From Bones to Bricks

Designing the 3D Printed Durotaxis Chair and La Burbuja Lamp

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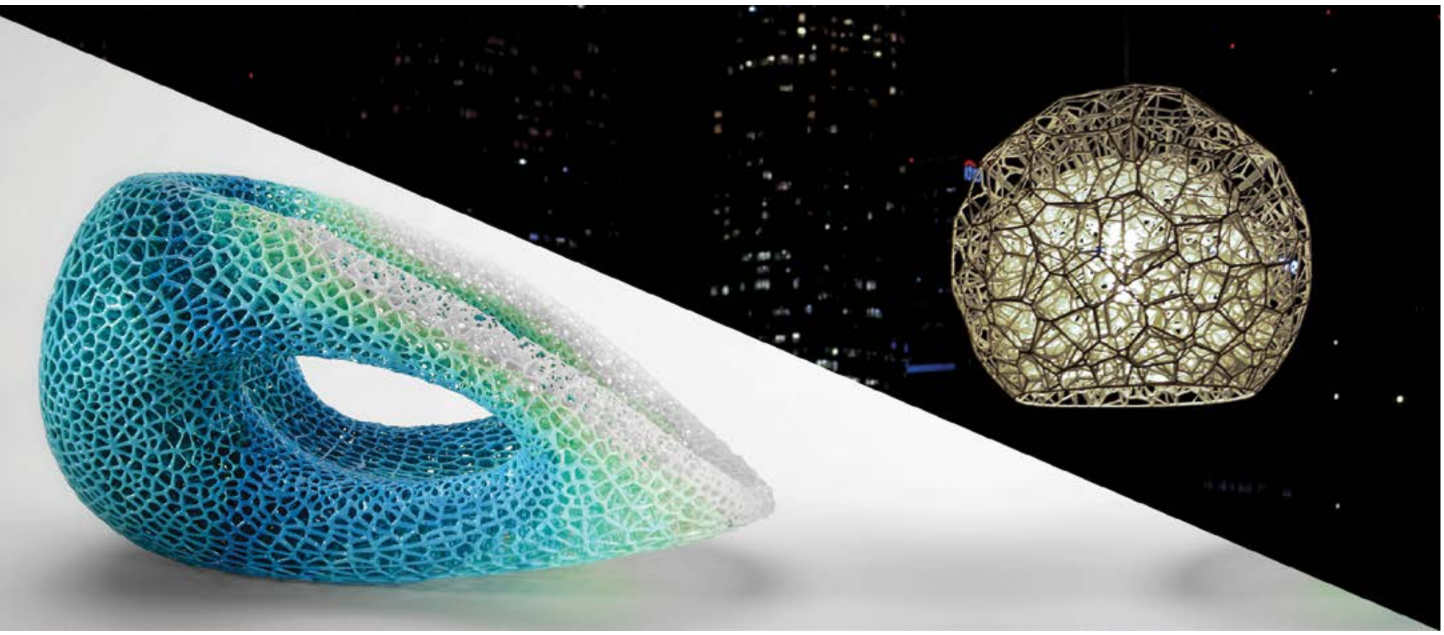

The prototypes: The Durotaxis Chair (left) & the La Burbuja Lamp (right).

ABSTRACT

Drawing inspiration from the variable density structures of bones and the self-supported cantilvers of corbelled brick arches, the Durotaxis Chair and the La Burbuja lamp explore a material-based design process by responding to the challenge of designing a 3D print, rather than 3D printing a design. As such, the fabrication method and materiality of 3D printing define the generative design constraints that inform the geometry of each. Both projects are seen as experiments in the design of 3D printed three-dimensional space packing structures that have been designed specifically for the machines by which they are manufactured. The geometry of each project has been carefully calibrated to capitalize on a selection of specific design opportunities enabled by the capabilities and constraints of additive manufacturing.

