2015 TxA Emerging Design + Technology Conference Proceedings

6–7 November 2015

Held during the Texas Society of Architects 76th Annual Convention and Design Expo in Dallas, Texas

Edited by Kory Bieg

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Texas Society of Architects

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The Same Strange World

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In the 1998 film *The Truman Show,** the main character Truman Burbank grows up as the unknowing participant of a television experiment. He spends his entire life in a fabricated reality that is meticulously staged just for him. The other participants in the world are actors, trained to manipulate Truman's behavior and emotions for the pure enjoyment of the audience. The show creates a representation of reality that feeds whatever drama can be thrust upon him to keep the plot fresh. After all, nothing kills ratings faster than predictability and routine. Though the set is made of real material and the constructed illusion is believable, the artifice collapses when the barriers between Truman and the real world start to unravel. When Truman begins to doubt the nature of his existence, even the basic elements of his world seem to waver. Rain is suddenly not quite rain and sun-like stage lights fall from the sky. The foundation of Truman's existence is shaken—not by the introduction of something alien, but by a strangeness found in the familiar. In the end, a deeper truth is revealed, one full of promise and possibility.

The third installment of the TxA Emerging Design + Technology Conference, held in Dallas during the Texas Society of Architects' 2015 Convention, brought together a diverse group of academics and practitioners who likewise questioned the basic foundations of their world, in this case, the conventions of architecture, building, and design. From our use of concrete as a compressive construction material to the standards of sheet metal manufacturing, from the discipline of architecture to architecture as a professional service, from texture to material to pattern and the basic elements of design, each paper looks directly through the real to see what is on the other side. As it turns out, the familiar can be a source of invention and innovation, too.

In these proceedings, authors interrogate the fundamentals of architecture and reveal something extraordinary in the ordinary. They propose new object assemblies, synthetic overlaps of material and data, new methods of project delivery, and composite structures that reject performance, optimization, and efficiency in favor of new architectural imperatives. By questioning what they think they know about the world, they open new territories for design and develop new materials for designers. Their quest for *strange*ness is their project, and the familiar is their wellspring. They call into question the conventions of our discipline by looking deeper at the world we already know and hold to be true so that the next generation of architects might find a new path forward.

**The Truman Show,* directed by Peter Weir (1998; Los Angeles: Paramount Pictures), film.

MACHINE


KUKA

Pop-Up Concrete: Digital and Physical Materiality

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1. INTRODUCTION

Concrete has been used for a long time, and the interest in building concrete free-forms has gained relevance in the last decade, which has encouraged a large amount of robotic and non-robotic research in flexible formwork systems (Bak, Shepherd, and Richens 2012). It is clear that when building concrete free-forms, one crucial decision is the choice of formwork to guarantee its quality and financial feasibility (Verhaegh 2010). Despite the increased interest in free-form concrete and the vast amount of research on flexible formwork, most digital forms are still built using traditional formwork and methods. The problem lies in the fact that construction processes still rely on a unidirectional workflow from "digital design" to "physical production." This means that designs have to go through a lengthy rationalization process where friction between form, structure, and material occurs. An integrated design workflow is researched and presented in this paper that integrates design and building through the use of new material technologies and digital fabrication tools.

Technical devices and digital fabrication tools allow for new practices and are capable of opening new understandings of matter, new ways of organizing, and new complex and irregular relationships that expand material processes to create new non-linear workflows and can lead to a new language characteristic of the robotic era in architecture. Using a new material technology within a pop-up process, based on patterns that embed the shape into the material rather than prescribe it, requires an experimental approach, as the material exhibits probable but not *certain* behavior. Thus, a new path, based on feedback loops, is proposed toward the design of curved, thin, flexible structures in concrete without the need for complex formwork that would be otherwise required (Kotnik and Weinstock 2012). Our shaping system allows for complex curves to be created through a combination of the concrete sheet material and the embedded pattern.

2. PRECEDENT ANALYSIS

In the context of robotic fabrication of concrete, projects to date have been divided into four major areas of exploration, each with a unique set of limitations:

1. *Concrete 3D printing*: Over 10 years ago, researchers at the universities of Southern California

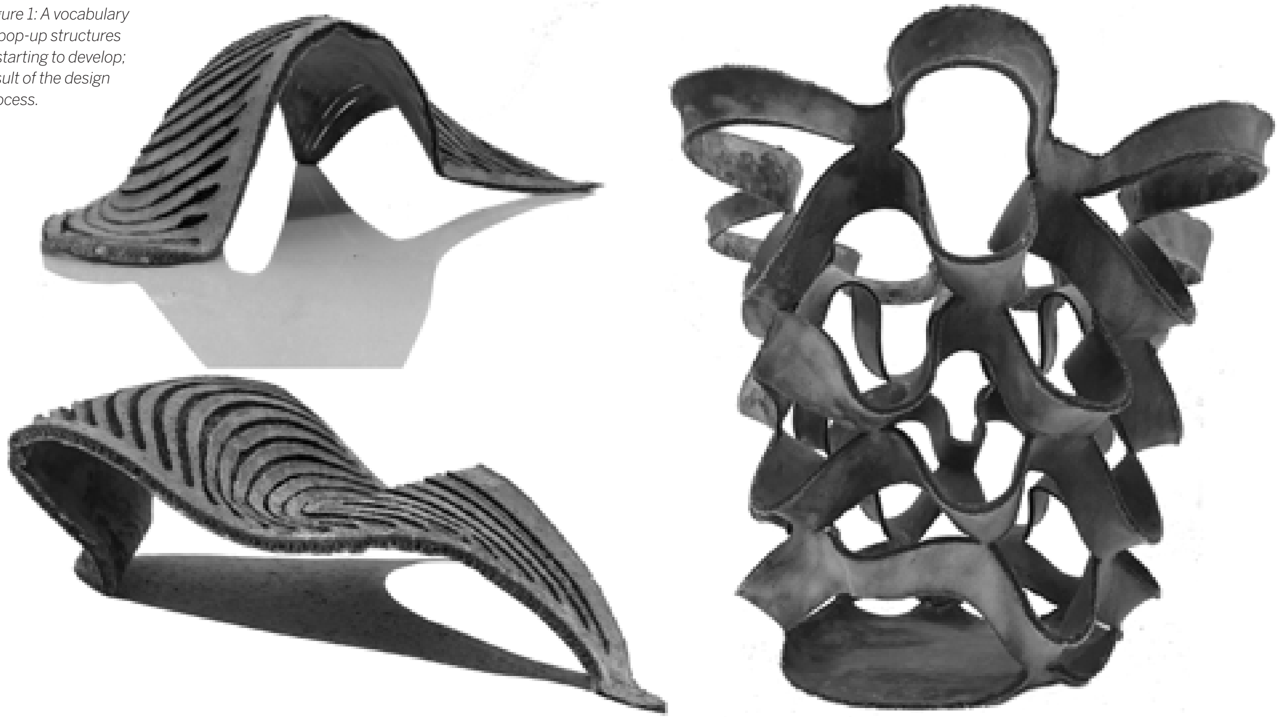

Figure 1: A vocabulary of pop-up structures is starting to develop; result of the design process.

(Khoshnevis n.d.) and Loughborough (Lim et al. 2011) started to investigate the potential of extruding concrete for printing buildings. Both attempts used an extrusion head mounted on a gantry crane to deposit horizontal layers of concrete. However, limitations exist regarding the scalability of the gantry, the hydration process, the loading capacity, the adhesion of the different layers, and the integration of reinforcement.

2. *Dynamic formwork*: "Smart Dynamic Casting" (Lloret et al. 2014) focuses on the vertical extrusion of concrete columns, using sensors and a feedback loop to monitor and control the hydrating of the concrete. This information is then used to determine the slip velocity, tackling the problems of previous 3D printing methods. The careful calibration of sensor feedback with the spatial movement allows for a high level of control over the formation process.
3. *Mould-based formwork, flexible and rigid*: TailorCrete developed a digitally controlled, recyclable, flexible wax mould system that is produced off-site, then brought on-site and inserted into standard formwork systems to produce complex concrete structures (Oesterle, Vansteenkiste, and Mirjan 2010). Conversely, the "UNIKAbeton" prototype showed the possibilities for complex concrete construction using digitally fabricated rigid EPS blocks (Sondergaard and Dombernowsky 2011).
4. *Leave-in formwork*: The Mediated Matter Group at MIT (Oxman, StevenKeating, and Klein n.d.) and the project "Mesh Mould" at the ETH (Hack et al. 2014) explore techniques where the robot 3D prints permanent formwork, which doubles in function as thermal insulation in the former and as reinforcement in the latter.

3. METHODOLOGY

Pop-up is a technique that transforms planar materials into 3D forms. Research in pop-up as a construction system in architecture and other fields remains relatively unexplored. Researchers in nanomaterials have only recently started to look at the potential of pop-up as a manufacturing technique and as a simpler route to achieve 3D frameworks by buckling planar structures, allowing them to create complex shapes using a variety of materials, such as silicon and semiconductors (Xu et al. 2014). There is also ongoing research using a pop-up system on modified crystals for implantable devices that can be triggered to morph once inside the body (Verduzco 2015). The formation of pop-up structures is not random—it is caused by set boundary conditions of the embedded cut and joint pattern and follows precise physical principles.

These concrete geometries rely on a system based on 2D cutting patterns performed in "Concrete Canvas," described below, that transforms into a 3D shape by buckling on-site using inflation to create a surface. The Concrete Canvas cures with the addition of water to become structurally rigid after an initial period of three hours and becomes fully set after 24 hours. Concrete shaping is possible as long as the concrete is in its wet state; this curing period or "transition" phase of the concrete opens possibilities for new shaping strategies where the form of the three-dimensional object is transformed. Digitally, 3D shapes can be collapsed into 2D cutting patterns to be popped back up into 3D surfaces. The design is not finalized until the material hardens, giving various opportunities for interaction between the architect and the material, and thus making fabrication an interactive process of creation.

4. PHYSICAL FABRICATION

4.1 Concrete Canvas

New materials provide an opportunity for designers to create new typologies (Thompson 2007). Material developments and higher-strength concrete have been used to explore 3D complex concrete shapes that pop up from flat 2D patterns. Concrete is not traditionally a flat sheet material. However, fabric impregnated concrete, a new hybrid material technology, combines the compressive strength of concrete and the tensile strength of fabric. This seemingly contradictory characteristic allows for a more intuitive design workflow that can lead to a flexible and adaptive design process. Through prototype testing, it became clear that a feedback step is needed within the process to address the possibilities and uncertainties presented by the material when used in novel ways.

Concrete Canvas (www.concretecanvas.com) allows easy deployment and rapid construction of thin concrete shells, as it only requires air and water for construction. Shelter structures up to 50 square meters have been built using this material. It consists of two flexible membranes on each exterior surface, with a 3D fibre matrix impregnated with cement. The top layer is a fibrous surface that can be hydrated, while the back membrane is made of waterproof fire-resistant PVC. The cement-based composite fabric uses inflation to create its surfaces that are optimized for compressive loading. When hydrated after 24 hours, the membranes harden, forming a thin, robust, and lightweight concrete structure. Concrete Canvas comes in different thicknesses (5, 8, and 13 mm). The experiments described in this paper use the 5 mm variety.

4.2 Robotic Tooling

A set of key variables was identified for the design of the robot tool, such as: the turning radius of the cuts; the depth of the sandwiched material; and the robot's cutting speed. A laser cutter was used initially, but the additional installation requirements made it unsuitable for on-site applications. Circular diamond saws were also tested, but the speed at which they needed to rotate caused concrete powder to eject and weakened the overall structure. A solution using a 45 mm-diameter, sharp circular blade was selected because it allowed efficient cutting, smaller turning radii, and lower rotational speeds. Enough depth is needed at the entry points so that it cuts all the way through the material using a single pass.

4.3 Surface Definition and Tool Path Generation

The process starts with the definition of a base surface. A control pattern of cuts and joints that will define the surface form is then applied. Four main criteria that define the final popped-up geometry are identified and parametrically controlled (Vazquez et al. 2010):

1. The cutting pattern defines the relationship between the 2D pattern and the 3D volume. The cuts on a flat material need to be offset to achieve a concave geometry. The spacing between the cuts needs to consider the material behaviour and avoid extreme clustering that will result in long, thin elements that can buckle, given a very small distance from the edges. If the cuts are too far apart, the pop-up will be too shallow. A minimum section of 30 mm has been established for the 1.0 x 1.0 m prototypes.
2. The joints between cuts affect the stability of the overall structure. The joints are the areas where there is no cut, and they are crucial for the popping of the unit. When joints are staggered, a more rigid structural system is achieved. Our experiments show that joints of 40–50 mm create rigid

Figure 2: (Left) 2D pattern laser cut in Concrete Canvas. (Right) Popped-up Concrete Canvas shell prototype.

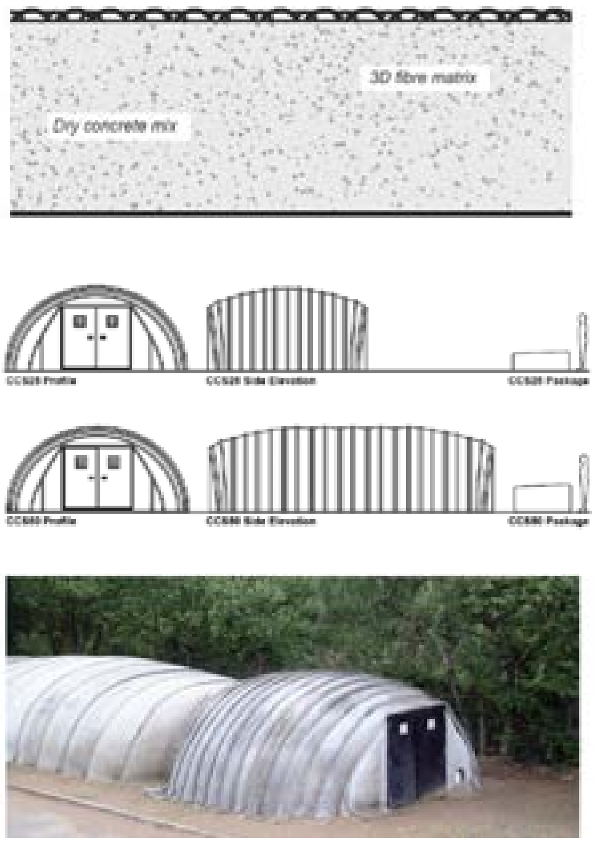

Figure 3: (Top) Concrete Canvas section. (Middle) Typical deployment sequence. (Bottom) Shelter structure. - images courtesy Concrete Canvas

conditions. Joints smaller than that create flexible and semi-flexible conditions.

