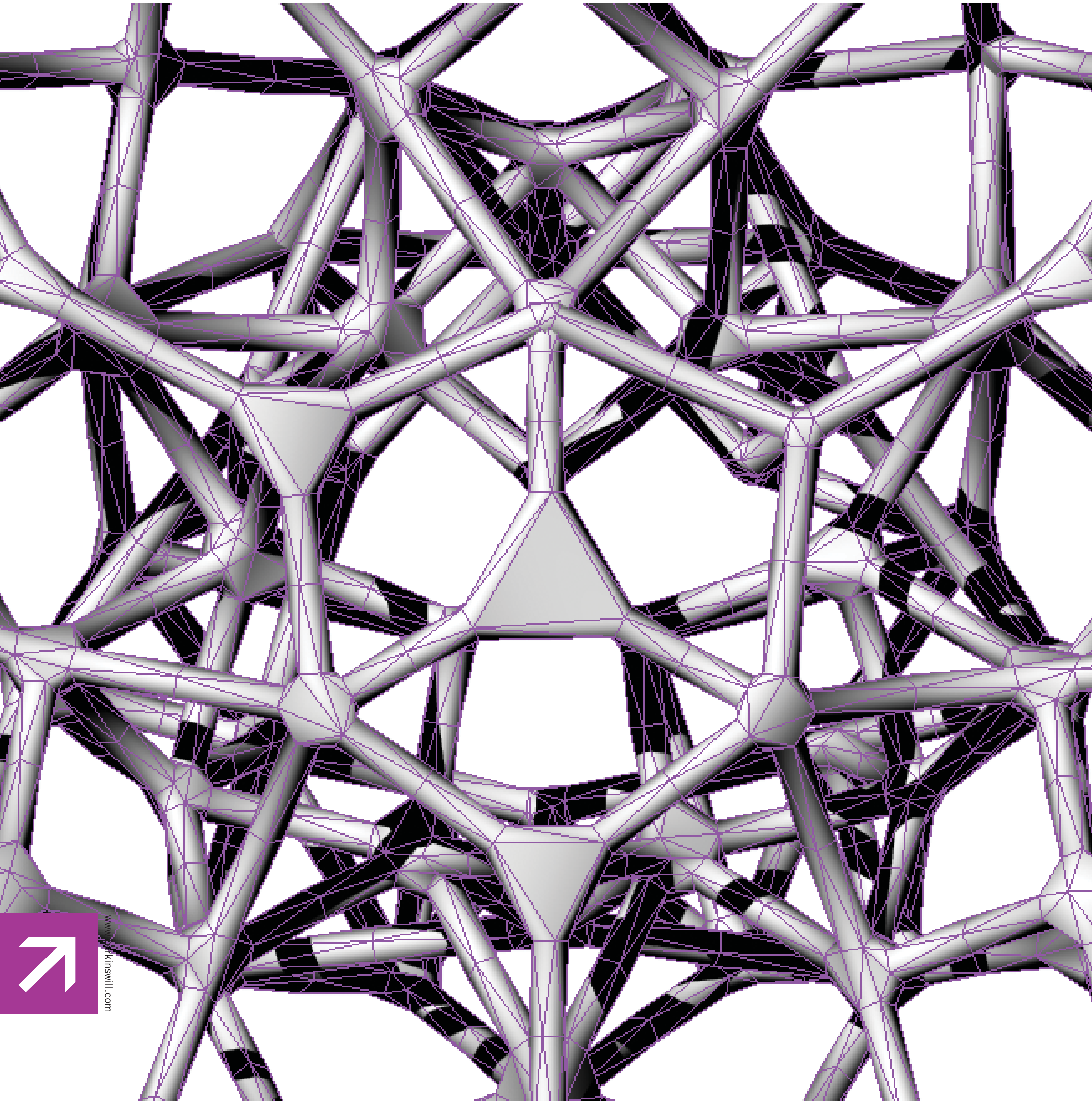
PERKINS+WILL
Research Journal

2016 / VOL 08.02



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02.
AUTOMATED ROBOTIC FABRICATION FOR TEMPORARY ARCHITECTURE:
Rethinking Plastics

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ABSTRACT
Driven by a bottom-up architectural approach to integrate phase changing materials and digital fabrication tools, such as industrial robotic arms, this article presents a novel materially generated fabrication process. The process 3D prints and stretches plastics, where the extruding and freezing temperatures, pulling speeds and angles are controlled through highly customized heads mounted on robots. The objective of the research was to investigate how the phase changing property of plastics can be exploited to its fullest potential using digital fabrication tools, specifically for temporary architecture. A fairly low working temperature bioplastic, polycaprolactone, was chosen as a material for its loose molecular structure, enabling the material to be reheated and reused as much as possible. Research methods included several material and digital experiments, conducted to control the height, temperature, and structural integrity of the pulled structures. As a result of surface tension, it was concluded that the triangle is the optimal shape to deposit the material and pull from. Thus, tetrahedron nodes are used to grow the structure as a continuous web. The research was used to investigate a specific case study, which resulted in a fabrication platform that addresses construction waste issue in London by presenting an autonomous robotic fabrication system and creates 100 percent reusable, biodegradable, self-binding and continuous temporary lattice structures, which can be welded on site. The fabrication process takes place in a mobile cell autonomously run by robots. Once the temporary structure is no longer in use, the unique property of the material fabrication system allows the built structure to be shredded down and refed into the fabrication system to build a new temporary architecture nearby or on another site.

KEYWORDS: material programming, bioplastics, robotics, 3D printing, digital fabrication

1.0 INTRODUCTION

1.1 Background and Motivation
Plastics have a wide range of usage in construction and architecture. Their adaptable technical properties allow for a wide range of form-making and finishes through thermal processes. This sets plastics apart from other materials in pursuing complex geometries with regards to digital fabrication procedures[1]. Yet, plastics are not used and exploited to their fullest potential. Its malleability has been mainly explored on an extrinsic level, such as form making and not on an intrinsic one, where the material behaviour is essential in informing the form and fabrication procedures. Thus, this research aims to highlight the intrinsic properties of plastic as a phase changing material and develop methods of fabrication that tease out its malleability to present a continuous mono material structure.