The Durotaxis Chair is a half-scale prototype of a fully 3D printed multi-material rocking chair that is defined by a densely packed, variable density three-dimensional wire mesh that gradates in size, scale, density, color, and rigidity. Inspired by the variable density structure of bones, the design utilizes principal stress analysis, asymptotic stability, and ergonomics to drive the logics of the various gradient conditions.

The La Burbuja Lamp is a full scale prototype for a zero-waste fully 3D printed pendant lamp. The geometric articulation of the project is defined by a cellular 3D space packing structure that is constrained to the angles of repose and back-spans required to produce un-supported 3D printing.

INTRODUCTION

3D printing has been heralded as the next industrial revolution (Anderson 2010). It is projected that in the near future, our homes, schools, and small businesses will all have the potential to become micro-factories for personal fabrication (Ratto and Ree 2012). Currently, the prevalence of 3D printing within the worlds of architectural practice and architectural academia has been evidence of the evolution of 3D printing from a novel and exclusive prototyping tool to a ubiquitous and accessible fabrication medium. However, this prevalence has led to the widespread overuse of 3D printing for the production of forms and geometries that have not been designed for the constraints of the machine, and in some cases could be better manufactured by an alternate process. Alternatively, a material-based design process utilizes computation to integrate the logic of fabrication technologies with structure, material, and form (Oxman 2010). With a material-based design process, the capabilities and limitations of 3D printing become latent design opportunities which can drive the design process.

This paper will explore the potentials provided by the constraints of additive manufacturing to provide design opportunities that are informed both by its capabilities as well as its limitations through the design and production of the Durotaxis Chair and La Burbuja Lamp. Both projects are fully 3D printed design artefacts that are designed specifically for the 3D printers which manufactured them, and are thus the projects of a design process informed by fabrication.

Designing a 3D print, as opposed to 3D printing a design, is the fundamental challenge we are confronting in both projects. Our goal was to produce structures which could not be manufactured by any other process. By prioritizing the chosen fabrication method and materiality as the generative design constraints that inform geometry, both projects are experiments in the design of 3D printed three-dimensional space-packing structures that have been designed specifically for these machines and materials by which they are manufactured. They have each been pre-calibrated to capitalize on specific design opportunities enabled by the capabilities and constraints of additive manufacturing.

In this capacity, both projects are experiments in Structuring—defined as the process whereby the elements of architecture develop a unique logic of parts-to-whole relationships where the static pattern of structural order (tesselations, configurations, etc.) can be mediated into a system of both generative and differentiated potential (Oxman 2010).

THE DUROTAXIS CHAIR

The Durotaxis Chair is a half-scale prototype of a fully 3D printed

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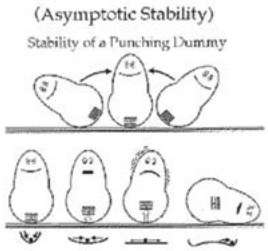
1 The fully 3D printed prototype of the Durotaxis Chair.

2 3D printed samples illustrating the multi-material capabilities of the Objet 500 Connex3 3D printer manufactured by Stratasys.

multi-material rocking chair that is defined by a densely packed, variable three-dimensional wire density mesh that gradates in size, scale, density, color, and rigidity (Figure 1). The chair is inspired by the biological process of the same name, which refers to the migration of cells guided by gradients in substrate rigidity (Plotnikov et al. 2012). The project also takes inspiration from the variable density structure of bones, utilizing principal stress analysis of its geometry to inform the distribution of matter.

