing of BP; development of the strategy for functional grading of the material properties to optimize the material distribution and reduce the building material waste. Following this constraints, methodology of this research was based on the circular design workflow, where each phase informs another, which was a consequence of the ambition to connect an empirical material design with a formal architectural approach.

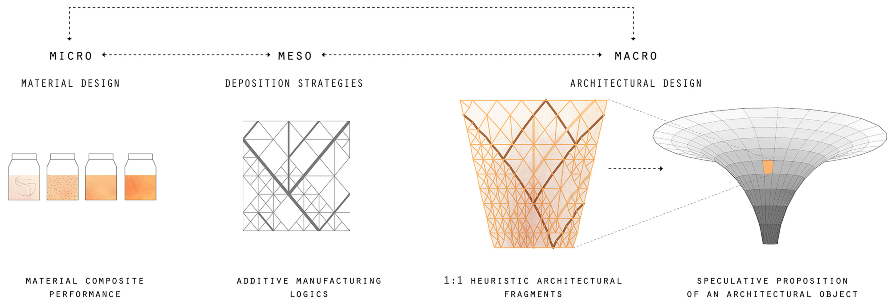

Figure 2. Scales of an architectural exploration incorporate material design (micro scale), deposition strategy within a pattern (meso scale) and architectural design (macro scale). .

4.1. MATERIAL COMPOSITION

The research was initiated by an empirical experimentation of the material search. Compounds of the base ingredients: fungal chitosan, seaweed derivatives agar-agar and sodium alginate were mixed with water, acetic acid and other additives like glycerin, olive oil, in various proportions.

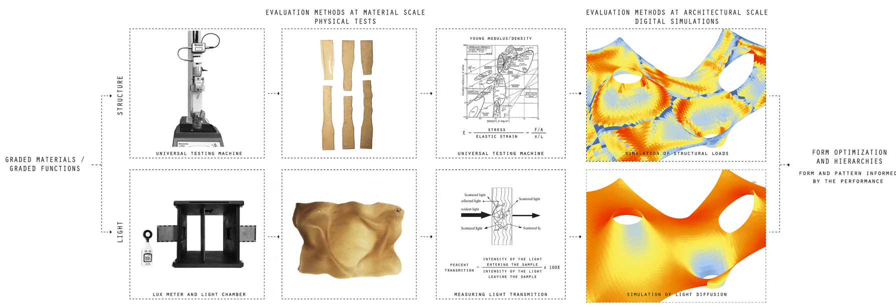

Figure 3. Methods of material evaluation develop material intuition through simulation.

Changing the proportions of these constituent ingredients results in a diverse property of the material samples, which varies on few levels: elasticity, stiffness, mechanical strength, flection, tension, transparency, density, color, transparency, strength and flexibility. Due to certain requirements of the architectural proposal, only color, transparency, tensile strength and elasticity were taken into consideration in this investigation. The material samples were tested using a universal testing machine to test the tensile strength and elongation. The best results show probe which consist of 12% chitosan with a thickness 0.02 mm, engineering stress σ= 19.2 GPa, maximum force Fn=21.3 N and Young Modulus

E=5.1 GPa, however elongation of the sample achieved only 2%. Adding 5% glycerin to the mixture improves ductility of the material to E=22%, at the same time reducing significantly tensile strength. The transparency was tested in the light chamber with a lux meter. The emission of the light through samples varies from 67 lux (9% chitin, 5% glycerin) to 1120 lux (15% chitin, 2% sodium alginate, 2% olive oil) with a light in chamber 1170 lux.

4.2. COMPUTATIONAL FRAMEWORK OF PROGRAMMABLE PERFORMANCE

FGM are those whose properties can be adjusted accurately and continuously and tailored to their particular use. The aim of this research was to create a system that gradually varies its functionality by varying the properties to achieve: an optimization of the structural performance of a tensile structure, decrease the solar radiation and gradation of the color of the material depending on the high of the structure. The gradient of transparent on the bottom, through yellow and red on the highest position on the structure, was determined by agricultural purpose of the membrane, where red is considered as a color which attracts insects. The structural and visual characterizations of the material grading were informed by the tests of the samples with various proportions of the components. Therefore, the project develops through an iterative cycle of physical and digital prototyping. The gradation of the material properties - rigid and pliable, transparent and solid or colorful, heavy and lightweight - is possible by combining the components with a particular property in various proportions. The variability of the material distribution aims to create a complex, multifunctional body.