Industrial robotic arms have been used for many years in many fabrication processes in numerous industries, especially in the car industry since the 1970's. They are powerful machines that can execute repetitive actions accurately. However, in the traditional use of industrial robotic arms, a clear relation between the handled material and the robotic control has not been clearly addressed or investigated. Architects look at industrial robotic arms differently by utilizing their potentials[2]. Material significance has increased dramatically in the digital fabrication realm due to the shift from software-based experiments of virtual material to a more physical-driven fabrication, which necessitates real material constraints and behaviour analysis. Typically, generative design in architecture refers to computer algorithms that generate form. Materially-directed generative fabrication enables the material behaviour to generate form. In this research, they are combined. The dialogue between customized material geometries, along with parametric algorithms, designer's input and robotic parameters serve as a novel model of fabrication for material-based design and construction.

Addressing the construction waste issue in London, the fabrication system this research presents aids in reducing the waste generated by temporary architecture. Research shows that 1,418 temporary structures existed in London in 2015, and the numbers keep rising. Architecture and construction contribute to 70 percent of the overall waste production in London. Seventy percent of this waste ends up in landfills. By the year 2020, London's municipality is aiming to reduce landfill usage to twenty percent and to increase recycling by 14 percent. This demands a system that rethinks the problem with a holistic approach from material to fabrication. Thus, we are proposing a flexible automated robotic arm fabrication system that is based on programming a reusable and biodegradable material with the parameters of robotic automation, as a result, generating a 100 percent reusable and biodegradable temporary architecture.

1.2 Literature Review

A number of plastics have been used in architecture, developed since the 1940's, such as polyvinylchloride (PVC), polymethacrylate (PMMA), polystyrene (PS), polyethylene (PE), and polytetrafluoroethylene (PTFE). Although all plastics may look alike, they come in two major categories: thermosets and thermoplastics. Thermosets have a cross-linked molecular structure, making it harder to recycle compared to thermoplastics, which have an uncrossed-linked molecular structure, permitting the process of heat deformation to be repeatable. Although both types of plastics allow for the production of highly complicated forms accurately and in mass quantities, thermoplastics are easily converted to their initial state compared with thermosets due to their loose molecular structure, making them easily recyclable as well. Yet, the majority of thermoplastics are made of raw materials that originate from oil and natural gas, a nonrenewable resource. Bioplastics on the other hand, are a form of thermoplastic that are made from renewable raw materials, classifying them as environmentally friendly material that biodegrades eventually once the life of the plastic is over. Special additives can control the life span of bioplastics before they start to biodegrade[1].

"Materially-directed generative fabrication multiplies the possible uses of established technologies (plastic deposition, industrial robotic sensing, and generative coding) to explore the limits of machine-material-sensor interfaces. The ability to sense material behaviour in real-time radically expands the potentials of matter to inform fabrication and influence form."[3]

Recently, plastic in architecture and construction is being explored, exploiting the material diverse properties in search for new forms of construction methods appropriate for these types of materials. Andres Harris's research, "1.0 Biomimetics" and "2.0 Formfinding", serves as a good example[4]. The aim of this project was to develop a structure based on self-forming and self-optimizing morphologies. These morphologies are derived from the manipulation of viscous materials using both physical experimentation and parametric computation to simulate in a digital environment the physical processes, such as fluids and other malleable materials that have the ability to harden under certain pressures. The material that was explored was a bio-resin. The bio-resin material manipulation uses plates and pulling techniques to create the material structures, as shown in Figure 1[4].

Traditional digital fabrication methods tend to generate forms first digitally, without a direct connection to the fabrication method, whether it is an additive process, such as 3D printing, or a subtracting one, such as a CNC router machining. A new approach to digital fabrication is a materially driven approach, which is based on material properties. Therefore, the fabrication method becomes intrinsic to the design process rather than being an aftermath, without considering the material potential at hand[5]. A relevant example of a project that uses a phase changing plastic in a depositing manner by an industrial robotic arm is the "Sense It" workshop held at RobArch2014. It combined robotic plastic deposition (RBD) with temperature and distance sensing as a first case of materially directed generative fabrication. The customized end-effector melts the polypropylene granules into a viscous mass that is extruded through

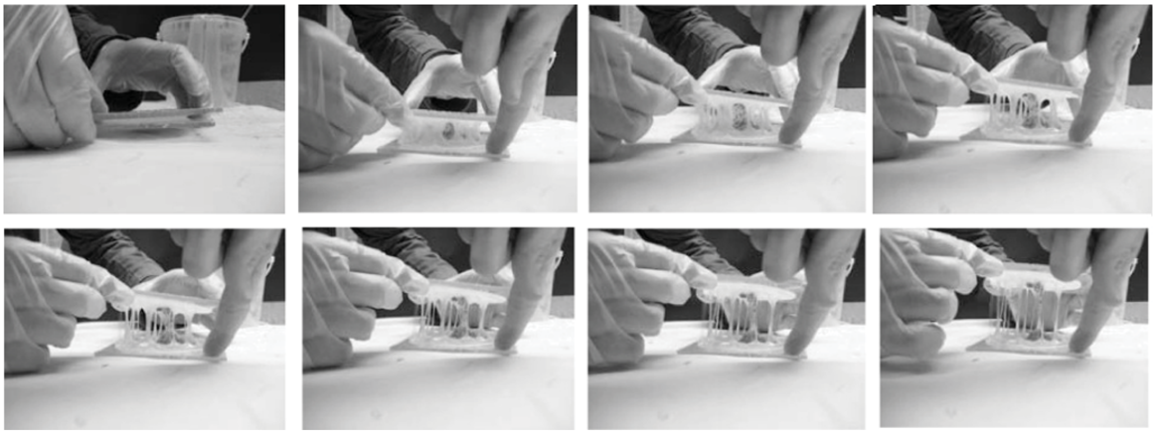

Figure 1: Using plates and pulling as a technique to create the material structure[4].

an aluminium nozzle. The shape and size of the nozzle affect the extrusion of the plastic deposition. By pausing the extrusion process in the code and moving the nozzle upwards exactly after each deposition, it prevents the plastic to harden on the nozzle itself, as shown in Figure 2. Due to the material intrinsic properties, the pouring mass hardens within seconds, right after its deposition, resulting in a lattice structure[3].