The chair is an ovoid rocking chair which has two positions, as an upright rocking chair and as a horizontal rocking lounge. The design of the chair was commissioned by Stratasys to showcase the capabilities of their new Objet 500 Connex3 3D printer. As a response to the recent ubiquity (and perceived overuse) of 3D printing within the design industry—just because you can 3D print something, doesn't mean you should—the challenge that our design team established for ourselves was to produce something which could not be manufactured without 3D printing, and more specifically, which capitalizes on the multi-material



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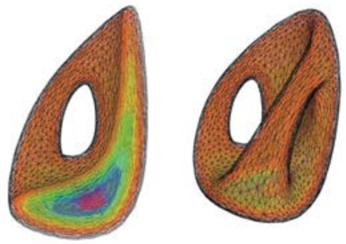

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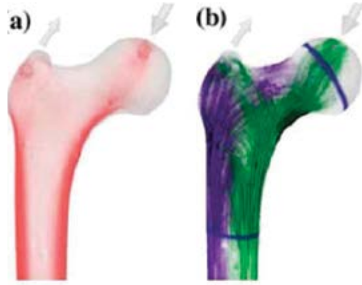

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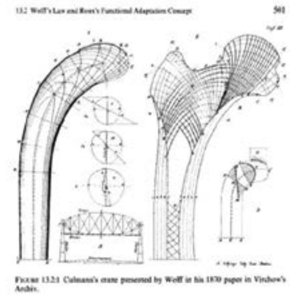

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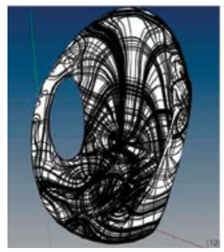

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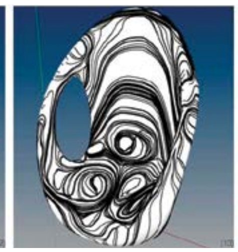

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3 Conceptual diagram illustrating the concept of Asymptotic Stability in an inflatable punching dummy.

4 Sectional diagram of the redistributed center of gravity of the densely packed three-dimensional mesh structure.

5 **(a)** von Mises stress distribution of the femur under tension and compression loading; (b) principal stress lines: green—compression, purple—tension.

6 Diagram of Wolff's Law of Bone Adaption, illustrating the trabecular bone and the way its structure grows most where needed, ending up following principal stress trajectories.

7 Composite principal stress analysis of the chair done in the Karamba structural analysis solver for Rhino.

8 Tensile principal stress analysis of the chair done in the Karamba structural analysis solver for Rhino.

9 Compressive principal stress analysis of the chair done in the Karamba structural analysis solver for Rhino.

printing capabilities of the Objet 500 Connex3 3D printer to produce gradients of material performance (Figure 2).