3. Relaxation, form manipulation, and inflation determine the final position and shape of the surface.
4. Pre-hydration and drying times affect both the structural rigidity of the surface and its elasticity. In our experiments, we tested different sequences of hydration and cutting to maintain the integrity of the final form and minimize concrete loss.

Once a pattern of cuts and joints is determined based on aesthetic and structural constraints, the curves need to be rationalized to maximize continuity. This ensures path continuity and decreases the possibility of singularities and out-of-reach positions for the robot. The end points of each curve are offset on the Z-axis for the robot to move vertically after each cut and allow for the joint areas.

5. DIGITAL COMPUTATION AND SOFTWARE WORKFLOW

The digital process is set with the aim to foresee materialization and control it during its forming. It requires the customization and integration of different software platforms for material computing, physics solvers simulation, and structural analysis. To achieve the initial goal of merging modelling, analysis, and fabrication into a single process, the form-found geometries need to be brought back into the digital world, and a direct link needs to be created between the digital and the physical models.

After the initial surface with the joints and cut patterns is defined and modified, it is exported to form-finding software based on particle spring systems. In this case, Grasshopper and Maya Nucleus solver were used to approximate the shape digitally. The Autodesk Maya N-cloth delivers sufficiently accurate results in replicating the material performance and pop-up behaviour observed in the physical tests, as it allows embedding and calibrating different physical constraints, such as damping, strength, stiffness, and density. Each pattern was established as a boundary condition and relaxed to find its resultant pop-up geometry within the pattern. Once the pop-ups are generated and evaluated, the pattern is turned into toolpaths using a custom-made robot communication platform for cutting and physical testing. Further research is being conducted to develop a workflow that integrates the robotic and physics simulation into a single platform, to enable a continuous workflow from design to realization of non-standard, material-driven fabrication processes.

5.1 Feedback Loops

Utilizing a commercially available 3D scanning application, a strategy was evaluated in this research project for its potential in establishing the following iterative feedback loop: material deployment; automated inflation process; measurement of deformations in the physical geometry; calibration of the digital mesh; structural and aesthetic analysis of both; live manipulation of the inflated concrete structure; and point-cloud 3D re-scanning.

In the implemented approach using Autodesk 123D Catch, the scanned information consists of a point cloud and a mesh that can be imported to the digital environment. This is then used to calibrate different parameters, such as damping, strength, spring stiffness, and density to approximate the digital and material behavior. This allows the designer to quickly understand and evaluate the many factors that influence the process and to “mould” the material. Feedback loops enrich the process, as this information is taken to the following cut pattern. Enhancements or modifications to the cut pattern of the flexible sheet material are related to the whole process, as the cut and joint strategy gives unique identifiable characteristics to the final rigid material. The iterative process allows us to integrate computational and material logic into the design with which we can predict and orchestrate sequential material behavior. It negates the unidirectional flow from “digital input” to “physical output” that pervades current processes of digital fabrication.

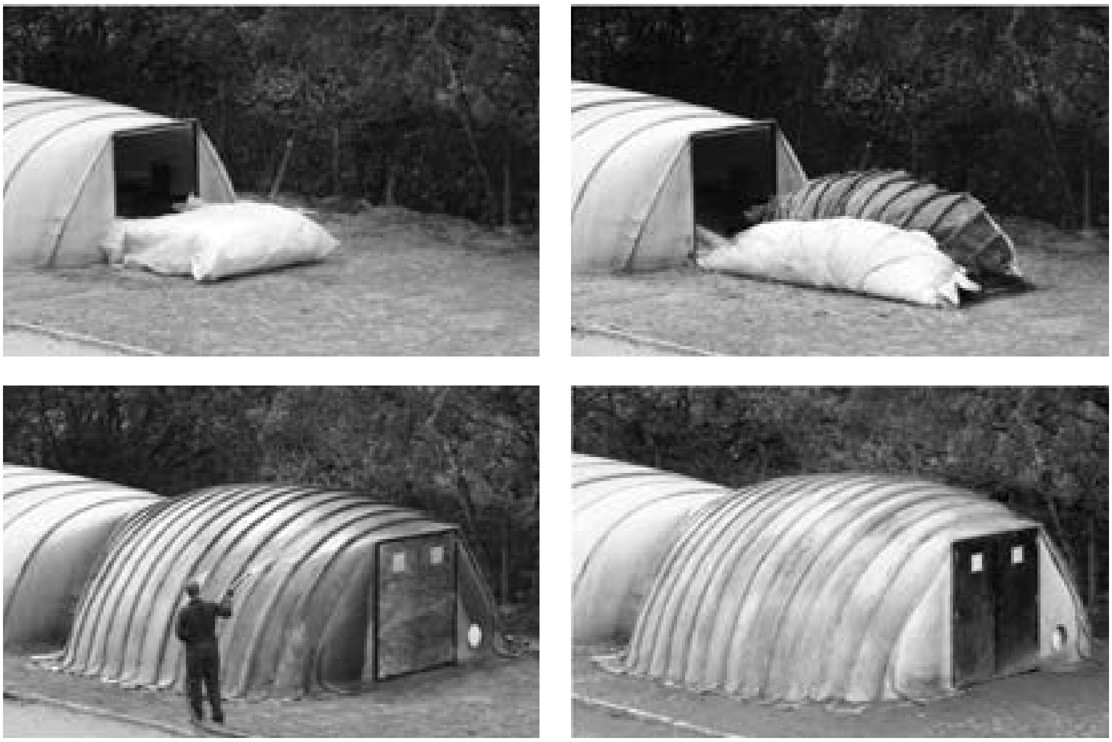

Figure 4: Detailed traditional deployment of Concrete Canvas. (Top Left) Delivery. (Top Right) Inflation. (Bottom Left) Hydration. (Bottom Right) Setting. - photos courtesy Concrete Canvas

5.2 Analysis

The uncertainties regarding the behavior of the Concrete Canvas with the applied "cuts and joints" pattern, intertwined with the fact that the pattern can allow for material extension beyond its safe limits, requires continuous analysis. Scale models were built and popped up. Through scanning, the response of the model to the pattern was measured, and its structural behavior analyzed and calibrated with the digital model. Modifying the control cut pattern gives different properties to the material. What was expected to be a homogeneous shell became flexible, semi-flexible, and rigid. Rhinoceros Scan&Solve was used to check the shapes qualitatively. This allowed a clearer image of the structural and material response to the cutting pattern.

5.3 Simulation

Iterative digital physics-based simulations were used to gain a deeper understanding of the relationship between the cut patterns and the final 3D form. The production of low-resolution meshes using particle-spring systems is an established practice for physics simulations. They provide the designer with an intuitive and qualitative knowledge during early design stages that can be augmented with structural and fabrication constraints through a feedback loop (Vazquez et al. 2014). Calibrating a digital low-resolution mesh with the high-resolution material input from the scanning process allows the designer to work interactively with the geometry while enclosing all the important technical details, such as singularity points, boundary and topological conditions, holes, clearances, etc. (Bhooshan and Sayed 2011). It also allows for an iterative quick evaluation of a range of options by adjusting key parameters that affect each realization (Williams et al. 2011).

5.4 Flexibility

The ability of the designer to intervene at any stage during the process is very important. During the inflation process through the feedback loop, the designer has the flexibility to interrupt and change the flow of information. The resultant geometry can then be analyzed for its structural and aesthetic characteristics, while changing the parameters, and consequently the geometry itself, before hydration and curing.

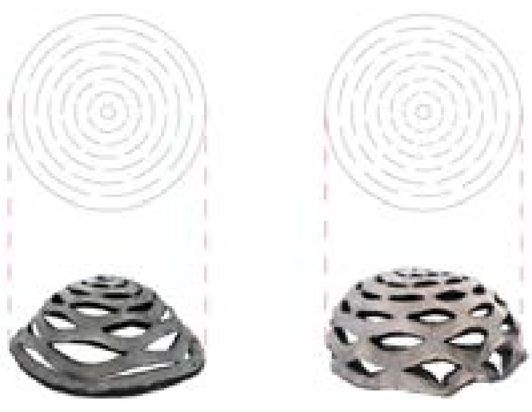

Figure 5: Changes to the cut and joint pattern; boundary conditions and relaxation constant.

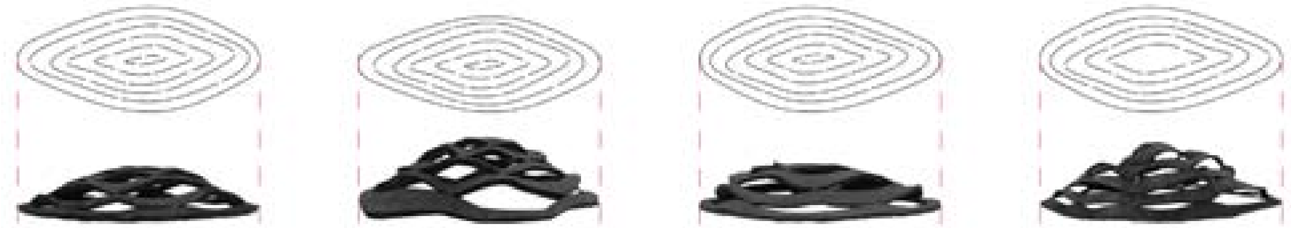

Figure 6: Comparison of geometric differences in the 3D pop-up surfaces; product of changes in boundary conditions and cutting patterns.

6. SCALABILITY

Unlike other material experiments, due to its native use for infrastructure, fabric impregnated concrete can scale up as it is normally used in large-scale infrastructure projects. Physical models have traditionally been the basis for the design of fabric formwork as there is a relatively direct relation between scaled and full-scale models (Manelius 2012). Professor Mark West, with 20 years worth of experience on the design and construction of fabric formwork, argues that "anything you can build in a scaled model, you can build at full scale" (West 2011). Anne-Mette Manelius at the KADK, Denmark, after several workshops working with students, confirms this relationship of causality (Manelius 2012).

Experiments so far have been limited in size by the maximum width of the fabric of 1,030 mm. To move into larger structures, Concrete Canvas geometries will have to be constructed assembling segments to complete the form before inflation and hydration. The fabric-like properties of the material enable the possibility of sewing various pieces together following a pattern as with traditional fabric formwork. This means that geometries that can be unrolled and cut out of fabric can be done using this technique. Concrete Canvas trademark shelters are built using this approach. To succeed at 1:1 scale using concrete impregnated fabric, adjustments to the sequencing and construction planning are being explored, while the fundamental concept remains feasible.

7. HYBRID TECTONICS

Additive, subtractive, and formative processes are the three main accepted fabrication categories (Chua, Leong, and Lim, 2010). Embedding patterns in the concrete fabric is mainly a subtractive process in a homogeneous material. The distribution of cuts and joints gives areas of varying rigidity within the final form. This is the first step in introducing heterogeneous properties to the material. Based on the analysis of the 2D patterns and their 3D pop-up resultant geometry, further research is being done on ways to add material to reinforce specific areas during and after pop-up. A 3D printing step before popping up can be an option to reinforce zones where more structural resistance is needed and that can be weak after pop-up. Introducing the possibility of adding material to the process gives the ability to tailor structural and material properties of an otherwise homogeneous material to improve efficiency and functionality in the final 3D geometry.

8. CONCLUSIONS

The implementations of pop-up structures that generate 3D surfaces out of 2D patterns clearly yielded

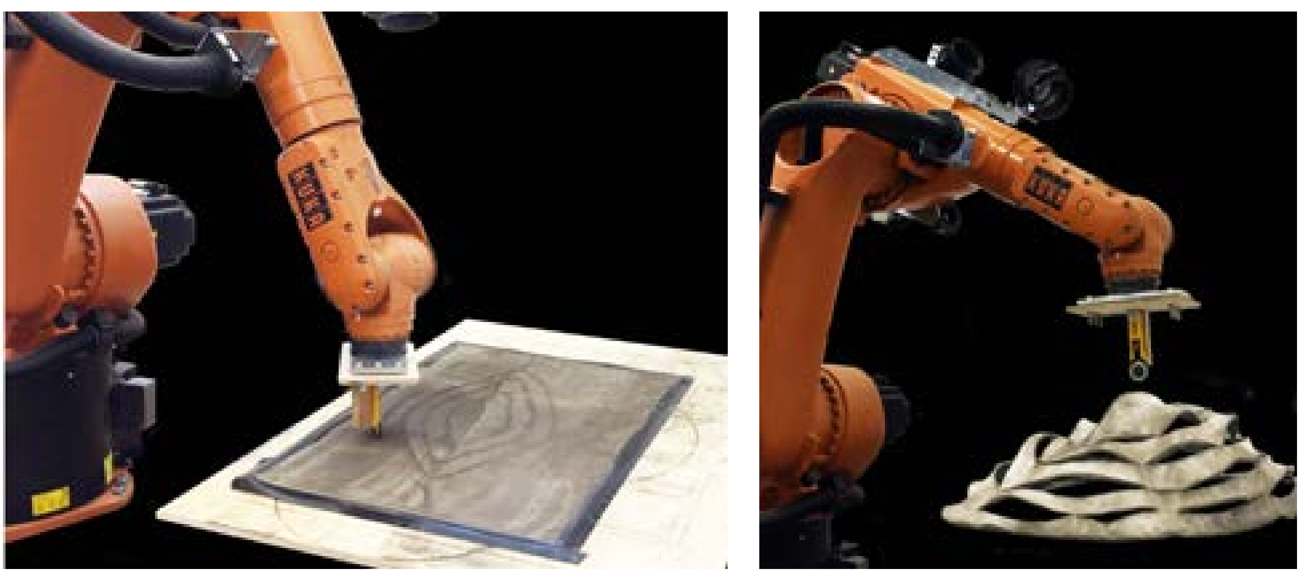

Figure 7: (Left) Robot cutting pattern in concrete. (Right) 1.0 x 0.7 x 0.7 m popped-up prototype.