2.0 PROJECT OVERVIEW

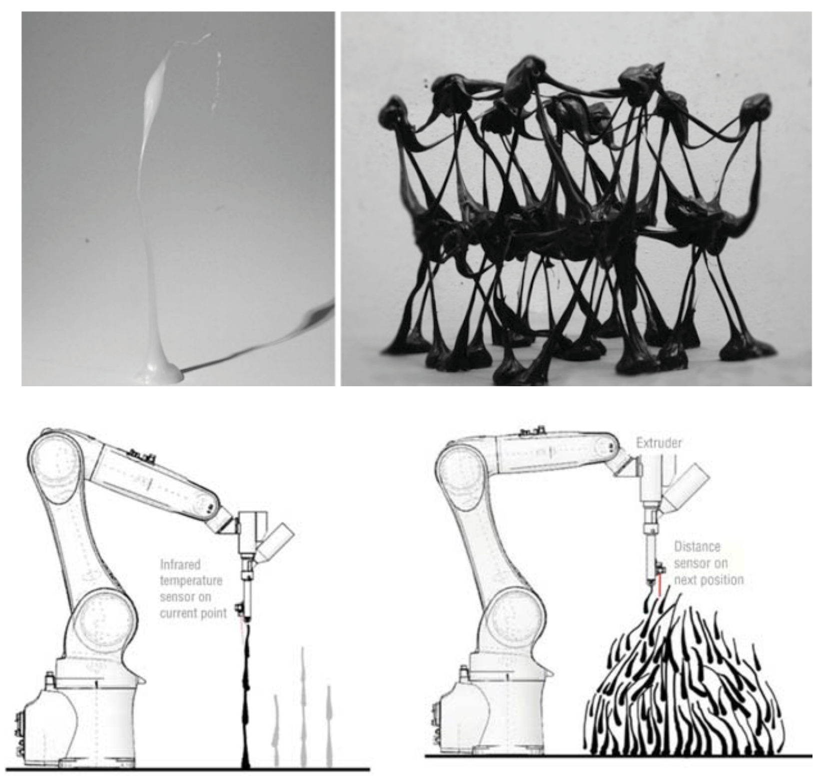

Figure 2: “Sense it” workshop held at RobArch 2014.

This study investigated the architectural and robotic fabrication potentials of 3D printing bioplastics, specifically focusing on the unique material properties of polycaprolactone. At just 60°C, polycaprolactone reaches a low melting point which breaks the material's structure into a soft, malleable consistency. This allows the polyester to be stretched into form and then hardened using a freezing spray. The stretched plastic grows as a lattice structure that can adapt locally to the expected loads within a single material system. The lattice consists of tetrahedron nodes and beams. To ensure all compression and tension forces reach equilibrium, the lattice is digitally "relaxed", redistributing all the nodes and beams lengths obeying the parameters obtained from the material experiments. Thus, depending on their structural capacity, heights of the extruded beams are maintained within a range of 15 to 60 cm long and an angle tolerance of 45 degrees from the normal of each face of the tetrahedron node. Due to the need of precise calculations in creating the complex geometric network, industrial robotic arms were used to control the pulling angles, extrusion lengths and nodes orientation in space. Moreover, the freedom in customizing the robot's end-effector along with its 6-axis movement match the need to freely pull the plastic in space at a controlled speed and temperatures. Therefore, customized pulling end-effectors were developed as the mediator between the material and the robotic arms to stretch the triangular deposition of the plastic between tetrahedral nodes. This dialogue between physical material properties input and digital fabrication creates a novel mode of fabrication. As one robotic arm stretches, another operates the freezing spray. To facilitate the ease of fabrication and eliminate the need to transfer the structure to site, the whole process is designed to fit in a standard truck, enabling the fabrication to take place on site. The fabricated units are assembled in place by welding meeting faces of the tetrahedron plastic nodes. Once cooled, the joined units work together as one structural system. Due to the phase changing property of polycaprolactone and the fact that the structure is all built from a singular material with zero joints, it can be easily shredded down into small pellets, which can be used again as an input material in the proposed fabrication system.

2.1 Project Objectives

The objective of this research was to investigate a robotically controlled and materially-tailored method for manufacturing biodegradable, reusable and lightweight structures with temporary functions. These structures address the temporary construction waste in London by challenging the conventional fabrication methods. The purpose was to investigate a fabrication system that is able to produce a reusable, biodegradable and temporary architecture. The fabrication process allows for flexibility in form, joinery, and reusability of the built structures due to the fact that is made of one material.

We addressed several questions during this research:

- Can we develop a fabrication method that utilizes industrial robotic arms and material intelligence?
- Can we rethink 3D printing by utilizing melting and hardening process?
- Can our method create reusable architecture?

3.0 RESEARCH METHODS

3.1 Material Research

A fairly malleable plastic was chosen, which can be easily reused and biodegrade. After many experiments in melting and stretching different kinds of plastics and researching their environmental properties, we identified a bioplastic called polycaprolactone, which is mainly used in medicine as a 3D printed implant and cast. Polycaprolactone falls under the bigger umbrella of thermoplastic polyurethanes (TPU). The technical name of the material is polycaprolactone (PCL) and its commercial names are many, among them are Polymorph, InstaMorph, CAPA, Shapelock, and Friendly Plastic. It is a biodegradable polyester with a low working temperature of 60°C due to its loose molecular structure, which permits the material to be thermally formed. It is considered easily recyclable due to its loose uncross-linked molecular assembly, which makes it ideal as a phase changing prototype material for our study. Initial physical state of polycaprolactone is solid granules that transform into a putty-like viscous mass when heated. The material can easily bind to itself or other plastics, as demonstrated in Figure 3. Polycaprolactone is classified as a low-temperature thermoplastic, with a density of 1.145 g/cm^3. It has an ultra-high molecular weight. It is a commonly used polymer, and was one of the first raw materials to be extruded through a RepRap extruder[6].