Surface vs. Solid vs. Lattice

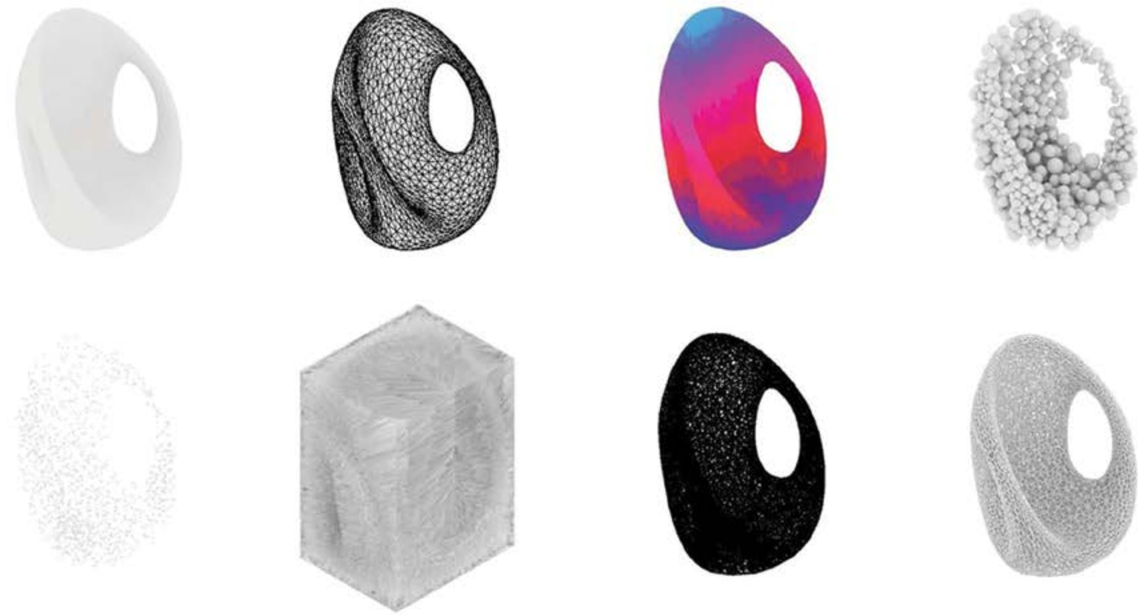
Due to the fundamental nature of 3D modeling tools and the process of preparing files for 3D printing, most 3D printed models are either defined as surface models (with thickness) or as solid models (with mass). All of these modeling techniques can be materialized (albeit with varying degrees of difficulty) through existing fabrication methods of molding, casting, or milling. As such, a decision was made to explore a design which was articulated not as a surface or a mass, but rather as a variable density three-dimensional lattice—similar to a sponge. For the design team, this was a fundamental paradigm shift in the way in which we thought about the chair, which enabled us to explore the gradient not only as a condition of materiality, but also as a condition of density (spacing) and thickness (dimension). The combination of these three gradient conditions allowed us an opportunity to explore gradients that were informed by three guiding performative criteria: ergonomics (rigidity of material), stability (distribution of mass), and structure (density of members).

As such, the starting point for the design was a manually modeled closed mesh (produced through low-poly subdivision modeling in Maya), which was then articulated as three-dimensional lattice. In short, the goal was to manually dictate global form, while computationally generating the localized articulation of that form.

Gradient Stability (Distribution of Mass)

The multivalent form of the Durotaxis chair allows for multiple readings and uses of its unique geometry. It is defined by an ovoid form, which has two principle resting positions: as an upright rocking chair, and as a horizontal lounge chair. The single curved belly and tighter radius of the upright position allows for a more dynamic rocking condition of rest, while the shallow curvature of the horizontal position provides for a more static resting condition. In both cases, the chair is able to roll from one position to the next. At a global scale, the geometry of the chair is defined by an ergonomic desire for multiple positions, an aesthetic desire to express continuity between those positions, and a structural desire to produce a closed system for force distribution.

However, the irregular form and multiple positions of the chair introduced a fundamental problem: balance. One of the primary concerns of the chair's design was how to redistribute its center of gravity so that it would allow the chair to consistently return to an upright position while rocking. To achieve this, the concept of "Asymptotic Stability" was applied (Figures 3 and 4). This is a strategy for using counterweighting forces through the re-distribution of mass to give a non-linear system a gravitation towards a particular orientation (Bender and Orszag 1999).



10 The generative sphere packing process.

By conceiving of the chair neither as a homogenous solid (with a consistent distribution of mass through an irregular volume) or as a hollow skin (with a consistent surface mass distributed by an irregular surface area distribution), we are able to re-distribute the mass of the chair through a variable density and variable thickness three-dimensional mesh matrix. The resulting hierarchical cellular structure allowed us to place the center of gravity of the chair (both pre- and post-occupant) in a position which naturally gravitates towards a vertical position.

Gradient Structure

As 3D printing is a layer-based additive manufacturing process, where each subsequent layer is placed upon the previous one, a fundamental paradigm shift in the way we conceived of the chair was to relate it towards the growth and performance of bones. Bones are thought of as solid homogenous elements, yet at a microscopic level they are what is known as hierarchical structures. They are actually a variable density structure of spongy cellular tissue, with increased material and density placed in areas of the greatest principal stress (Figures 5 and 6). The structural density of bone adapts over time to the forces and loads that are applied to it (Wolf 1892).