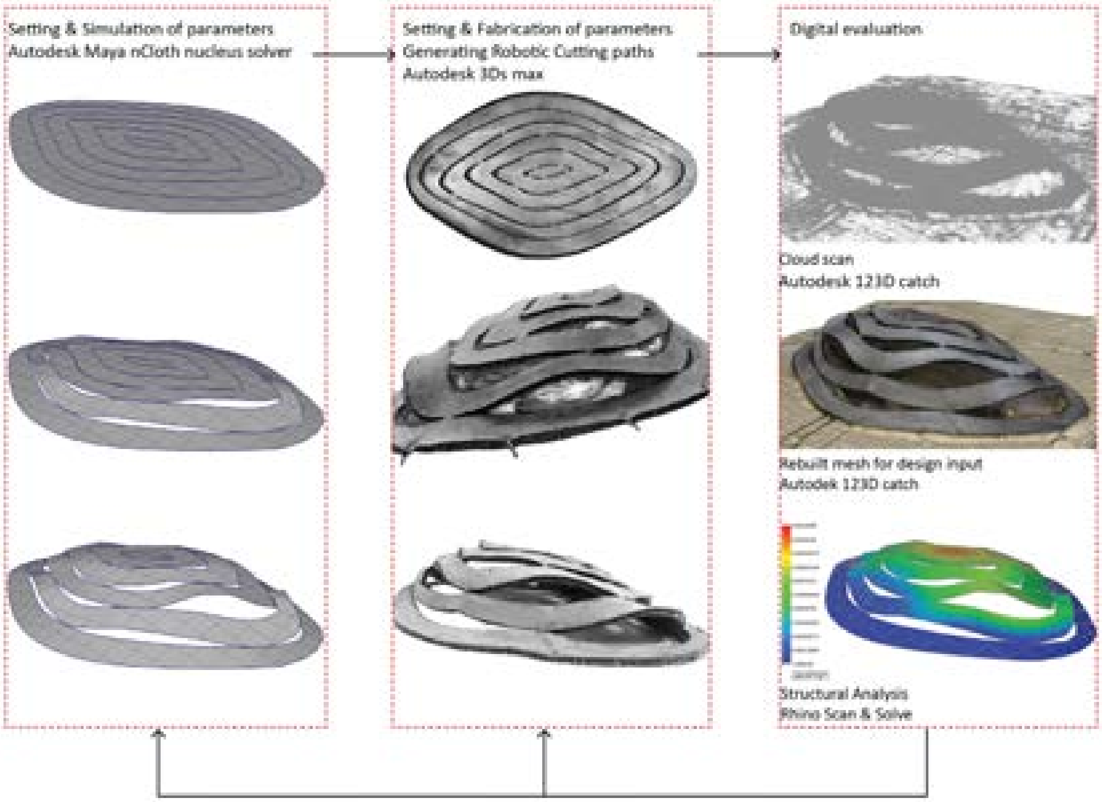

Figure 8: Diagram showing the workflow setout and digital–material feedback loop.

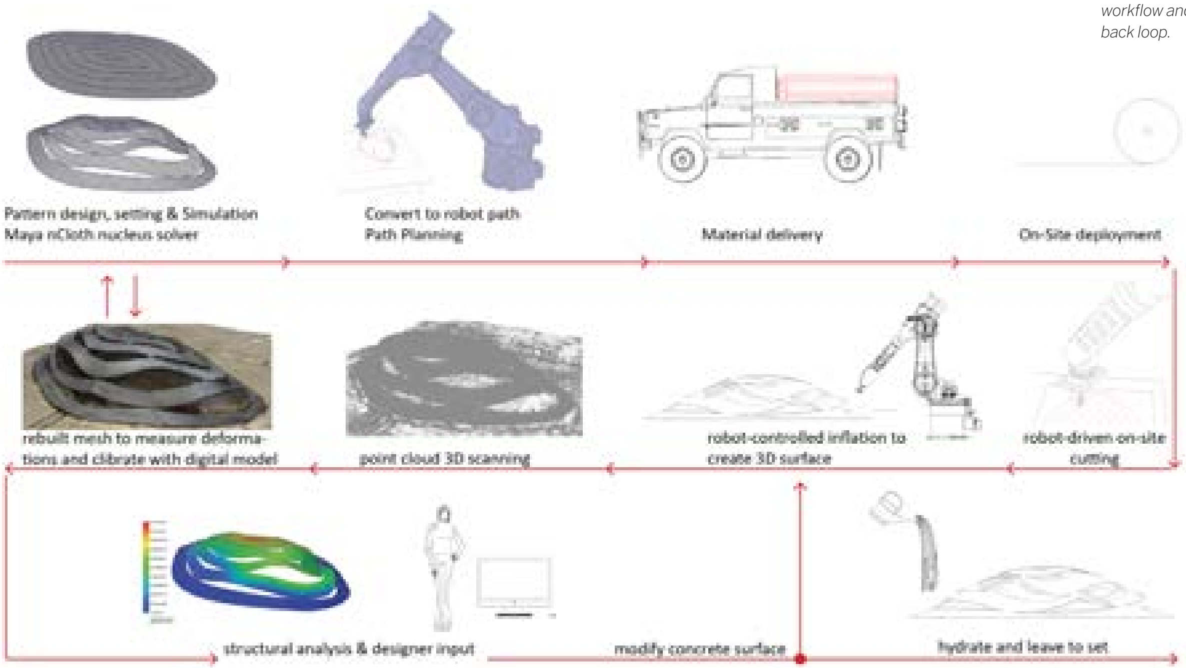

Figure 9: Path planning workflow and feedback loop.

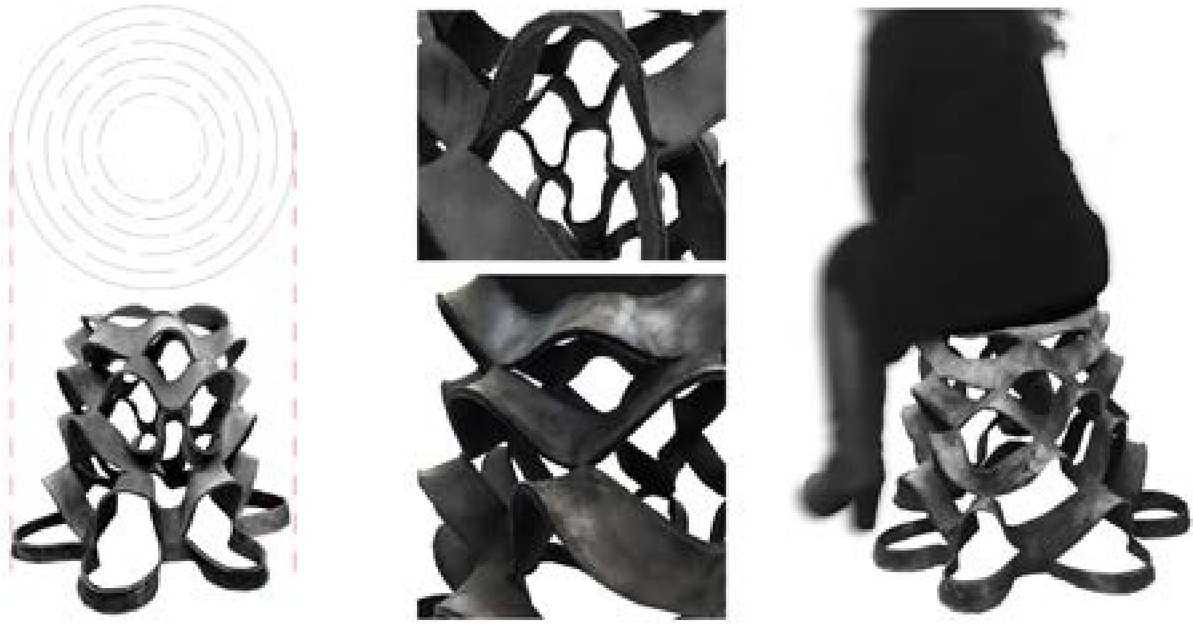

Figure 10: (Left) Pattern and resultant pop-up geometry. (Middle) Concrete details. (Right) Live load testing to calibrate with structural assumptions.

an expanded domain for design exploration that can generate a new language for architecture in the robotic era. The generation of pop-up structures is not random but caused by set boundary conditions of the embedded cut and joint pattern and follows precise physical principles during its pop-up. Through the feedback loop, and with defined boundary conditions, the results can indirectly be controlled and emergent shapes created by stopping the process at any point in time during the "pop-up" phase of the concrete. 3D pop-up geometries can achieve a space-enclosing surface faster than 3D printed ones. A main challenge of this technique is that while the desired end 3D shape is known, the pattern to produce it is not, an inverse situation to that of traditional construction methods (Ye and Tsukruk, 2015). Future work will be conducted to develop 2D patterns that pop up into the desired 3D structure.

Initial experiments were concentrating on the development of pop-up strategies for industrially prefabricated products like Concrete Canvas. However this product is mainly used for infrastructure, and its structure and finish often don't allow the desired forming. For the next test scenarios, the authors want to include the design of the composite material itself, as it promises a huge impact on the formal results caused by the formation strategy.

At a design level, the aim is to establish more intricate and larger patterns where two or more sheets are sewn together and their initial configuration responds to more complex geometries. The scanning of the physical geometry after being streamed to the digital simulation for analysis will be used to automate the control of the popping up, in order to investigate viable inflating and interaction sequences that allow for closer relationships between designer, robot, and material before implementing them in real time for a full-scale prototype. Through this exploration, we anticipate the realization of complex concrete geometries responsive to embedded performance criteria.

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Proto-Skins: Designing and Fabricating Architectural Skins Using Incremental Sheet Forming with an Integrated Workflow

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1 INTRODUCTION

Recent developments in sheet metal fabrication methods for producing custom architectural components have allowed for greater efficiencies in volume production and lower tolerances. However, these advances still lack means to mass customize significant formal and geometric variation, especially articulated double curvature surfaces. Prototyping and research on conventional stamped architectural facade components is excessively costly due to the cost involved in producing stamping dies and the time associated with that. Hence, a process called incremental sheet forming (ISF) provides opportunities to prototype rapidly and produce highly variable and cost-effective components (fig. 1).

Over the course of this research project, many individual experiments and tests with ISF as a fabrication method for architectural panels were combined to create more complex systems. A significant part of the design process was informed by these experiments, as well as the intrinsic relationship between the tools, materials, and geometric possibilities.

The aim was to always hypothesize about the "formability" of certain geometry and materials, then realize those results with full-scale prototypes and tests. Possessing the ability to quickly iterate design options and fabricate them as fast is one of the great benefits of linking the design workflow to the fabrication needs and limits in a closed loop.

Tolerance management, material integrity, and proposed architectural applications will be used to support the argument for using ISF as prototyping method for alternative ways of designing enclosures and second skins.

This research is not intended to compete with conventional facade manufacturing techniques, nor does it aim to produce systems with low tolerance industrial precision. Rather, the purpose of this investigation is to re-examine the ways in which "architectural" skins are designed and fabricated in an integrated workflow.

2 RATIONALE

The work described is a continuation of a larger research trajectory aimed at developing the necessary tools and techniques to discretize parametrically designed prototypes of building skins using ISF.

ISF is a fabrication process that involves turning flat sheets of metal into three-dimensional shapes using

Figure 1: Incremental sheet metal forming.

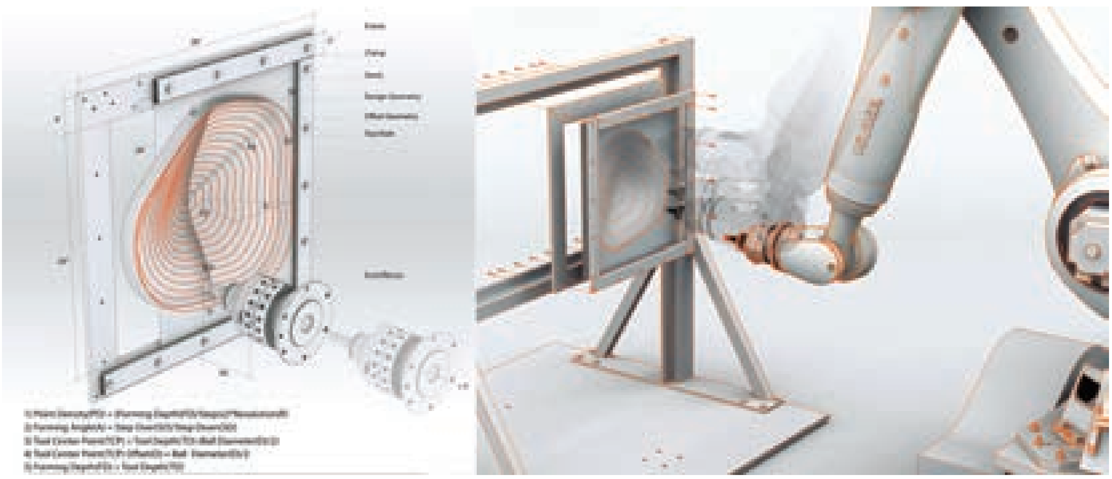

Figure 2: Incremental sheet metal forming process diagram and toolpathing strategy.

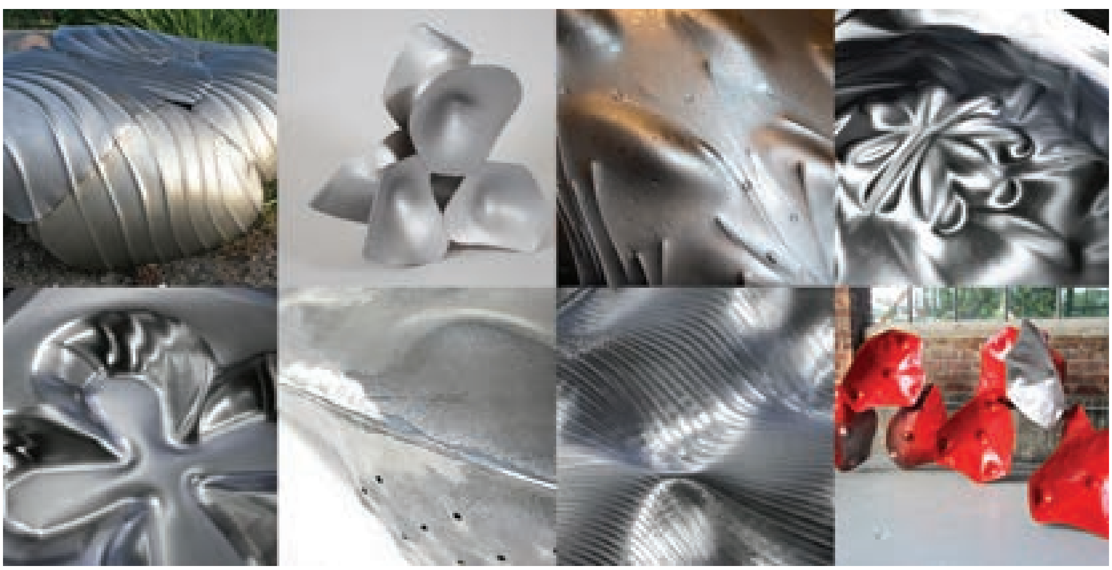

Figure 3: Examples of previous work of this research trajectory.