Although it is very malleable when heated, this material gets very rigid once set, becoming a fairly structural material in its solid state. Amongst its many advantages are its high abrasion resistance and elasticity across the entire hardness range, its excellent low temperature and impact strength in addition to its resiliency to oils, greases and numerous solvents. Moreover, it has good flexibility over a wide range of temperatures, robust weather and high-energy radiation resistance, pleasant tactile properties, suitable for bonding and welding, easy to colour and most importantly can be reused and it is 100 percent biodegradable[6]. This research chal-

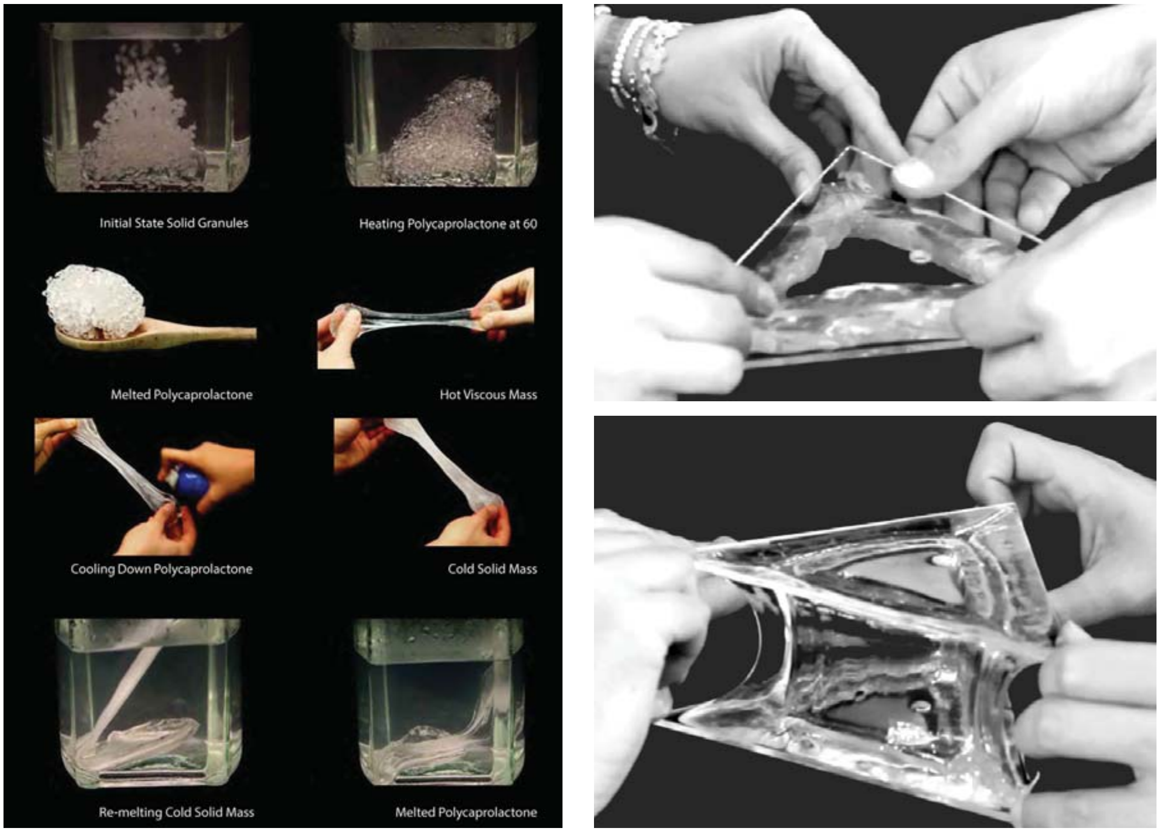

Figure 3: Demonstrating the phase changing cycle of polycaprolactone. *Courtesy of: Architectural Association Design Research Laboratory (AADRL).*

lenged the structural ability of plastics by pulling the material while hot to achieve structural beams.

Taking into consideration the material's potentials and constraints, several experiments were executed to understand its behaviour. We tested the material deposition pattern, temperature, quantity and height. After several experiments, shown in Figure 4, it was clear that our technique offered a unique fabrication method, where the shape of the bed that the material is being printed on has a direct effect on the stretched plastic structure and form. The experiments at this stage were conducted manually using triangular acrylic plates, where the plastic granules are heated through dropping them in 60-70°C hot water until they turn into elastic mass. The weight of the granules was monitored before each trial, as well as the height, pulling and freezing time of the stretched plastic. It took approximately three minutes for polycaprolactone plastic to reach the desired viscosity, stretch to the desired height and revert to a rigid state with the aid of a freezing spray.