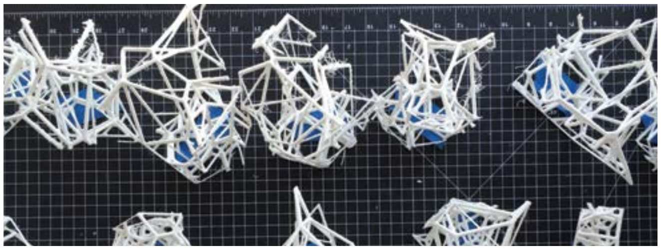
We approached the analysis of the Durotaxis chair as an opportunity to take a similar strategy. Through the use of the Karamba structural analysis plug-in, we were able to analyze the mesh geometry of the chair to discover its principal stress flow lines (Figures 7, 8, and 9).

These principal stress lines illustrate the flow of vectors through the geometry in both pure tension and pure compression, and serve as the basis for generating a gradient heat map that informs the redistribution of mass, and reorientation of structure to accommodate and respond to structural force.

Generative Sphere Packing

In order to achieve the desired effects of a variable density three-dimensional space frame, a computational process for generating the articulation of the sponge-like structure was proposed. The workflow for generating the variable densely packed 3D mesh jumped among a number of software packages and oscillated from the manual and intuitive modeling of the global form of the chair, to the analytical study of structural forces, to the generative articulation of gradient conditions into a cellular matrix (Figure 10).

- The chair geometry is developed through low-poly subdivision modeling in Maya.
- The subdivision mesh is exported to Rhino, and the mesh topology is processed through a plug-in called Weaverbird.
- The refined mesh is analyzed in the structural analysis plug-in Karamba to discover principal stress distributions.
- The structural analysis is converted into a gradient heat map through the associative modeling plug-in Grasshopper.
- A dynamic springs & nodes is utilized to “sphere pack” a variable density cloud of points within the boundary of the mesh, utilizing the gradient heat map as scalar distribution map.
- Each of the nodes of the network (the centers of the spheres)



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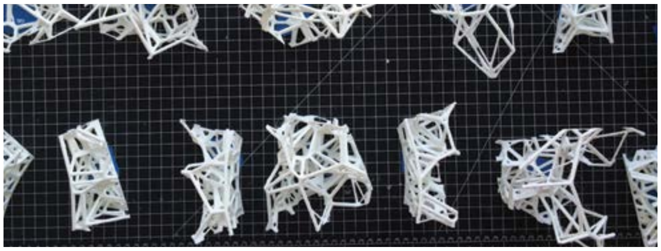

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11 Breakdown of the chair into 5 build volumes, and each build's respective gradient steps.

12 Mapping the gradient steps against a material and color gradient.

13 The 3D printing and post-production process.

is extracted as a point cloud, including the centroids of all boundary mesh faces.

- The composite point cloud of both sphere-packed volume and the boundary mesh topology are used to generate a three-dimensional voronoi network.
- All voronoi cells outside of the original boundary condition are removed, and the wireframe network of the cells is extracted to create the underlying topology of the new mesh.
- The wireframe network is given a variable thickness and color gradient in relation to the heat map of its principal stress analysis through the plug-in Exoskeleton.

The Connex 500 is able to print in a smooth gradient, but the process of providing gradient information to the machine to print was a much more painful process than expected. At the time of production, the only process for printing the multi-material conditions of the chair was to break the file into a series of stepped gradient conditions as separate closed meshes. Grasshopper was used to break the color and scale gradient into precisely ten color/scale steps, each resulting in a single closed mesh (Figure 11). The resulting ten-step file is combined into a single STL file, which is broken down into exactly 4 pieces: a back rest, seat, and two arm rests (Figure 12). These pieces are split to be able to fit the bed of the Objet 500 Connex3.