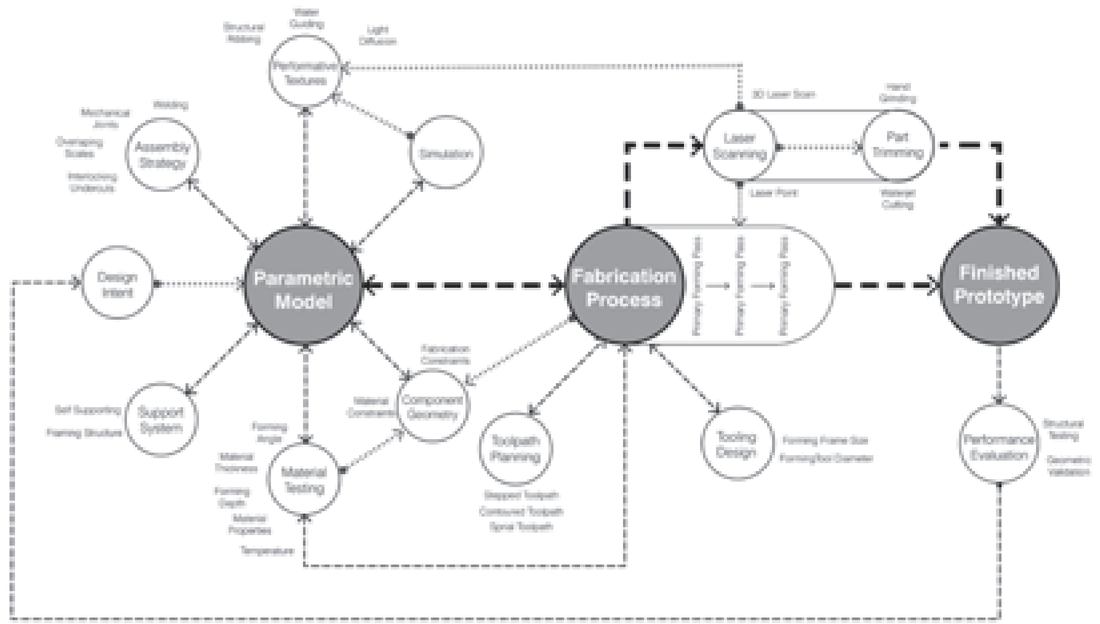

Figure 4: Diagram of a networked design and fabrication workflow.

a CNC machine (Laperrière and Reinhart 2014). It's a process whereby the stock is locally stretched using a custom tool running along a pre-programmed toolpath (fig. 2). The forming stylus could be mounted on any CNC machine with enough strength to overcome thin gauge metal forming forces; however, using an industrial robotic arm allows for more degrees of freedom and a more versatile workflow. A spherical forming stylus is mounted as an end-effector to the robot, which moves along a preprogrammed path that is generated from a 3D model. The path starts from the perimeter of the designed part and continuously pushes against the surface of the sheet metal until it reaches the center of the deepest concavity in the design. Depending on the geometry, forming may require secondary paths for refining the overall shape or articulating local features.

Proto-skins largely builds on previous efforts that focus on computer modeling methods, parametric tool path generation, forming practices, material testing, part validation, and basic aggregation strategies.

The multitude of functions that this metal forming process enables helps in focusing on key aspects to develop. For example, instead of thinking about designing with low tolerances and fighting against unpredictability in the material system, Proto-skins takes advantage of the unpredictability and inaccuracies, and utilizes them in a loose, shingle-like arrangement.

3 ARCHITECTURAL CONTEXT AND RELEVANT WORK

In 2001, Asymptote architects designed Hydra, an information center that features a complex surface achieved by double curved panels that were formed using explosion forming. This technical innovation involves a very tedious process of producing multiple positive and negative molds of different materials for each unique panel (Eekhout 2008). On the other hand, High Line 23, designed by Neil Denari, features three stamped panel types that assemble into a tileable pattern. These are also rotated and follow an undulating surface to add a higher degree of variation (Denari 2012). Stamping sheet metal is usually associated with the automobile industry, but in this instance, the architect employed this technology to gain surface variation (Simmons 2008).

There are very few examples of architecturally relevant applications of incremental sheet metal forming, but recently, a research group at RWTH Aachen University built a full-scale prototype of a self-supporting folded structure using components that employed incremental forming (Trautz et al. 2013). All those components were formed using incremental sheet forming to maximize customizability at low costs. However, for these components, the designers used a partial die that has a common center shape across all the parts. In addition, the Center for Information Technology and Architecture in Denmark recently informally published work developed using single-point incremental forming to produce a vaulted self-supporting structure. Early investigations done as part of the work presented in this paper also explored self-supporting aggregations with discrete cells incrementally formed (Kalo et al. 2014) (fig. 3).

Incremental forming is a currently studied as a feasible replacement for stamping, at least in the prototyping phase. The U.S. Department of Energy recently sponsored a joint academic-industrial project to develop this technology further into a robust mass production process (U.S. DoE 2013). Ford, one of the primary

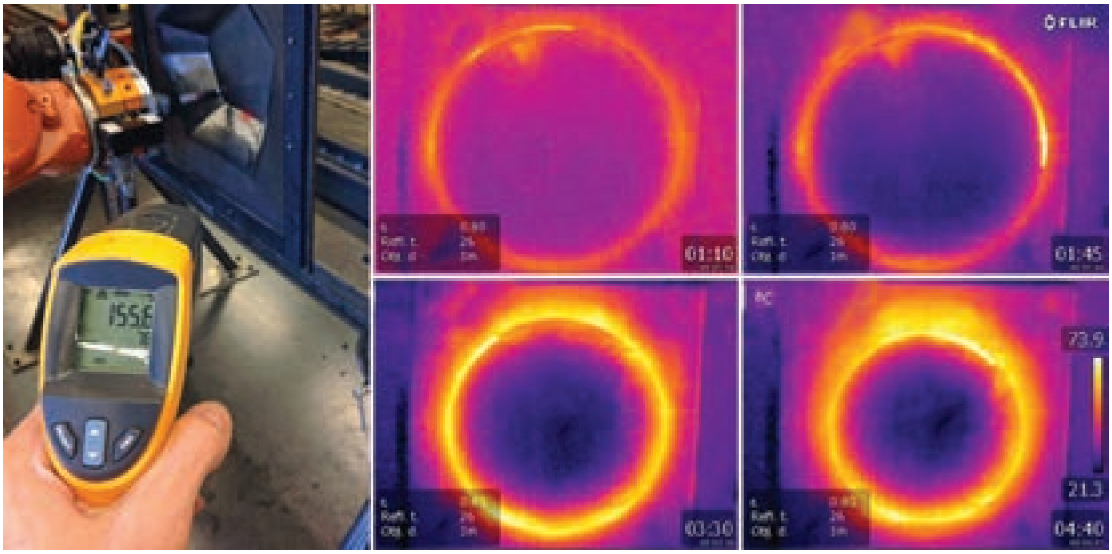

Figure 5: Infrared images showing increased temperatures along forming paths.

Figure 6: Digital scans of formed panels with structural textures with differences in springback between.

Figure 7: Multi-axis forming.

investigators of this grant, has been researching the benefits of near immediate prototyping of design iterations with ISF.

Current incremental metal forming processes cannot compete with the speed in which stamped facade panels are produced, nor can they compete with their extreme precision and high tolerances. However, for highly customized panels, incremental forming becomes more efficient, as it doesn't require the production of unique dies for each panel. When comparing the two processes, stamping and incremental forming, the former promises better energy savings when compared one-to-one in an established setup (Ingarao et al. 2012). With the ability of the process to rapidly prototype and produce full-scale formed metal panels, incremental forming begs for a thorough investigation in other disciplines, such as architecture and the building construction industry.

The potential of developing architectural skins using incremental forming is very promising. It's an area of investigation that is ripe with opportunities to produce work that has a broader impact on how architects design and fabricate building components but also to create truly unique work. There are plenty of engineering-driven studies on incremental forming, which greatly helps in developing the technical aspects of the process.

4 METHODOLOGY AND FABRICATION

Akin to the position taken by Ford employing ISF as prototyping technology, this research project adopts a similar approach by which designs could be quickly iterated and physically made in a matter of hours instead of weeks, when compared to the more conventional metal pressing. In both instances, the prototypes are then further refined.

While Ford is still testing ISF's feasibility as a mass production method, this research assumes ISF's viability and speculates on potential applications. One research goal was to have enough prototypes that demonstrate the efficiency of the process and begin conceptualizing and considering practical connection strategies.

While a large portion of the work is geared more toward figuring out the intricacies of the fabrication process, conceptual design explorations are more grounded when coupled with solid physical evidence. It also validates any form of speculation and moves the dialog away from fabrication and back to design.

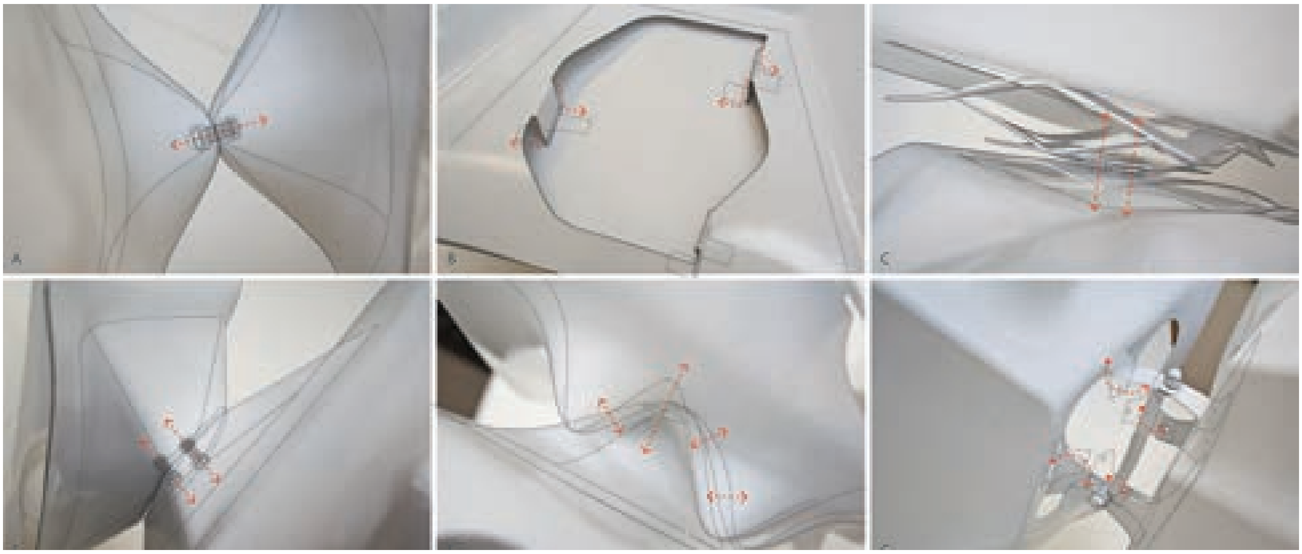

Figure 8: A collection of different face-face connections studied.

4.1 Workflow

Proto-skins are designed to embody computational and fabrication flexibility, as well as customizable contextual adaptability. The intention was to ultimately produce physical prototypes as a proof of concept and demonstrate the systems' flexibility and versatility (fig. 4).

This was done by first establishing a design and fabrication workflow that encompassed the entire process. Previously, the project was set up in a linear fabrication workflow, even though it had the potential to be much more integrated with the design process. However, as the research developed, a more integrated circular workflow was established, describing the relationships between computational design models, physical prototyping, and testing. Intuitive knowledge acquired from physical experiments was codified into a parametric script that used the data as inputs to further refine the models before physically testing them again. The two are interlinked, and going back and forth between the physical and digital refines the process further.

Geometric parameters control the overall shape, while toolpath-specific parameters contribute towards refining the surface appearance and finish of the formed parts (Kalo and Newsum 2014). The software package for modeling the input geometry will be McNeel Rhinoceros® 5.0, along with the plug-in Grasshopper,™ which houses most of the parametric definitions. A few custom Python scripts are used for specific post-forming tasks, such as parsing laser points and redrawing new toolpaths.

4.2 Fabrication Refinement of ISF

Once a workflow was mapped out, the next step was to refine a number of technical process aspects in order to realize the desired results. Achieving repeatability in terms of fabrication and producing predictable prototypes with exactitude was essential. The motivation is to explore whether this repeatability is not only reflected in the physical prototype but also matches the results of studies on these thin shell-structures. This means having the ability to quantify variability in sheets between multiple production runs, and to quantify the variation of outcomes under changes in sheet material and toolpathing.

Previously, early studies showed promise in terms of geometric complexity but were not developed further since the fabrication process was still being investigated as a reliable method. Since the basics are already established, this project's objective was to develop a complex set of geometries and geometric operations to demonstrate the efficiency of the fabrication system. Complex formed parts were also a means to challenge some technical hurdles and to showcase the level of detail that can be resolved.

Figure 9: Digital simulations of connection nodes.

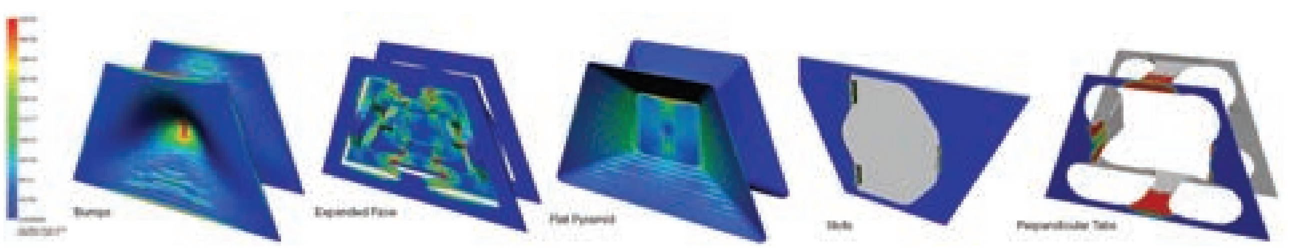

Figure 10: Examples of potential lighting features.