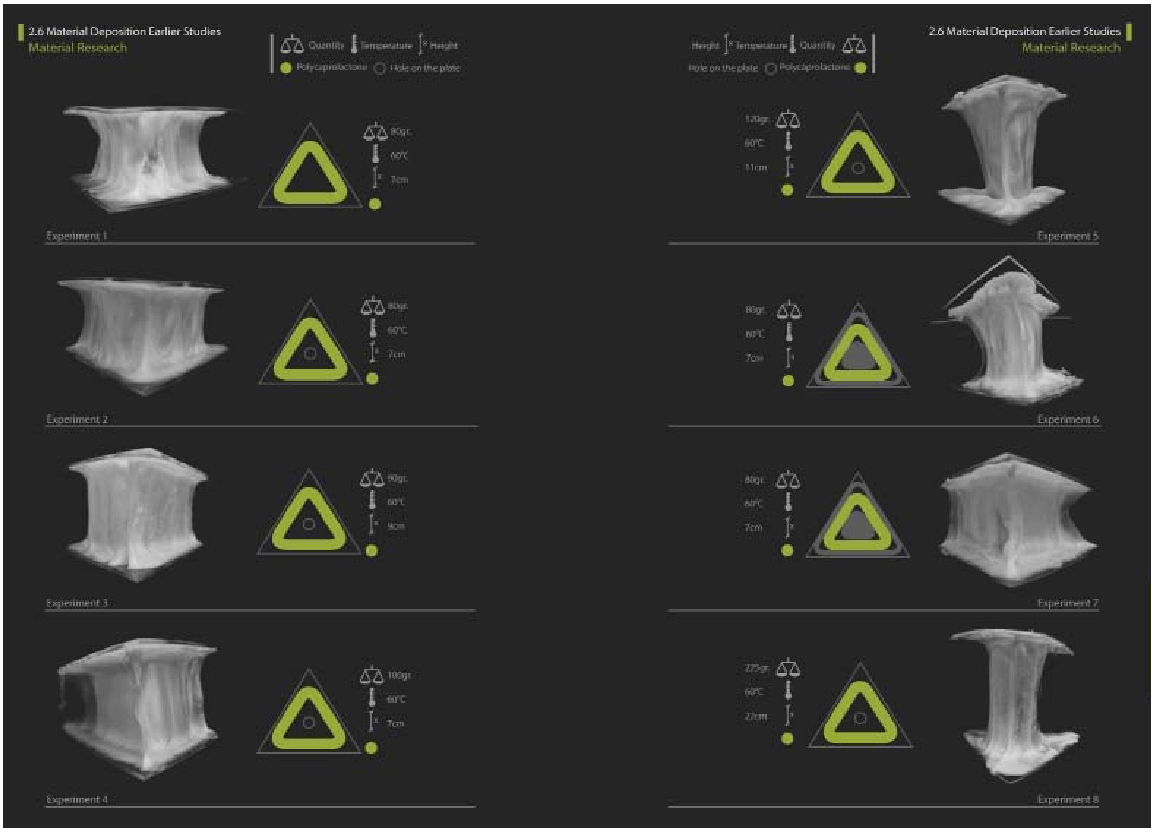

Figure 4: Material programming catalogue of some of the experiments with pulling different heights, weights and temperatures. *Courtesy of: AADRL.*

The optimal height ranged from 15 cm to 60 cm, with direct relationship between the weight of the amount being printed and the desired length, as shown in Figure 5. The weights for 15 cm, 20 cm and 60 cm high beams have been noted and used in this research as the optimal lengths for the fabricated lattice structure, which was tested in a 1:1 prototype discussed later in the article. Although surface tension of the triangular node controls the pulled beam's middle section, we concluded that other factors play a role in determining the plastic's structure integrity. These factors are:

- Deposition temperature
- Length of the plastic beam
- Pulling angle
- Pulling speed.

Special plates and nodes were made of tetrahedron nodes to permit material and structure continuity, resulting in homogeneous material elements, as shown in Figure 5. The nodes allows the pulled beams to grow in almost any direction. Tolerance angles are identified, as shown in Figure 6, before the material starts to shear. The angle range is wide and covers almost a 360 degrees sphere. At this stage it was necessary for the digital and fabrication work to become integrated. Thus, digital structural studies were conducted to simulate the physical behavior of the material and to study the growth logic of our material, in what direction and angle does the plastic gets pulled at and the position of the tetrahedrons in space. Because it was almost impossible to control the results every single time manually, the curtail parameters identified above needed to get controlled by robots and machines. Industrial robotic arms served as the best digital fabrication tool to use, due to their six-axis movement and the freedom to attach any custom head to them. It was concluded that there is an optimal temperature of the plastic that results in the best structural coherency of the material. Thus, an extruder machine was used to replace hot water to precisely control the temperature of the plastic while it is being printed and pulled.

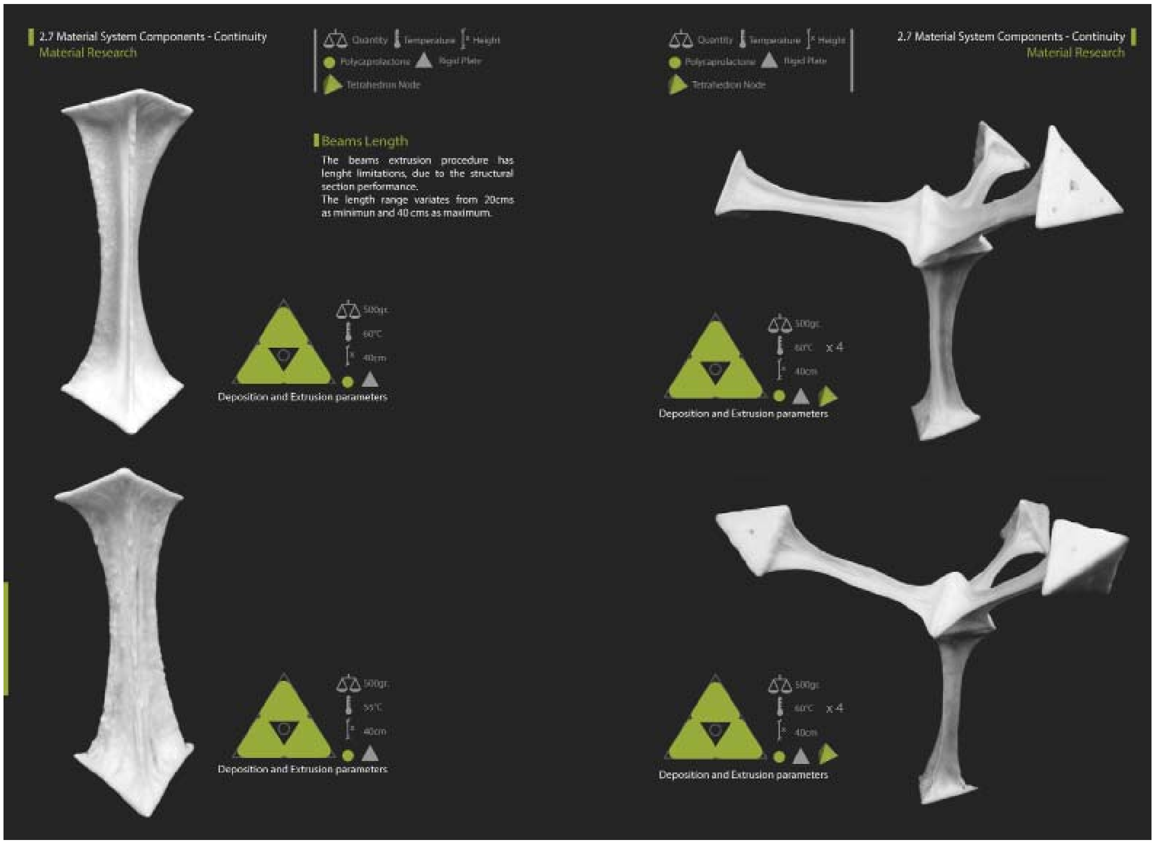

Figure 5: Material programming catalogue of some of the experiments with pulling different heights, weights and temperatures. *Courtesy of: AADRL.*