Fabrication

Though the translation of information to matter is an automated translation of computational protocols, the end result involves an intense amount of manual labor and a high level of precision with hand craft. The post-production process of the model far exceeded our expectations for the amount of time and labor required to produce the part. This process can be defined by the following steps:

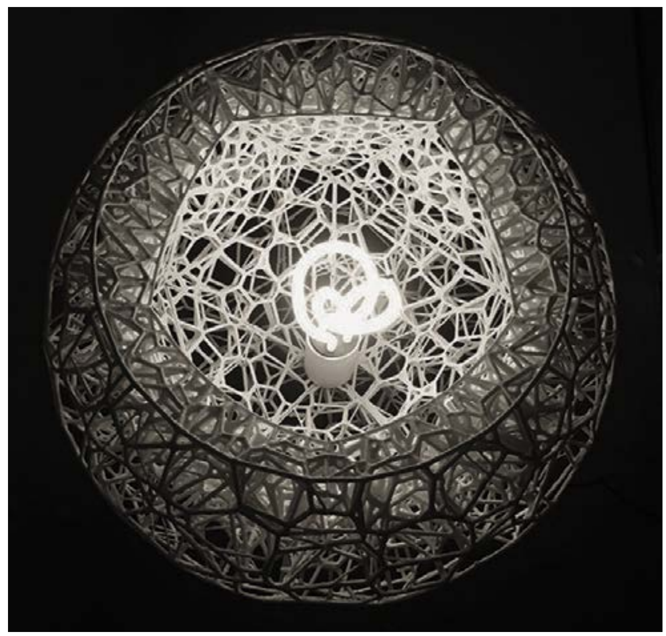
- The individual pieces are 3D printed with full support material on the Objet 500 Connex3. You can see in Figure 13 that volume of the chair is printed as a solid object with the support material filling the voids of the model.
- The raw 3D prints are placed in a chemical bath which dissolves the support structure. Nearly 70% of the printed material is wasted. This waste is non-recyclable and cannot be repurposed or recovered.
- The individual pre-fabricated pieces of the chair are removed from the bath and post-processed to clean off any remaining support structure. The individual pieces are carefully and precisely welded together by hand using chemical adhesives.

LA BURBUJA LAMP

The La Burbuja Lamp is a bespoke 3D printed pendant luminaire articulated as a densely packed three-dimensional field of virtual

14 The La Burbuja Lamp.

soap bubbles. The intricately articulated lattice of the pendant is the result of a design research experiment in three-dimensional space packing structures that are constrained by the limitations of the angles of repose required to support extruded PLA plastic in a supportless FDM 3D printing process with zero waste. The object can be read as a series of multiple micro figures embedded within a monolithic macro figure via the constitution of over 1200 virtual bubbles computationally packed into its spherical bubble-like mass. The juxtaposition of two primitive and platonic global forms is defined by an internal decahedron skin and a spherical exterior skin, with the volume between them defined by variably localized articulations, including lace-like forms which produce multiple readings of figures within figures.



15 The filligree effect of the La Burbuja Lamp.

Following the completion of the Durotaxis Chair prototype, we began to question some clear redundancies in the fabrication process for the chair. The cost of the support material for the build was extremely high. Over 75% of the printed material was support material, which was removed and wasted. The process of post-production (removal of support material) was highly laborious and manual. We proposed a second challenge to the design team, which was to produce another similarly intricate 3D printed prototype, but this time, with zero waste.

To achieve this, we were inspired by three basic ideas:

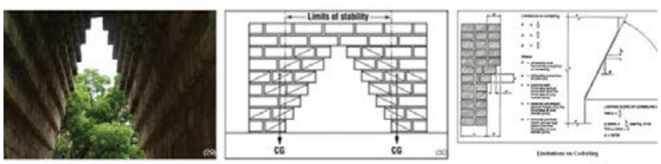
- The fact that most 3D printing software such as MeshMixer currently utilize various algorithms for the generation of scaffolding as support structure for cantilevered elements.
- The fact that 3D printing is currently being used to fabricate scaffolds with complex internal structures for synthetic bone replacement materials (Leukers et al. 2005).
- The concept of corbelling bricks, which consists of incrementally cantilvered layers of purely horizontal brickwork that meet at the top (Rovero and Tonnieti 2014).