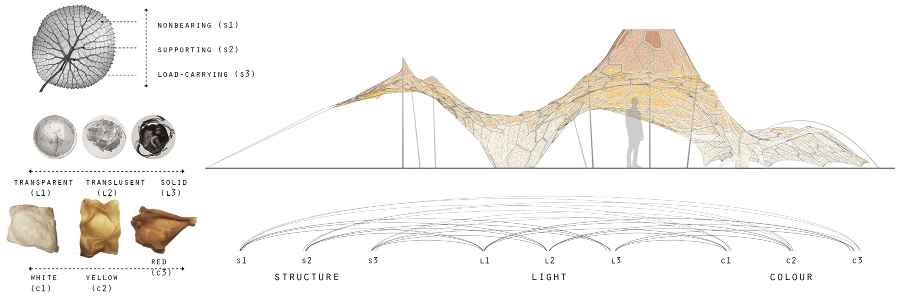

Figure 4. Left: The key parameters for a material distribution: Structure, Light and Colour. Right: Visualisation of a digital model with generated data about material distribution.

The global shape of the architectural membrane was form-found using a physics engine in mind to be reminiscent of typical membranes used on farmlands. The membrane was divided into the elements to simplify the assembling process, which were further generated by clustering the mesh points using the k-mean method, which relies on a simple machine learning algorithm. The learning input included position of the elements and direction of the mesh normals. The elements were further partitioned using aforementioned algorithm and their edges were subsequently relaxed and developed into specified pattern of customized panels for the sake of fabrication and assemblage. The functionality of the materials implemented in the system was investigated in two main directions: structure and light. Therefore, the structural performance of the global form, as well as solar radiation on a specific site, were computationally simulated.

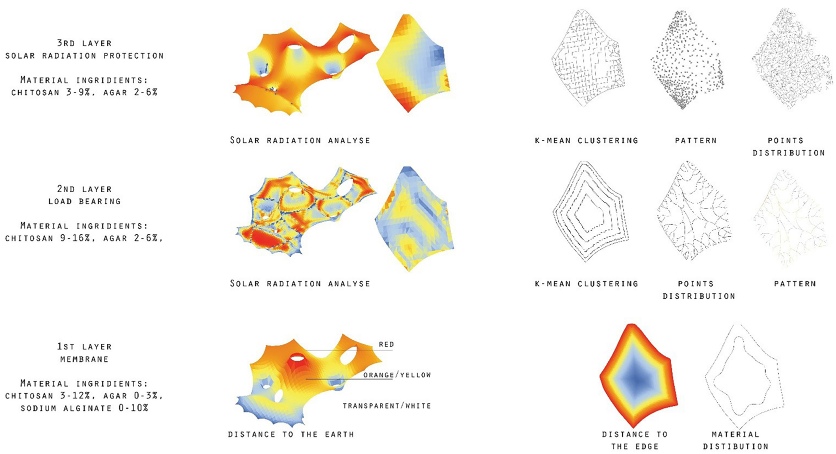

Figure 5. Digital model informed by the data of the material results and simulation of structural performance, solar radiation and distance to the ground as a base for pattern generation of material deposition.