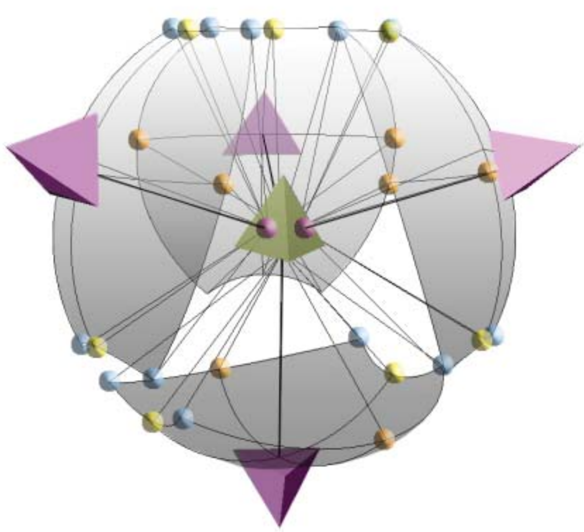

Figure 6: Pulling angles of polycaprolactone stretched beams. *Courtesy of: AADRL.*

3.2 Structural Studies

In line with the system constraints, different types of lattice structures were developed. These different lattices were evaluated according to their structural behavior, in order to define a configuration that best fits the material behavior and the structural requirements. Following the physical research, we simulated our physical experiments digitally to further understand the parameters controlling the behavior of polycaprolactone. It was concluded that the temperature, speed and angle of pulling affect the structural integrity of the material. As a result, varying those parameters digitally generated different thicknesses and holes in the simulated beams, affecting their structural behavior. The plastic network grows according to the nodes distribution in space, which are led by predefined support and load points. The material behavior generates beams that tend to have smaller section in the center of the beam; therefore these elements work better with pure axial forces when they are exposed to bending moments. Taking into consideration the material physical parameters, such as length range and angle requirement, tension and compression elements were defined in the structure digitally, which were then reconfigured to reach equilibrium by “relaxing” (tensioning) the lattice structure digitally. 3D Software Autodesk Maya and Grasshopper Karamba were used in this research to generate these structural studies, seen in Figure 7.

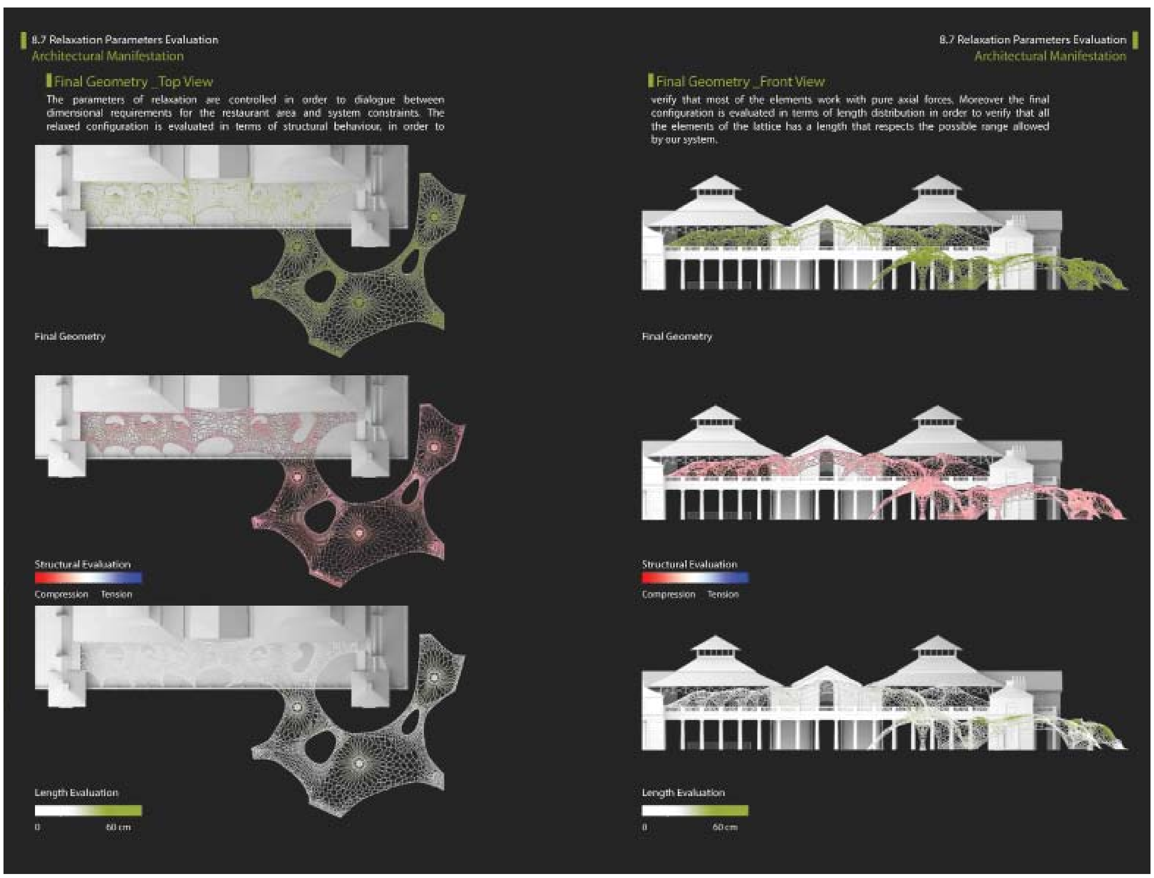

Figure 7: Mesh relaxation in order to redistribute the axial forces reaching equilibrium. *Courtesy of: AADRL.*

3.3 Industrial Robotic Arms Parameters

As mentioned previously, industrial robotic arms can be used in various fabrication processes. These processes mainly include fabrication of components, which are further assembled by humans. However, the execution time of these processes in terms of assembly, delay the efficient production of components by industrial robotic arms. Autonomous building robots as a system mimic the processes in nature, where self-organization concepts are applied intuitively. Hence, every component of the system, such as the robotic arm, end-effector and material, work together as a whole to create internal and external networks that go on to feed the system. Industrial robotic arms are excellent as free platforms to attach almost anything to their end-effector. It is a very flexible open platform for communication, where the software can be customized by artists, architects, and engineers to communicate to the robot from the same room or via the internet.