The advantage of using ISF as a fabrication method is its lack of reliance on dies or molds, which makes it more cost-effective for prototyping and provides a more readily customizable workflow. Conventional forming processes, such as hydraulic pressing or stamping, require costly positive and negative molds, which are also time-consuming to produce. While forming the same part in high-volume batches is efficient in terms of time and production, adding any variation to the stamped part requires redesigning the molds. Hence, with a parametric design process in place, employing ISF as a fabrication method allows quick and cost-effective prototyping of custom and highly-variegated designs.

To work with the issues that arise from ISF, additional toolpaths and geometric modifications must be tested. Running the same toolpath multiple times on the same part is a strategy that has been proven to increase forming accuracy and help to reduce the maximum deviations up to -0.5 mm (Meier et al. 2009). This increased the accuracy of the part everywhere except for the perimeter, because this region is drawn past the desired depth. Adding geometric "skirts" to the parts' edges stiffens the geometry and provides a deeper forming condition, hence reducing the overall deviation at the edge (Kreimeier et al. 2011).

Once the parts are formed, additional features can be added after the initial forming stage to stabilize the panels locally and globally. The heat generated from the process can reach up to 160 °F (fig. 5). This temperature rise softens the metal and makes it easier to form, but also works to harden the metal.

While precise articulation of the formed parts can be achieved by running the same toolpath multiple times, their accuracy could only be determined by a digital scanning method. Results will be validated using a handheld laser scanner, which is used to scan the material at various stages of fabrication, as well as to compare two closely varied prototypes. Initial studies done with a handheld laser scanner were used to capture the whole formed part. In later studies, a 1D laser point scanner was used to measure exact points on the formed surface and compare it with the digital model. The model or toolpath produced by the scanning process is then used for additional processes after the primary forming for the next prototype. The model is also measured at the edge of the designed part to verify and reconstruct a toolpath for cutting the material from the stock sheet (Kalo and Newsum 2014) (fig. 6).

4.3 Panel Types, Connection Resolution and Digital Simulation

Over the course of this project, a number of different unit designs were developed. The first iterations were very basic in their overall geometry and lacked any refinement in terms of connection detailing as well as lacking geometric stabilization after trimming. The second generation of panels introduced the notion of performative "ribs," which corrugated the panels for added stiffness. They also functioned as indexing features to align panels

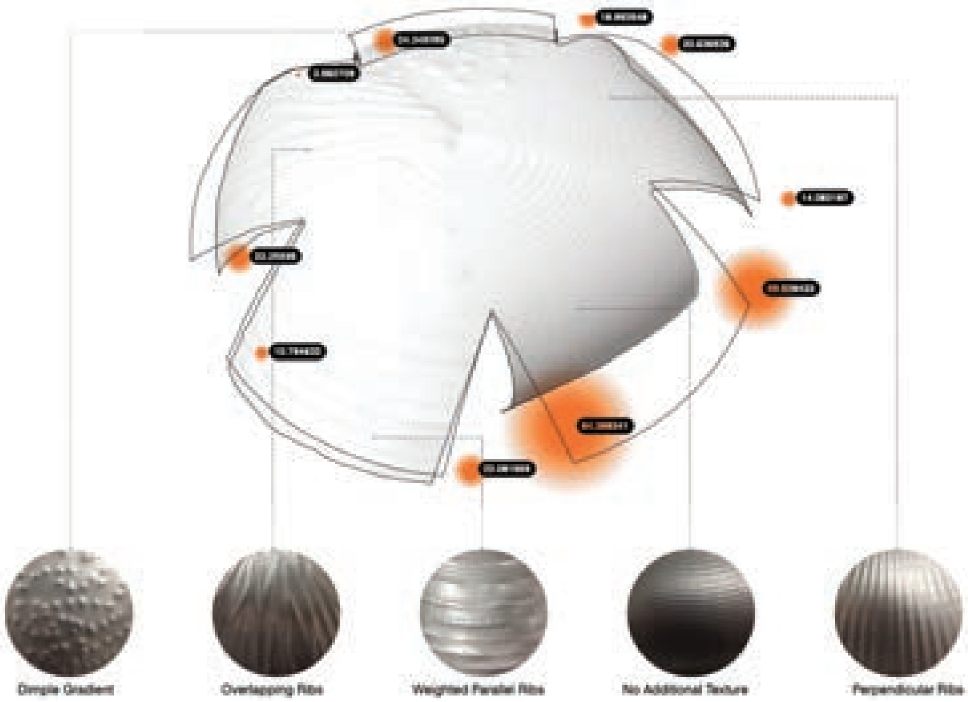

Figure 11: Performative textures studied for this research.

easily. The third and final generation of units feature more complex formed geometries, in addition to a precise placement of textures as field conditions. This array of units started integrating geometric and structural expressions for connection nodes on the panels. Features with undercuts were also introduced in this series, which can only be achieved with the extra axis of freedom that a robotic arm affords (fig. 7).

Achieving connections between the panels was an important aspect of the research, and multiple strategies were developed over the course of the project. Several of these connection designs were fabricated by forming a basic geometry first, and then introducing cuts or slots to refine the connection. Other designs involved using a 3-axis waterjet machine to cut patterns onto planar formed faces, which then connect to similar cut shapes, or in some cases, the negative shape. All of the explored connection nodes utilize mechanical fasteners; however, the intention was to ultimately express these connection moments through geometric means that tie back to the fabrication process (fig. 8). In addition, these studies focus on face-to-face connections—which are more complicated to program than side connections—to investigate ways in which both forming strategies and mechanical fasteners could work together more effectively. This was also done to contrast the first few iterations, which solely utilized spot welds and rivets, and eventually proved to be too cumbersome.

Aside from fabricating and physically testing the strength of connection in the studies mentioned earlier, a series of digital simulations confirmed the physical test results and added some insight into why certain components failed (fig. 9). In addition, another set of FEA simulations were done to study the differences and effects of varying surface curvature. Figure 8 shows simulations of three discrete panels with the same outline and support locations.

4.4 Design Features Development and Performative "Textures"

As the validation and cutting methods improved, it became more feasible to introduce openings and lighting features in the panels. Some of the opening designs explored (fig. 10) demonstrate that a flat surface isn't required to introduce openings. Three-dimensional changes in the geometry might begin to suggest, or even assist,

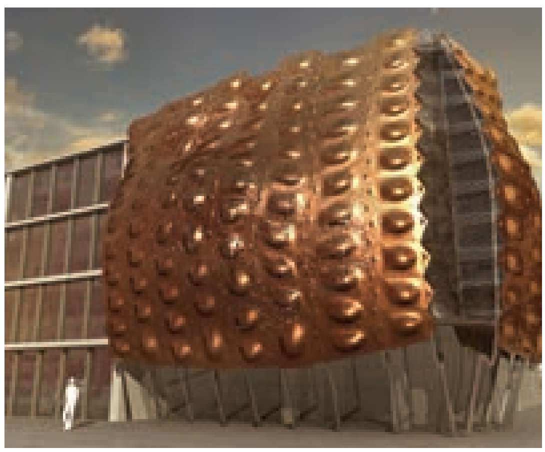

Figure 12: Echinus overlapping morphing arrays.

Figure 13: Physical mockups of Echinus panels.

in locating these lighting opportunities. In one instance, the surface depression allows for light to enter in a controlled way, with apertures that follow shadow lines at certain hours of the day. Light scoops can be easily formed and then cut in response to an environmental condition.

Bespoke ribs, bumps, and surface textures aren't formed solely on their aesthetic value, but are born out of the conflation of design, fabrication process, and structural stiffness. In addition, they deliver a performative relationship between the panels and the materials formed (Hensel and Menges 2009). A textured metal surface increases the cross-sectional depth and adds more rigidity and stiffness to sheet metal (Bruscia and Romano 2013). However, the aim is to avoid any kind of superficial patterning and allow for the expression of the performative aspects embedded in the panels. These patterns were a result of trying to find a design solution to minimize springback after trimming.

The second generation of these textures (fig. 11) were developed as field conditions instead of linear vectors that are perpendicular to the part edge. Fields of miniature surface "dimples" work surprisingly well to keep the geometry from deforming, with the part edge only springing back 5-10 mm. The hypothesis is that by inducing local double curvature over a larger surface area, the internal stresses in the panels spread in multiple directions instead of travelling along a certain vector as with the other patterns tested.

Most of these features will be used later as part overall aggregations and surface variation in the proposed designs.

5 PROTOTYPES AND APPLICATIONS

In conjunction with the various studies on connection types, unit designs, and digital simulations of those designs, two distinct skin systems were developed and prototyped. These systems aren't designed to be environmentally sealed envelopes, but rather permeable passive screens with embedded performative aspects.

5.1 *Echinus:* Overlapping Morphing Arrays

The first of these prototypes is an overlapping array of morphing cells (fig. 12).

Units of this proposal overlap like roof shingling and are supported by a framing system. Each of the panels connects to the structure via a mechanical connection using regular threaded rods and bolts (fig. 13).

Expression of the meeting point between the fasteners and the panel is done by forming a surface protrusion, referencing the "softness" of metal during the forming process. This "elastic skin" expression also serves to stiffen the local area where the connections are located. The difference in deflection between a flat surface and a double-curved panel with the same connection point locations is shown in Figure 14.

Echinus performs as a rain screen, with panels mounted on structural framing right outside a sealed wall condition. This allows for flexibility in terms of surface variation. Portions of the skin could be completely opaque, other areas could features small openings for indirect light, while some areas can be heavily perforated to allow light in front of a glazing component for example. Also, performative functions can be embedded in the

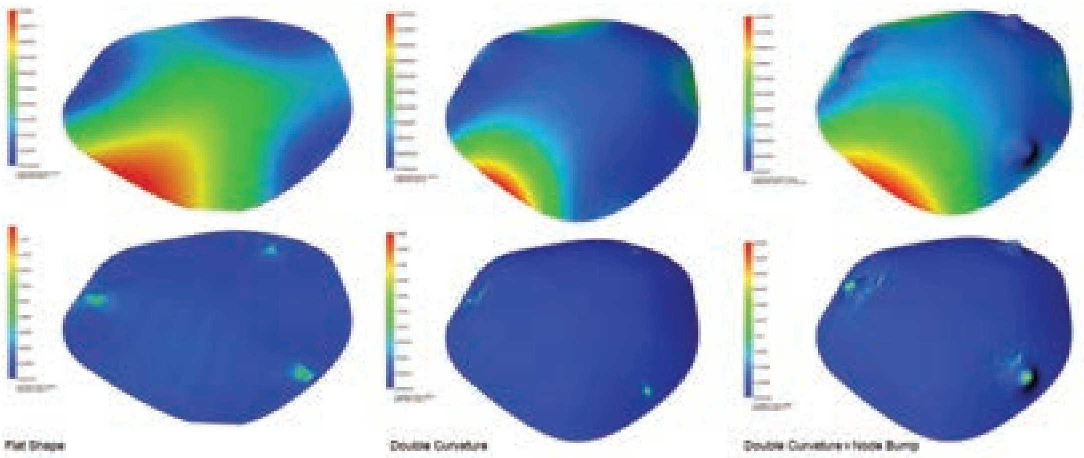

Figure 14: Loading simulations for three panels with the same connection locations and outline, but with different surface curvature.

panels, such as ribs, which can provide local stiffness but also act as water-guiding features that could assist in collecting water. Central bulges can be formed at asymmetrical angles to allow light in but not any of the water flowing on those surfaces. Panels change in scale in response to programmatic needs behind them, as do the lighting apertures.

5.2 *Spotty:* Cellular Snap-Fit Screen

In this proposal, the system is treated as a shading screen that could be used externally, but also in interiors as space dividers.

Unlike *Echinus, Spotty* intentionally avoids the overlap or contact between the panels (fig. 15). Each cell is positioned at an offset to a main hexagonal grid. The gaps allow for high tolerances and account for any forming inaccuracies.

As described earlier, emphasis on the ways in which formed panels are connected plays an important role in designing and forming the panel geometry. At the center of each panel, there are three bumps that indicate where panels meet the structural system beneath. A simple truss system is used as a structure for the panels (fig. 16). The lattice could be self-supported or mounted on another structural system. Although these bumps may look similar to the ones described in the previous system, they perform a much different role here. They're formed with undercuts, perpendicular to the surface they protrude from, to allow for the bent rod joint to connect to the panels from behind. The tight neck of three bent rods can snap fit into the bumps, providing a secure holding for the panel without any

Figure 15: Spotty cellular snap-fit screen.

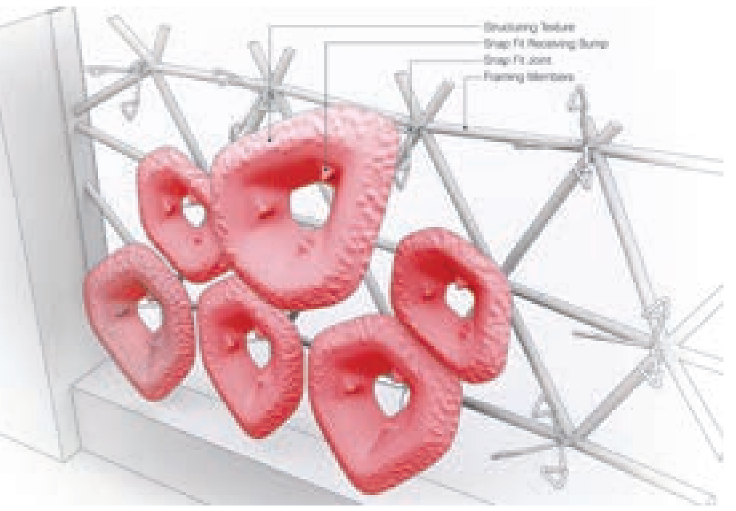

Figure 16: Spotty's main system elements.