In short, the goal was to prototype a complex structure that was actually composed of scaffolding as opposed to supported by scaffolding, thus omitting the requirement to print or waste support material. Furthermore, we wanted to propose a prototype which could capitalize on a secondary purpose for the intricacy of the geometry, thus deciding to produce a pendant lamp which would also profit from the richly varied pattern of light and shadow produced by the lattice network.

Experiments in Unsupported 3D Printing

The hypothesis of our experiment proposes that there is a potential connection between the angle of inclination and the amount of back span within each horizontal layer of a 3D print, which works similar to the concept of corbelling in brick structures. The restrictions of corbelling are based on the horizontal length and vertical depth of each brick, and the resultant center of gravity of each building unit. This position of the center of gravity in the horizontal axis defines the maximum unsupported cantilver length, which in turn defines the maximum angle of inclination (Figure 16). In short, the greater the back span, the longer the unsupported cantilever can extend until it reaches a ceiling where it must be intercepted by another angle, thus allowing us to discover the extreme non-linear relational constraints that can inform the design of the mesh.

Utilizing a Makerbot 2.0, a fused deposition desktop 3D printer that prints layers of PLA plastic, a series of material experiments were conducted to test over 50 combinations of various angles of repose against various thicknesses (Figure 17).



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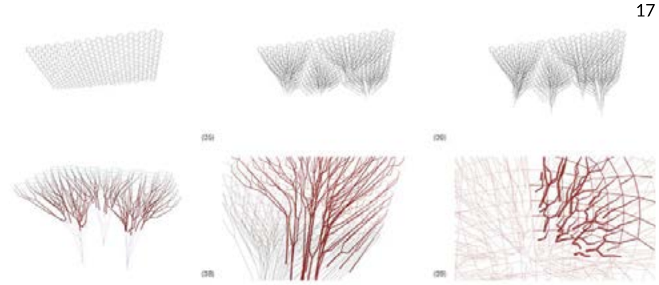

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16 The concept of corbelling bricks.

17 3D printed experiments in unsupported cantilvered angles.

18 Branching growth algorithms constrained by maximum angles of repose.

Geometric Rationalization

In order for the build process to work, it is required that each build had to start from a flat construction plane. Given the build constraints of the 3D printer, the spherical form of the out skin of the lamp was constrained against the planar faces of a polyhedron. A decahedron was used to create 20 build faces in order to build the organic growth from a two-dimensional plane, thus producing 20 individual 3D printed components (Figure 19). This polygonal-faceted form is then assembled into a continual composite sphere.

Fabrication

Each of these segmented components was printed through the Makerbot Replicator 2, with all support structure options turned off. Each component had an average build time of 12 hours, with no post-production for the removal of support material. Subsequently, all of the components are welded together to form the complete entity of the La Burbuja lamp.

CONCLUSION

Both the Durotaxis Chair and the La Burbuja Lamp challenged us as designers to consider both the constraints and opportunities offered by 3D printing. By employing a material-based design process paired with a strategy of structuring as a form of design exploration, both projects were able to be materialized as 3D printed prototypes.

By simultaneously considering the structural, material, and fabrication constraints of 3D printing, our hope is to further pursue these discoveries at larger scales and further explore the benefits of 3D printing for producing highly precise complex geometries. These are especially notable for capitalizing on the material and geometric opportunities afforded by 3D printing without the costly drawbacks of wasted material and unnecessary post-production.