Taking into consideration physical and digital material studies, and respecting the accuracy and constraints of industrial robotic arms, structural beams were printed and stretched through simple repetitive actions. We used two six-axis Industrial robotic arms. Robotic arms have movement limitation and must move in a certain choreography to reach a certain point in space. This reachable space is called “working area”. It has a bolted plate at the end of its arm, which can accept any customized hand or end-effector. The freedom in customizing the end-effector plays a crucial role in controlling the material. Several important industrial robotic fabrication parameters were investigated, including industrial robotic working area, start-up position, their arrangement in space, distance to the extruder machine and nodes. The setup of those parameters, which needs to be designed beforehand, is called the robot’s “choreography”. The choreography of the fabrication in this research was first determined digitally using 3D software Rhinoceros.

3.4 Fabrication Process

To proof our concept, we fabricated a 1:1 prototype at Robofold I.O in London, where a 1.5 m tall column was fabricated in two pieces and joined manually by welding. The whole fabrication process was automated, except for the freezing spray, as shown in Figure 8. Prefabricated nodes, consisting of tetrahedrons made from polycaprolactone, sit in a predefined location on a moving belt. The robot was autonomously programmed to pick through the tetrahedron-node pulling end-effector to the extruder machine. The extruder machine then prints the melted mass on the tetrahedron node surface in a controlled temperature to ensure that the right viscosity is met, in order to achieve the structural integrity of the material. The industrial robotic arm then picks the node with the freshly printed material while it is still hot and adheres it onto an assigned point of the beam growth, while pulling it at a predefined speed and angle. The integrity of the lattice structure is adhered, by maintaining the temperature of the material being extruded, and the accuracy with which the robotic arm is capable of controlling the speed and angle of the extrusion. This process is repeated as required by the design to complete the lattice units, and the corresponding meeting surfaces will be joined on site. The whole fabrication process is intended to happen in a standard size truck with the material supply on board, so that it can happen on site to minimize the transport of the fabricated units. Once the use of the structure is over, it can either be shredded and re-fed to produce another configuration, or just left to biodegrade.

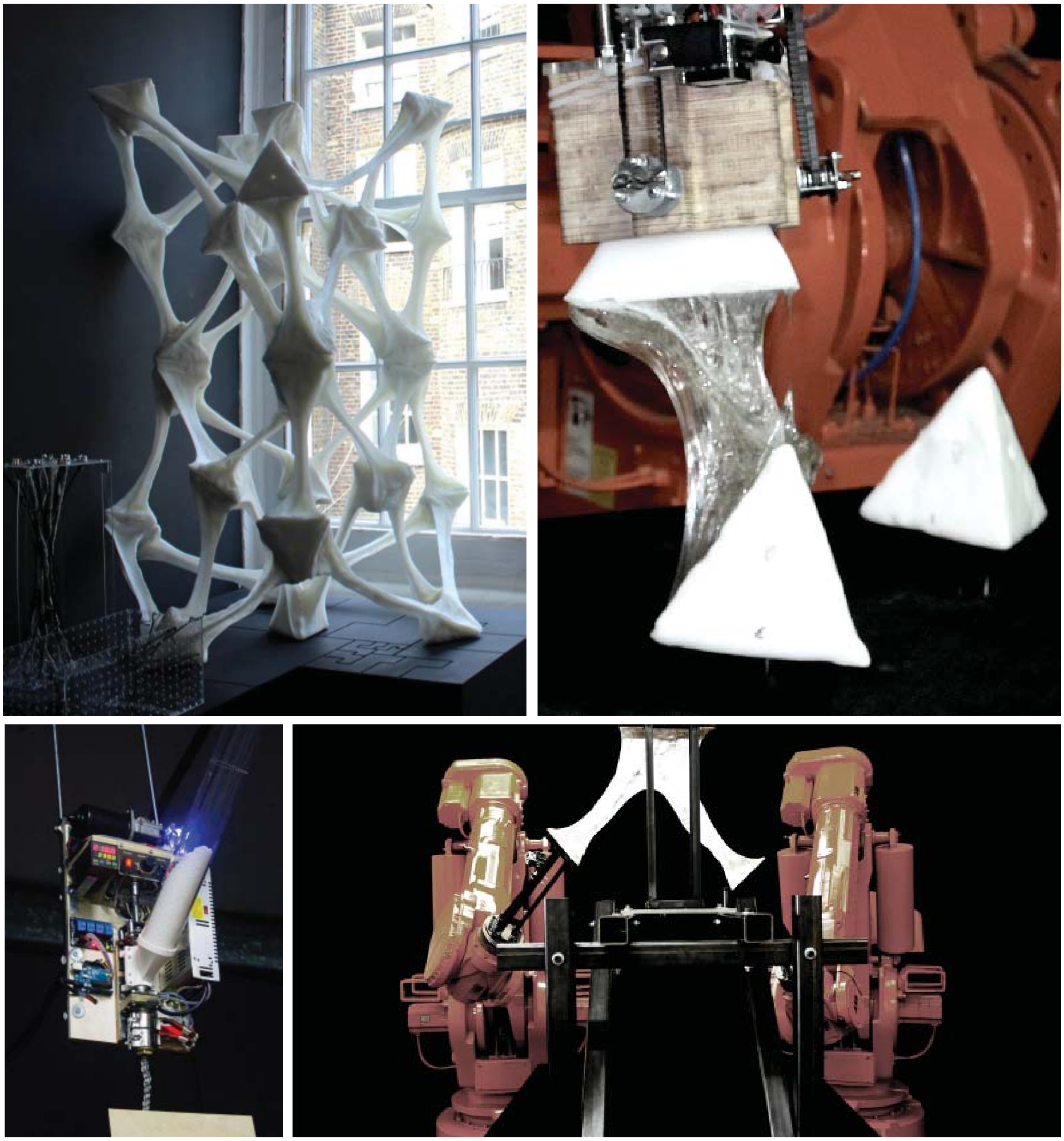

Figure 8: Prototype fabrication proof of concept at Robofold I.O. *Courtesy of: AADRL.*