Figure 17: Close-ups of Spotty's panel details.

additional fasteners (fig. 17). Removing and placing units onto the structural frame is done with ease and takes a fraction of the time it takes to secure a panel with bolts. The connection isn't designed to take any load besides its own, which is why this aggregation system is best suited as a shading screen or space divider. However, for external use, the panels could be secured with small U-bolts from the back side, where the snap fit joint meets the panel bump. At the rim of each panel, there is a ribbon of structural ornament, surface dimples that significantly help in stabilizing the edge as described in previous sections (fig. 18).

Units can grow or shrink in size to accommodate for programmatic requirements in a particular space. A parametric script was developed that not only produces the panels and their structure, but also alerts the user about certain geometric angles which cannot be fabricated. In the physical mockup, all the cells have planar perimeter edges; however, it's also possible to fabricate non-coplanar cells, as the parametric model would compensate for any extra forming depth required to achieve the desired edge shape over the input surface geometry.

The global scalar difference in the panels is first randomly generated, but then the script iterates through a few more rounds of edge scaling operations, which affect only hexagons with almost equal edge lengths. It also takes the local surface curvature of the input surface into consideration and rescales some of the panels accordingly.

6 CONCLUSION

Overall, most of the project objectives were met, and the process developed demonstrates how rapid fabrication and prototyping with ISF could be integrated within a seamless workflow. Reliable repeatability and geometric complexity were achieved in the process. Possessing the ability to quickly iterate design options and fabricate them just as fast is one of the great benefits of linking the design workflow to the fabrication needs and limits in a closed loop. The limitations, however, reside in the incapacity of the process to produce high-volume custom parts.

Other avenues of research could include an expanded study of other forms of aggregation, enhanced connections methods, and new forms of performative textures. Also, because the process itself is scalable, it would be beneficial in the future to produce larger components using larger forming frames.

As discussed earlier, the precedents show a desire by architects to achieve variability in building skins most efficiently. Showcased as a potential facade paneling fabrication method, ISF promises a significant advancement in this area of research.

This research wasn't intended to compete with conventional facade manufacturing techniques, nor does it aim to produce systems with low tolerances and industrial precision. Rather, the purpose of this investigation is to reexamine the ways in which "architectural" skins are designed and fabricated within an integrated workflow. The prototypes serve as an amalgamation of various fabrication and design studies demonstrating the capabilities and potential of using incremental sheet metal forming for producing highly customized architectural skins.

Figure 18: Physical mockups of Spotty panels.

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METHOD

Discrete Assemblage as Design and Fabrication Strategy

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CONTEXT: FROM ANALOGUE TO DISCRETE

Architectural experimentation with computational processes in the past two decades, the so called first digital age,[1] has proposed a "morphogenetic" [2] model based on ideas of continuity, growth and organism. Architects such as Greg Lynn, used concepts of Deleuze and D'Arcy Thompson to imagine an organic model for architecture. A digital blob growing, adapting and folding under influence of a field of abstract forces. This idea of architecture corresponded to new ideas of topology, found within 3D modelling software packages. This particular focus on topological continuity resulted in research which privileged surface over volume. However, the growth of this architectural "embryo" had no initial relation to a structure or tectonic system, due to the fact the field of forces it developed in had most often little to no relation to structural force or constructive constraints. Initially, the only tectonic systems that could be relied on were grid based "waffle-cut" or "egg crate" systems. These rectangular grids were usually constructed out of CNC-milled timber or metal sheets to recreate the desired form. Architects were forced to post-rationalize their complex surfaces into discrete, mass-customized elements, which had to be numbered and micro-managed in a labor intensive process of assembly. Most of these projects suffered from intrinsic structural problems, and in effect ended up being a mere panelization held up by a standardized, Cartesian structure. This practice quickly became popular and after a mere two decades is seen in many contemporary buildings today. For example, the *Soho Galaxy,* by Zaha Hadid Architects, follows exactly this approach. Its form is an initially continuous shape that is sliced into horizontal floor plates, then held up by a grid of columns, stiffened with cores. This grid is then wrapped with a metal frame and panelized to achieve a fluid, continuous effect.

Recent research in generative design by offices such as Kokkugia, Biothing and EZCT, have focused on a more bottom-up approach, where the final form is less predetermined and emerges from the interaction of lower level elements. As Mario Carpo describes in his article "Breaking the Curve":

> *The inherent discreteness of nature [...] is then engaged as such, ideally, or in practice as close to its material structure as needed, with all of the apparent randomness and irregularity that will inevitably appear at each scale of resolution.*[3]

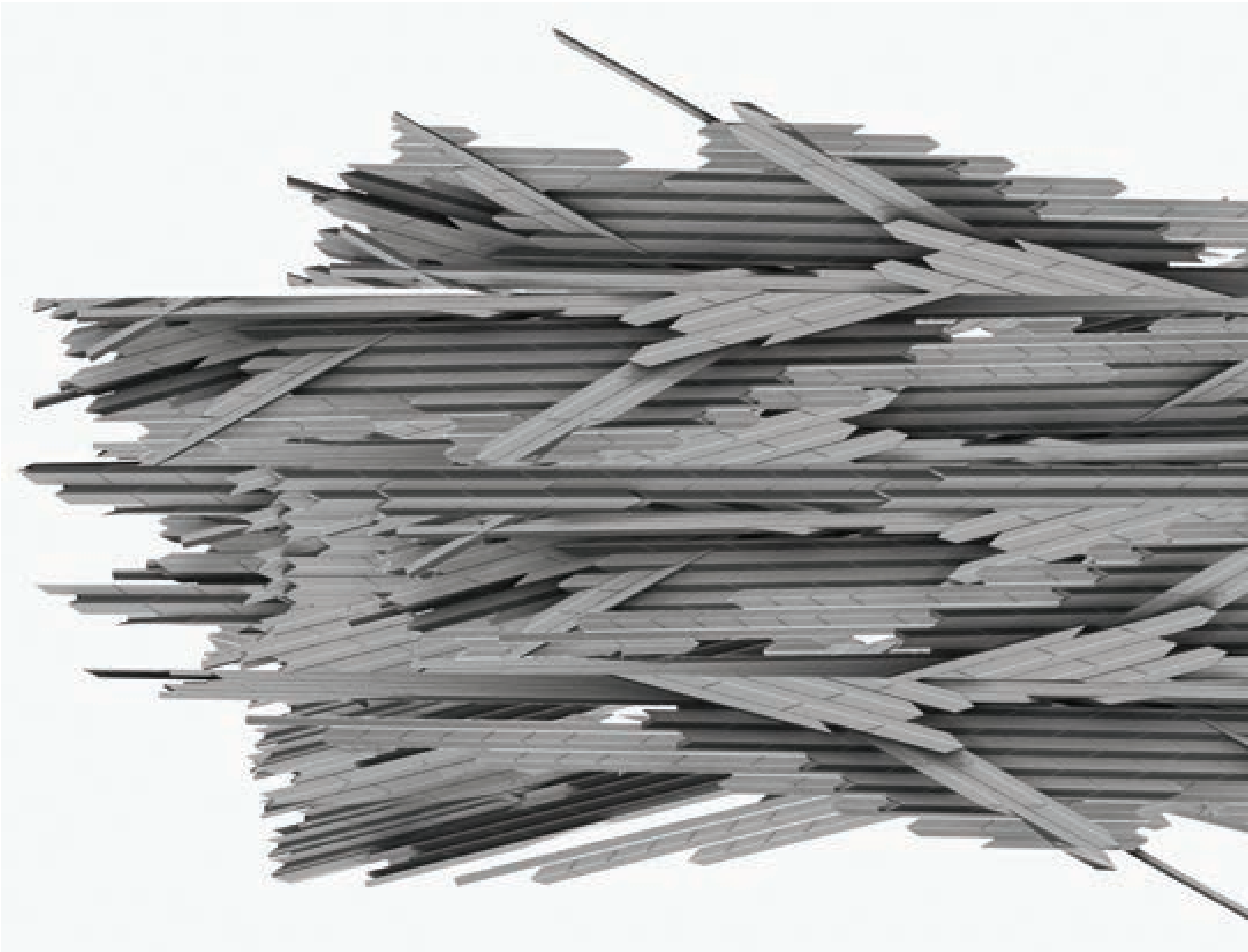


Figure 1: Blokhut drawing.

However, just as in the first digital age, this second digital age of "big data" is in intrinsic trouble with tectonics and materialization. To materialize the second digital age's explorations, old techniques are required: CNC milling molds, 3D printing, and mass-customization of building components. Just as the continuous-organic approach, the generative paradigm has an inherent limited economy of means. It requires complicated, time-intensive manufacturing and micro-managing of thousands of elements during assemblage, and it often ignores structural and constructive parameters. Although the work takes into account large amounts of data, it is still developing algorithms which require continuous fabrication. Most of the algorithms underlying the "big data" work, such as recursive subdivision, fractal growth, cell-division, agents or reaction-diffusion are driven by observations into natural systems, effectively found-objects, which are then appropriated to become architectural. The algorithms used often don't take into account any constraints relating to materialization, structure or constructability. This results in a big gap between design and fabrication. To solve this gap, increasingly complicated and expensive processes are required, such as extreme computing power, robotic vision, expensive sensors, and extensive human labor. This tools are used as problem-solvers to patch up the gaps between design and fabrication, rather than as powerful computing devices which could streamline a fabrication process.

Digitally intelligent architecture will always remain in trouble with tectonics if it does not align its algorithmic logic with the logic of materiel organization or fabrication. So what does it actually mean for buildings or material organizations to be discrete and digital? Can material be organized in the same way as data?

Current rapid-prototyping machines are fundamentally continuous or analog processes. Although many fabrication machines are digitally controlled, these machines continuously cut or add material to make parts. Can machines additively assemble multiple materials to make functional structures rather than simply cutting or extruding material into representational objects? [4] *(Ward, 2010).*

In other words, analog fabrication is based on continuously aggregating material with an infinite connection scheme. Whereas digital or discrete fabrication is based on assembling parts, which the geometry provides metrics and constraints, limiting the connection scheme to a precise digit: yes or no.[5] 3D printing, just as CNC milling, is fundamentally a continuous fabrication process, which may leave us with an interesting form at the end, but fundamentally produces objects which are completely analog. A 3D printed vase, which may have been generated with a complex algorithm, is still going to be analogue once printed. Whether you 3D print a Mickey Mouse, a Corinthian column or a digitally generated sculpture, there is no difference in the final product beyond the form. The organization of material is in all cases the same: it is a continuous extrusion of material, sintered or stuck together with a binder, and it has no relation to the underlying computational process. This is different with discrete fabrication. The part computed digitally is also the part assembled physically. The organization of physical parts is the same as the organization of the digital data.

When fundamentally addressing this issue of discrete or digital fabrication versus analog fabrication, the concept of assemblage and prefabrication comes back into play. For example, Skylar Tibbits researches how discrete elements can self-assemble into an object, which can continuously disassemble, aggregate and change. Jose Sanchez argues for differentiation to emerge from the interplay of resources and social innovation rather than a centralized idea of growing form and differentiation by an omnipresent designer (Sanchez, 2014).[6]

Further back in time, there are several precedents of discrete architecture. Consisting of a limited number of serially repeated timber joints, the traditional Chinese Dou Gong bracketing system can also be understood as a digital material. It is able to produce heterogeneous structures with a multiplicity of scales. In the twentieth century, Frank Lloyd Wright's experiments with the textile blocks engaged with the idea of discreteness. Also, late-modernist structuralism by architects such as Hertzberger, Van Eyck, and Tanghe explored rule-based designs to systematically relate discrete spatial components and programs.

The design method described in this paper is based on the assembly of cheap, standardized, discrete elements into indeterminate, heterogeneous, and differentiated spaces with a high degree of economy. The focus is on a minimum degree of customization for a maximum of differentiation, detail, adaptability and economy. Instead of continuous computational processes which require heavy computational power, these processes are light and can be run in a browser. They don't require expensive equipment and super-specialized knowledge, which remain the monopoly of big institutions or companies. The tools to compute and fabricate are accessible to everyone. They can be run in a browser or from simple applets. Instead of technologically complicated and expensive continuous fabrication, discrete manufacturing is fast, cheap and accessible.

DISCRETE DESIGN

Blokhut: Dutch for Log Cabin. A hut built of whole or split logs.[7]
As a case study of aligning discrete computation and fabrication, the "Blokhut" (2014) was developed. Initially a study for a villa in a Belgian suburb, the design became prototypical for the new approach towards computational

Figure 2: Blokhut atrium study.

design discussed before. The prototype started out with a given: due to a limited budget, a large part of the structure would have to be standardized and made out of cheap elements. The large model of 2x1.5x0.3 m, weights over 150 kg and is built using 4000+ pre-cast plaster components, intersecting and joining around a limited number of customized 3D printed zones. The plaster component is designed as an arrow-shaped brick, with a male and female connection. The arrow-like connection is able to interlock two bricks together in a fixed position. This discrete arrow-shaped building element can be understood as a digital material. *The design possibility, or the way how elements can combine and aggregate is defined by the geometry of the element itself — which leads to a "tool-less" assembly (Cheung 2012).* The Blokhut prototype establishes a differentiated and adaptive architectural system which consists for 90% of serially repeated, discrete, prefabricated concrete elements, and for 10% of unique, customized 3D-printed pieces. The argument shifts from a system where everything is mass customized, with a labor intensive assembly process, to a limited number of super intensive, rule-changing customized zones or glitches and a large number of serially repeated, cheap material. The finished state of the model is undetermined. It can be extended or contracted at any time. The final geometry is messy, redundant and un-simplified. The Blokhut prototype can be constructed without the need for micro-managing thousands of unique, numbered pieces. Instead, the 3D printed components and bricks set out the instructions for assembly. The assembly is "plan-less" and "tool-less", as the geometry of the pieces defines the aggregation.

The material organization does not respect topological continuity. Different strata of elements are self-intersecting, and building elements not only aggregate linearly into surfaces, but can also aggregate three dimensionally into thicker volumes. The organization of building components follows different intensities and patterns in different parts of the structure. For example, towards the ends of the cantilevers only one layer of tiles exists, whereas in the middle parts and towards the central area, double and triple layers are used to deal with higher levels of stress.