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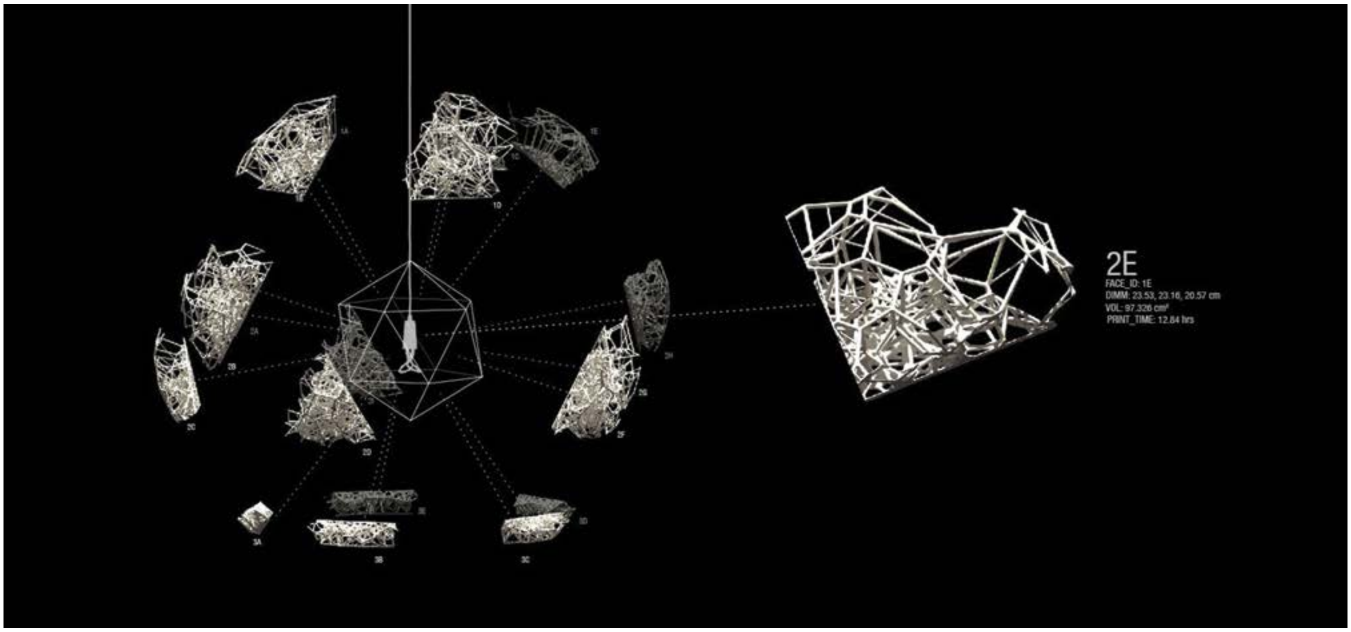

19 The rationalized components of the inner decahedron.

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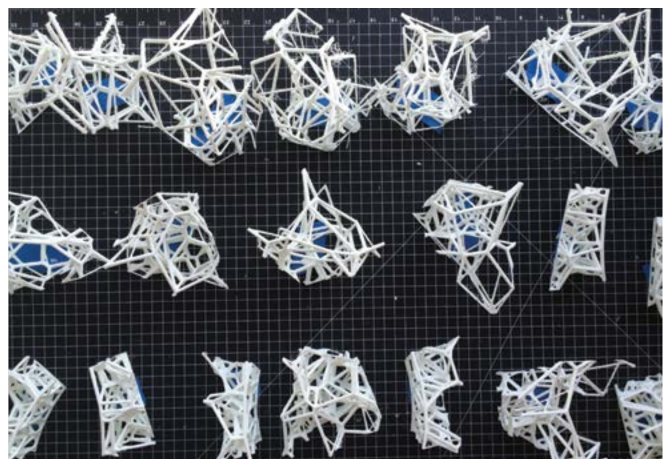

20 Branching growth algorithms constrained by maximum angles of repose.

IMAGE CREDITS

Figure 1: Imstepf., 2015
Figures 2–20: Synthesis Design & Architecture, 2015

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