4.0 RESULTS

4.1 Optimal Scenario

The materially driven fabrication system discussed in this research article presents a fabrication process that is fully automated in a controlled cell, where different parameters play a big role in the fabrication of the desired geometry. Our system uses prefabricated polycaprolactone nodes, currently in the shape of a tetrahedron. The results offer a fabrication process that builds upon material programming of a bioplastic, while being challenged to produce a 100 percent reused and biodegradable temporary structures using two industrial robotic arms that can be choreographed to control the pulling angles, speed and temperature. The proposed optimal fabrication scenario takes place in a standard mobile cell with two medium size industrial robotic arms facing each other 1.3 m wide, as shown in Figure 9. These two robots share a rotating table in the middle and two extruder machines on either side in the center. As one robot pulls the viscous 3D printed mass, the other freezes.

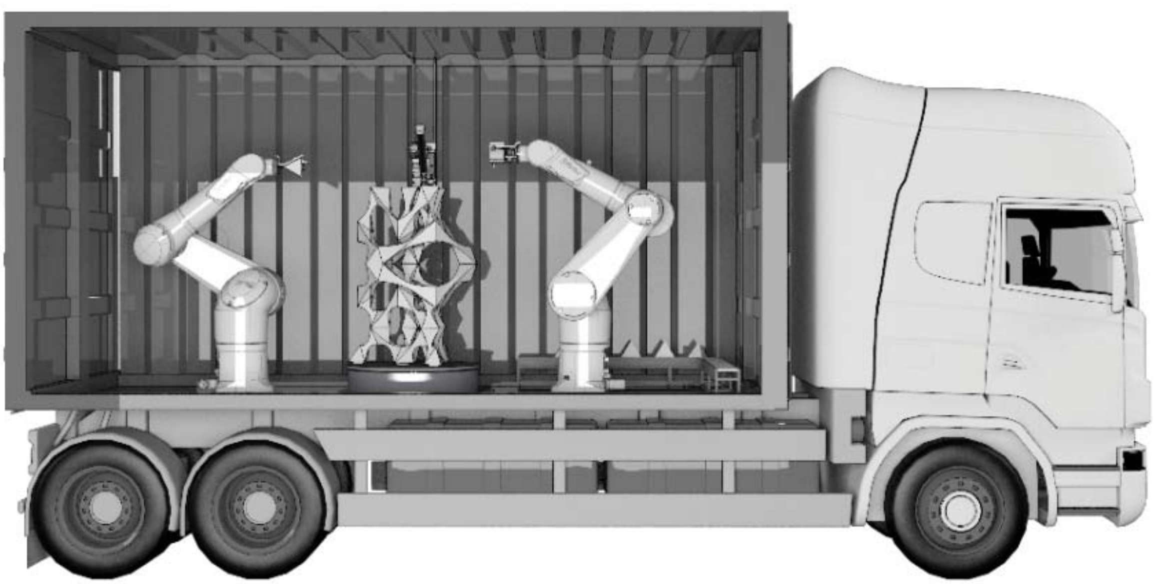

Figure 9: The proposed fabrication scenario. *Courtesy of: AADRL.*

We considered Covent Garden in London as a site to propose a temporary structure, which would act as a Market Pavilion. Circulation study diagrams were conducted, where a 2D tensioned mesh was populated with the pattern growth, then relaxed in 3D to redistribute all the forces to reach an equilibrium. To maximize the performance of the beams into different directions in space, it was necessary to study the maximum angles that the material can stretch before losing its structural integrity. Taking in consideration the normal of each face of the tetrahedron, which is the optimum extrusion, a 45 degree of tolerance was established in between each X, Y and XY axes from the normal. The result of this definition is a volume enclosed by tetrahedron structure, as seen in Figure 10.

Figure 10: Covent Garden as a case study. *Courtesy of: AADRL.*

5.0 CONCLUSION

We presented a materially-driven design process and a unique fabrication methods, which uses robotic manufacturing process for creating bioplastic structures. This approach offers an innovative, environmentally-friendly approach to temporary architecture. Due to the pulling technique of the bioplastic while still in its viscous state, the surface tension of the material causes the pulled structure form to be affected by its base. Therefore, it was concluded that the triangular base gave the best structural stretched beam resulting in a three star middle section. Triangular faces of the tetrahedron nodes were used to print the hot plastic and create a three dimensional lattice network. As a result, precision in melting and pulling the plastic in space is essential to achieve structural characteristics. Therefore, through designed choreography, industrial robotic arms were used to control the pulling speed and angles, along with two pulling end-effectors and a custom-built extrusion "3D printing" machine. Polycaprolactone is a biodegradable polyester used as a prototype material in this research, but any other plastic with similar characteristics can be used to achieve similar results. In addition to the material being biodegradable, the crucial properties of the material are its ability to have a fairly low working temperature and it being self-bondable which enable the creation of joint-less single material structures. By only varying the amounts of melted plastic and pulling lengths, different thicknesses and densities can be achieved to respond to various functions or structural requirements within a single unit. A 1:1 150 cm high column was fabricated using two robots as a proof of concept prototype, using two pulling end-effectors mounted on the industrial robotic arms and a fixed extruder in the middle reachable by the two robots. These structures can vary in usage from pavilions to temporary kiosks (pop-ups), or even scaffolding. Applications of the design can vary in scale and function, from lightweight dense panels to more porous large structures.

Acknowledgments

The authors would like to thank individuals who helped inform and guide this research, and for their collaboration and contribution to the research work presented in this article, as well as the Architectural Association Design Research Laboratory.

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