The Blokhut prototype proves that serial repetition of very simple, cheap, prefabricated digital materials is a feasible and accessible method to achieve detailed and adaptable forms. However, the system could have been further optimized if it would introduce an economy of scale. The construction system has no hierarchy of scale in the building elements, there is only one size. A good reference would be a process like Octree optimization, a procedure used in 3D graphics where a space is partitioned with different scales of voxels depended on the resolution required. Translating this to an economic concept; it would make more sense to work with a range of scales in elements. Assembly time could be radically reduced if the core of a model would be made with a few large-scale elements, instead of a few thousand pieces. This economy of scale is an important advantage over classic 3D printing methods, which are not scalable. Moving on from the rather simple and constrained arrow-shaped digital materials used in the Blokhut prototype, elements could be imagined which don't only construct a whole, but are more clearly at the same time part and whole. For example, a digital material which acts

Figure 3: Blokhut column study.

at the same time as brick, surface, column and beam would improve structural performance, and establish a more radical diffusion between different hierarchies in the model. Increased capabilities for parts to interlock and support neighboring parts can be developed, introducing patterns of structure in the system. After the initial prototype for the Blokhut, several more test cases were developed. For a museum competition at the Karlsplatz in Vienna, the bricks construct a series of horizontal strata which develop into large column-like elements. Another abstract atrium-like model was developed which shows how an entirely different spatial structure can be achieved with the same method. The same elements were also used as a base unit for a masterplan in Shenyang, China, which is introducing entire buildings as autonomous discrete units within a master plan.

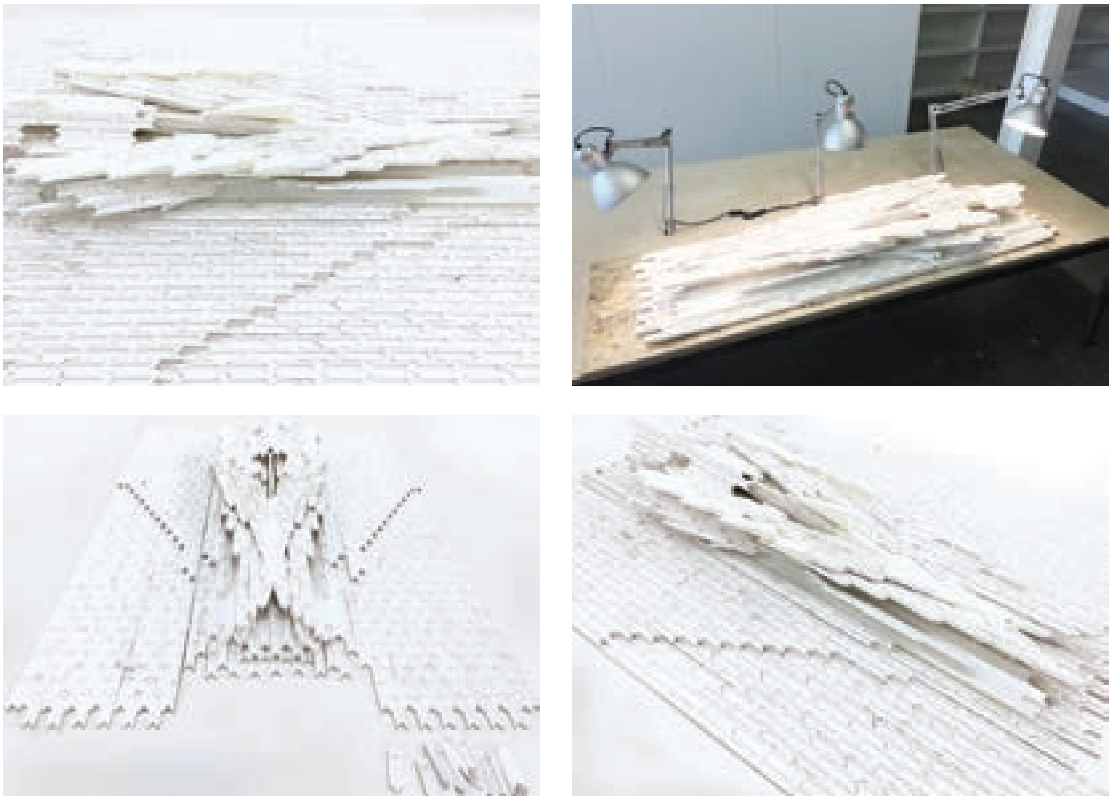
DISCRETE FABRICATION

There has been a lot of speculation in the building industry about 3D printed buildings—including by myself and the SoftKill Collective, when we proposed the Proto-House in 2012, one of the first designs for a fully 3D printed building. The main interest from industry and government lies in the promise of speed and simplified workflow, rather than the formal or aesthetic properties. A 3D printed dwelling, however, will always be constructed slower than a robotically assembled, prefabricated dwelling which makes use of larger components, parts or particles. The potential of rapid assembly and prefabrication in the digital age is illustrated by the Broad Groups project for a 57-story skyscraper. This was assembled in just 19 days in Changsha, China, due to their advanced control over the workflow.[8]

As a continuous method, 3D printing fundamentally suffers from scalability, structural problems such as cantilevers, and more importantly, it has a big problem with multi-materiality.[9] For example, a process which can print at the same time glass and concrete, is hard to imagine, as both materials require different printing techniques. This means that even if a building would be printed out of concrete, one would still have to rely to ideas of assemblage to incorporate insulation, transparency, finishes, etc. On the other hand, it is easy to imagine a prefabricated brick consisting of multiple layers of materials, such as a structural layer, a layer of insulation, waterproofing, finishing and so on. An assembly based process has the potential to differentiate the materiality of parts and particles, introducing transparency, electrical conductivity, channels for air or water flow, all on different recursive scales.

Robotic arms are used in the industry for a number of discrete, repetitive operations. For example, in the car industry, robots spot weld a number of edges, or lift a heavy object from one belt to the other. In architecture, it was Gramazio Kohler who initially explored the first use of robots as serial assemblers, through stacking bricks in the *Programmed Wall* (2006).[10] The *Programmed Wall* is however controversial as the brick as an element is specifically optimized for handling with a human hand. The robot is not used to its full potential as it could easily lift 10 times the weight of the brick, while maintaining the same precision. Gramazio Kohler's assembly process can be understood as a continuous process, as the bricks placed have no fixed geometric position. Pure robotic assemblage

Figure 4: Blokhut chunks.



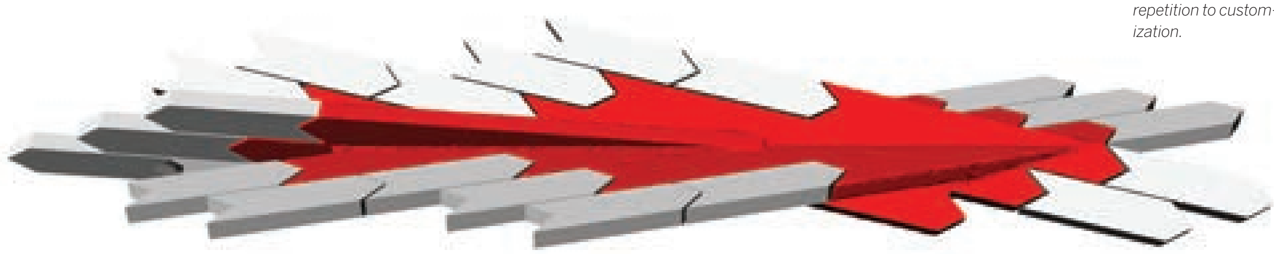
processes prove to be very difficult, and have probably been pushed furthest projects such as Gramazio Kohler's *Complex Timber Structures* (2012).[11] The main constraints in robotic assembly are so called singularities. These are made up of intersections with material which have been previously deposited, or with the robot itself. A project such as *Complex Timber Structures* has to be carefully planned over a period of several weeks in order to be assembled, as every assembly sequence is different. Complex assembly processes require increasingly advanced technologies to function, such as real-time sensors and robotic vision.

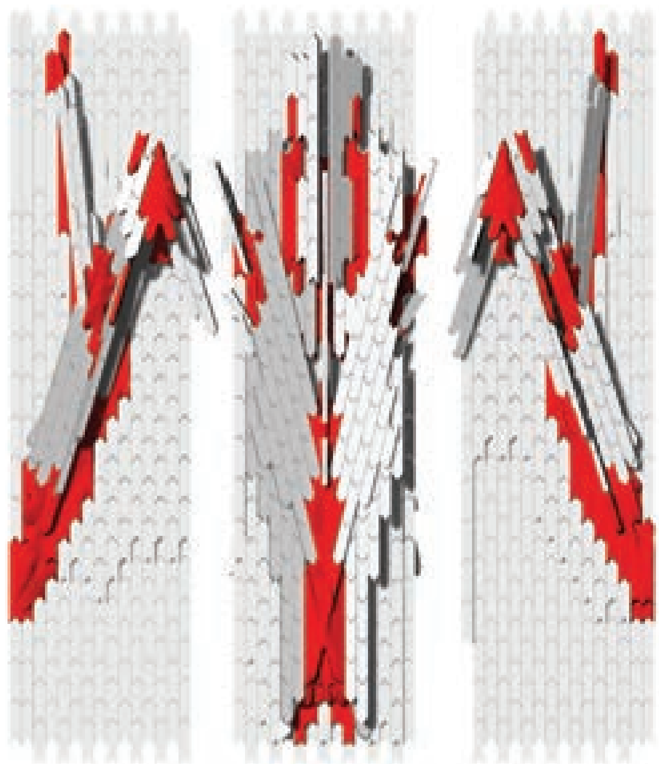
Robotic assembly is only feasible in the context of digital materials and discrete computation, which has a limited set of connectivity problems and as such requires little troubleshooting or problem solving. The components and high degree of serial repetition in the Blokhut makes a robotic assembly process more feasible. The parts are organized in a grid or voxel-like pattern, the connection between elements is repetitive, and the connection problems themselves are always discrete, neighbor-neighbor or part-part problems. The discrete element can be understood as a brick on the scale of a machine rather than a human. With a length of 1.8 m and a weight of 150 kg, it would be not feasible to manually assemble the parts, but an industrial robot would do what it is best at: high precision combined with high payload. Using one or more robots, the Blokhut prototype could be assembled, adapted and disassembled quickly. The proposed methods do not necessarily have to rely on the use of expensive industrial robots. Other types of robots or machines could be used, such as cable robots, or parallel "termite bots,"—small robots which can carry a digital material, and use the already deposited digital material as a geometric guide.[12]

STRANGE MEREOLOGY

What are the implications of a fundamentally discretizing architecture? In the Blokhut project, the basic unit operates at an intermediate scale between brick and spatial module. This intermediate scale effectively increases the resolution of the tectonic articulation, while diffusing and fragmenting fixed architectural types such as columns, slabs, and stairs. In a similar connection to voxelization, the Blokhut introduces a simple piece of architectural matter that is able to diffuse vastly different geometries and different architectural typologies—even those who were previously taboo for the digital age such as the Miesian slab. This shifts the discussion from topological form and spatial definition to purely a discussion about part-to-whole and part-to-part relations. The discussion about the spatial articulation, the actual "whole" constructed out of the parts, becomes in itself secondary to the question of the politics of the part. This allows harvesting from different spatial types which have been developed over time: Miesian slabs, Adolf Loos's Raumplan, Eisenmann's grids, or Gehry's paper bags all become accessible and lose their ideology.

Figure 5: Organizational diagram showing the transition of serial repetition to customization.





This is one of the underlying reasons why the Blokhut project and subsequent experiments articulate themselves as "modernist" slabs. It is a provocation to argue for the importance of the tectonic material organization, the politics of the parts, rather than the spatial manifestation. This is a provocation for the more holistic and morphogenetic approach advocated by the generative designers, which would like to see "true" spatial form emerging from the interaction between the parts. However, it has to be pointed out that a recursive range of scales could be developed in the parts; with the largest scale becoming for example a spatial unit.

To better understand the relationship between part and whole in the particular case of the Blokhut, we can turn to the concept of Strange Mereology developed by Levi Bryant. Wherein mereology is the philosophy of part-to-whole relationships, pioneered by Lesniewski,[13] Bryant develops strange mereology as a situation where *parts aren't parts for the whole, and the whole isn't a whole for the parts*.[14] There is a complex set of part-part relations, and part-whole recursion. In the morphogenetic first digital age, parts are domesticized by the whole and derived from the whole. In the generative or second digital age, the emphasis is often reversed; there are only part-part relations, and the part-whole relation is one of emergence. The whole is not predefined, and expected to arise out of the interaction of lower level parts. The final whole is established at the moment that the designers' criteria, whatever they are, are satisfied. The strange mereology approach aims to overcome both problems: parts are not a product of the whole, and at the same time the whole can't be reduced to the logic in the parts. The Blokhut achieves this partly through the customized glitches, which allows the system to gain form from a maneuver which lies outside of the design agency of the tiles. The introduction of columns as new, independent, autonomous architectural objects is also complicit in establishing "strange" part-to-whole relationship. The columns develop autonomously from the bricks. This introduces an agency in the mereological system which enhances the aggregation logic of the bricks, allowing them to cantilever and proliferate horizontally. At the same time, they reduce their agency and impact the overall whole. The columns effectively establish a sort of ecology of interdependencies within the mereology of the model. Although there is no formal coherence between the column and the bricks, their position allows the bricks to bypass extreme deflection and tension forces appearing at the ends of the large cantilevers. Within the morphogenetic first digital age, the addition of the columns would be considered a taboo. And the argument would be made that the basic elements should take the extreme cantilever into account. However, I would like to argue here that the use of the columns introduces a higher degree of differentiation and heterogeneity in the system, which would otherwise only consist of a single logic, or a single object. The model cannot be reduced to a singular, homogenous logic or