Grading of the materials was obtained by generating distinct layers for specific functions. Thus, three layers of customized patterns were generated for each panel. The first layer acts as a membrane and it is specified by the distance to the ground. Therefore, the upper panels of the structure are red (in order to attract insects) and the closer to the ground, the more yellow, white and transparent the material becomes. The material grading on this level was achieved on the macro scale by creating one material composition per one panel. The composition was adjusted by changing the components: agar-agar, chitosan and sodium alginate in order to reach desired color and transparency. Additionally, the area of the edges contains more glycerin, which makes the material flexible in order to enable sewing to assemble the panels together. Next layer consists of load-bearing pattern, informed by the simulation of the structural behavior of the membrane. Points on the mesh of the panels were grouped by the k-mean clustering method by the distance to edges and structural behavior. On this base, a branching pattern with varying width was generated. Parallel to the visual pattern, the database which informs the robot about material composition was created. This varies based on the computational simulation results and the physical tests of material samples. The chitosan differs between ratio 9-16 % and agar-agar 2-6%. The higher the ratio of both ingredients is, the stronger and heavier is the pattern. The final pattern is responsible for the solar radiation protection. Therefore, the pattern of this layer was created by grouping areas of similar radiation results of the computational simulation. For each of the areas random points were generated with various density and connected it with the shortest path. In this way the created pattern was denser for the areas with the highest radiation results. As in the previous layers, parallel to the pattern generation, the data for fabrication process were created. This varies in ratio of chitosan, agar and sodium alginate based on the distance of the panel to the ground and density of the pattern. Material should vary from transparent on the ground and orange and red the higher the panel is position and the denser is the pattern.

Figure 6. Fabrication tool for robotic deposition of bio-polymers.

4.3. FABRICATION

The project employs an additive manufacturing (3D printing) as a method of fabrication of liquid BP, by extruding the paste of the BP composition via robotically controlled system. This method was chosen because of its sustainability approach - it allows for an in-situ fabrication and no need of use of additional molds. The system of fabrication process consists of a 6-axis Robot arm UR5-e with a working radius of 850 mm and maximum payload up to 5 kg, dosing dispenser eco-PEN600 with a speed control plug'n'dose (ViscoTec), and a custom-made extrusion system (see figure 6). The set-up of the hardware was based on research of Dritsas et al. (2018), who explored a manufacturing process deploying natural composite materials, where the objection of the project was in the concurrent design and developments of the material along with the manufacturing process. To determine gradient in material deposition, following aspects were investigated: material composition and concentration, pressure variation, which results in continuously varying material accumulation and layering, which provides higher degree reinforcement rather than one-layered surface. Working with the multiple material properties of functionally graded structures, requires adjustable deposition setups. Because of multiple material compositions with various properties, refining the deposition set up - inter alia flow control, speed and pressure needed to be considered. This was solved by testing chosen material compositions and applying an adjustable flow configuration to each material, which was informed by the material analyses and real-time tests of the deposition. The intermolecular attractions of the particles in the wet water-base material allow to create a continuous graded system of heterogeneous performance, which would not be able to achieve using other fabrication methods. The viscosity of the materials allows also for total self-bonding and self-repair of layers in the print. The fabrication process of creating a material from the ground up and deposition in a viscous state required properly controlled environment and process setup in terms of production. Due to the viscosity of the material, after extruding each layer, the following panels needed to be cured in an air-pressure box under 40 Celsius degree to obtain quasi-solid state. The wet depositions of the BP are under internal directional evaporation stresses, while drying. This means it is very important to control the environment of the extruded artifacts while the evaporation process.

Figure 7. First generation of robotically fabricated panels and mock-up for assembly test. .

5. Conclusion

The contemporary architectural workflow includes a stark division between design, performance parameters, and fabrication techniques. Most of the designs are iterated using CAD technologies, without reference to scale, performance, or material, neither thinking about the ecology of the design nor fabrication process. This paper has presented a conceptual and methodological framework of material-based, large-scale design to fabrication process implementing customized BP design for the real-world application of the temporary membranes with circular life cycle in the form of seasonal agricultural shading system. It shows a strategy of rethinking materials and fabrication methods in the development of new fabrication and design tools in a sustainable approach. Driven by novel biodegradable bio-materials, this research showed a new structural design perspective, combining mushroom- and algae-derived BP, which create a sustainable manufacturing process from the material selection to the fabrication and post-fabrication use. The material design and organization were informed by the structural performance of the plastic film, creating homogeneous and complex architectural elements for temporary architecture of shading system, which degrades in soil and in water after the seasonal use and improves the quality of the soil. An early integration of performance parameters and fabrication methods into a threaded workflow, may produce an integrated design process resulting in designs which embody their performative constraints and fabrication procedures. In this way research investigates a multiscalar modeling, connecting empirical material design with a formal architectural approach.

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