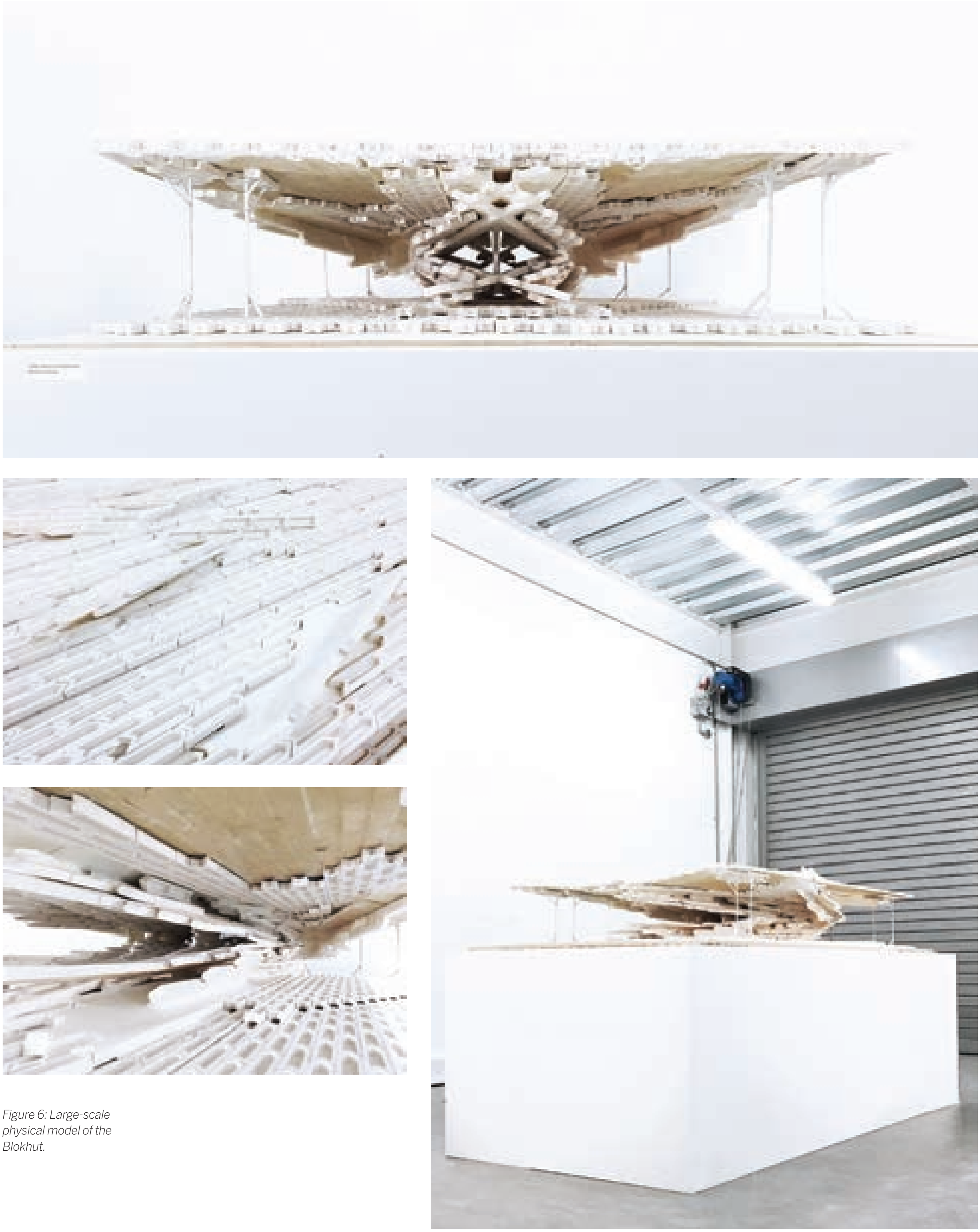


Figure 6: Large-scale physical model of the Blokhut.

whole, but introduces a far less predictable and more agile system with more formal possibilities. For example, the large cantilever and visually uninterrupted facades would have been obstructed if the morphogenetic logic was followed. The strata of aggregated tiles effectively depends on the exact positioning of the columns to be possible. An ecology of interacting, mutually interdependent architectural objects is created, resisting a singular, wholifiying ideology and emphasizing discrete systems which are morphologically autonomous from each other, but functionally related and computed.

LOW-ENTROPY HETEROGENEITY

The gap between simulation and fabrication emerged as a problem coming from the morphogenetic research's failure to align design and fabrication methods. The first digital age designed continuous, fluid forms, which had to be discretized into thousands of analogue bits of material. The morphogenetic-generative work which followed afterwards introduced a more complex and discrete part-to-whole relationship, based on the idea of emergence. However, they relied on the same analogue, continuous fabrication techniques like CNC milling and 3D printing. This focus on continuous fabrication methods deepened the gap between design and materialization. To bridge between simulation and reality, increasingly expensive and complicated technologies are needed. Caught up in a spiral of problem solving with expensive equipment, the second digital age also became inaccessible for many. The part-to-whole relationship or materiel organization of the objects produced, however, is still analogue. In order to make digital objects, to effectively bridge the gap between computation and fabrication, a shift is required towards fundamental discreteness. By aligning discrete computation and discrete fabrication, a new kind of fundamentally digital architecture, which has a complex or "strange" mereology, is uncovered. Through serial repetition of cheap, digital materials, a detailed, adaptive, and complex architecture becomes feasible and accessible.

ENDNOTES

1. Mario Carpo, "Breaking the Curve: Big Data and Design," in *ArtForum*, February 2014.

2. Branco Kolarevic, "Digital Morphogenesis and Computational Architectures," in *Proceedings of the 4th Conference of Congreso Iberoamericano de Grafica Digital, SIGRADI 2000 - Construindo (n)o Espaço Digital (Constructing the Digital Space),* Rio de Janeiro, Brazil, September 25–28, 2000, eds. José Ripper Kós, Andréa Pessoa Borde, and Diana Rodriguez Barros, 98–103.

3. Carpo, "Breaking the Curve."

4. J. Ward, "Additive Manufacturing of Digital Materials" (PhD thesis, Massachusetts Institute of Technology, 2010).

5. Kenneth Cheung and Neil Gerschenfeld, *The geometry of the parts being assembled provides the dimensional constraints required to precisely achieve complex forms (Cheung).*

6. J. Sanchez, "Post Capitalist Design: Design in the Age of Access," in *Paradigms in Computing,* eds. David Jason Gerber and Mariana Ibanez (New York: eVolo, 2014).

7. Oxford Dictionaries, accessed October 22, 2015, http://www.oxforddictionaries.com/definition/english/log-cabin.

8. http://www.telegraph.co.uk/news/picturegalleries/worldnews/11485389/Chinese-company-builds-57-storey-skyscraper-in-19-days-in-pictures.html.

9. The Objet printer gradually differentiates stiffness and color within one material.

10. Fabio Gramazio, Matthias Kohler, and Jan Willmann, *The Robotic Touch* (Zurich: Park Books, 2014), 44.

11. Gramazio, Kohler, and Willmann, *Robotic Touch,* 384.

12. Neil Gerschenfeld and Kenneth Cheung (Cheung 2012), as well as Justin Werfel of the Wyss institute at Harvard University (Werfel 2014), propose these types of robots as Voxel Assemblers.

13. Mereology (from the Greek μ, "part") is the theory of parthood relations: of the relations of part to whole and the relations of part to part within a whole. The term was coined in 1927 by Polish philosopher Leniewski. In "Notes to Mereology," accessed October 22, 2015, http://plato.stanford.edu/entries/mereology/notes.html#1.

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Figure 7: Blokhut renderings.

Gramazio, Fabio, Matthias Kohler, and Jan Willmann. 2014. *The Robotic Touch*. Zurich: Park Books.

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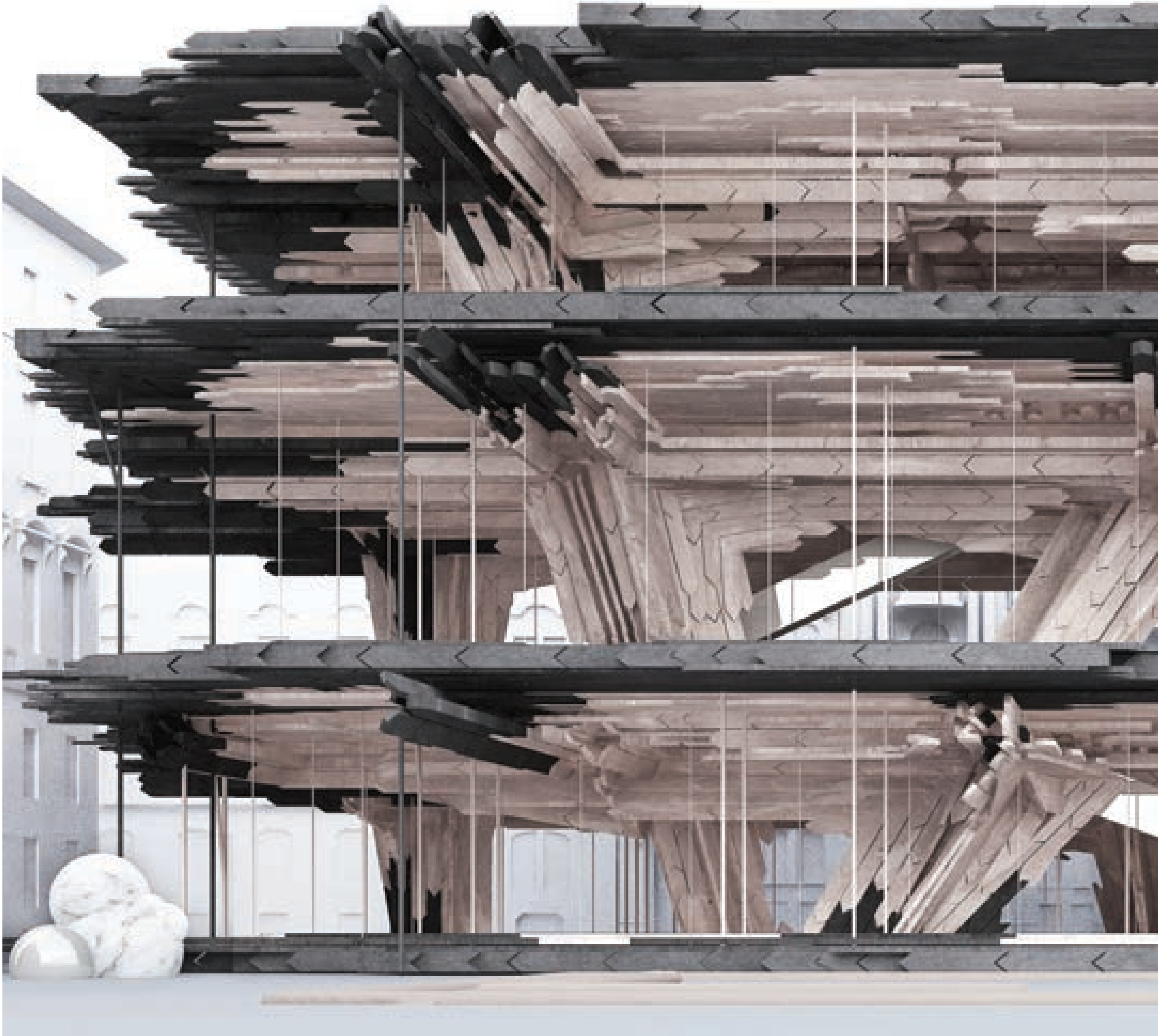


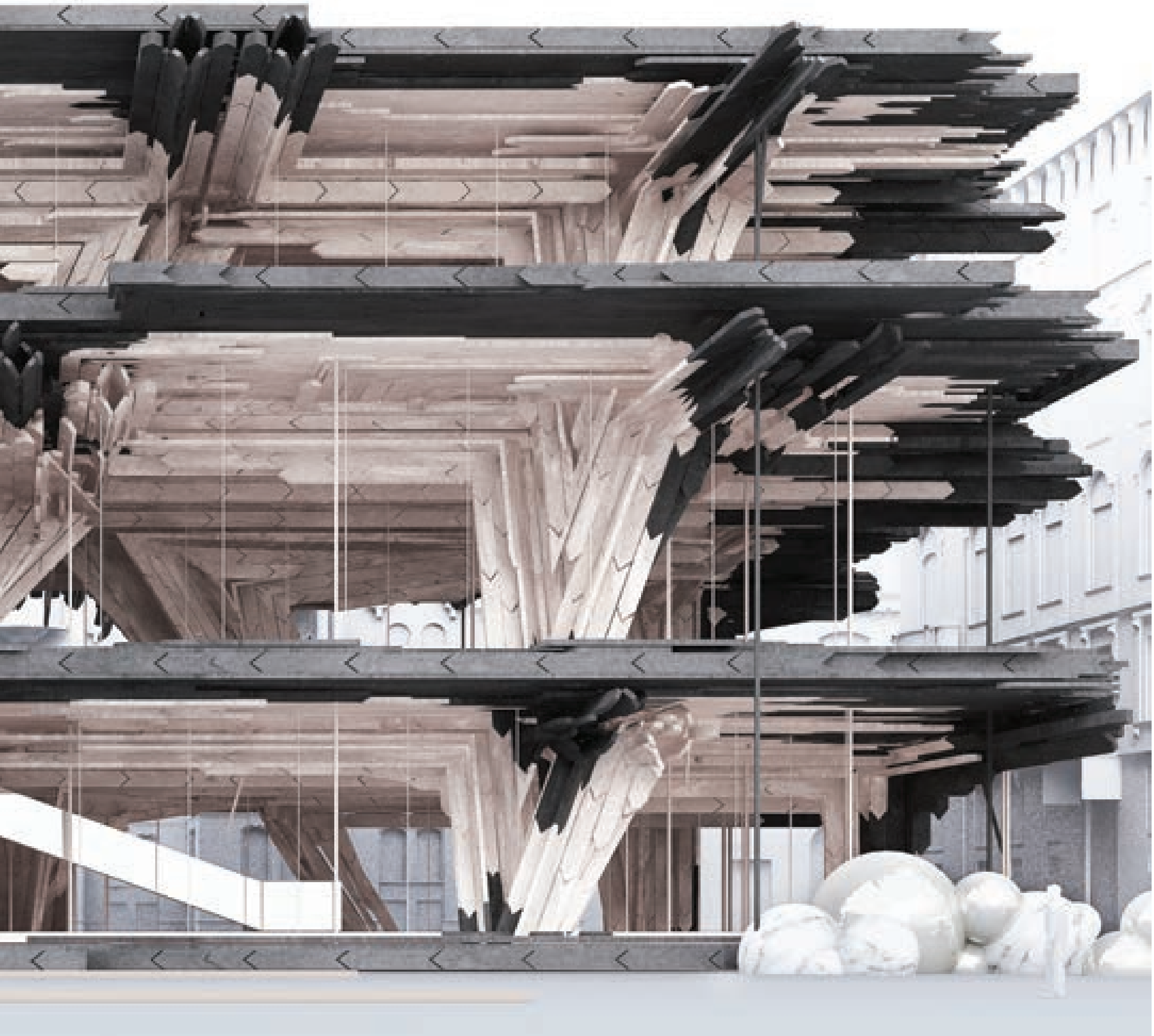
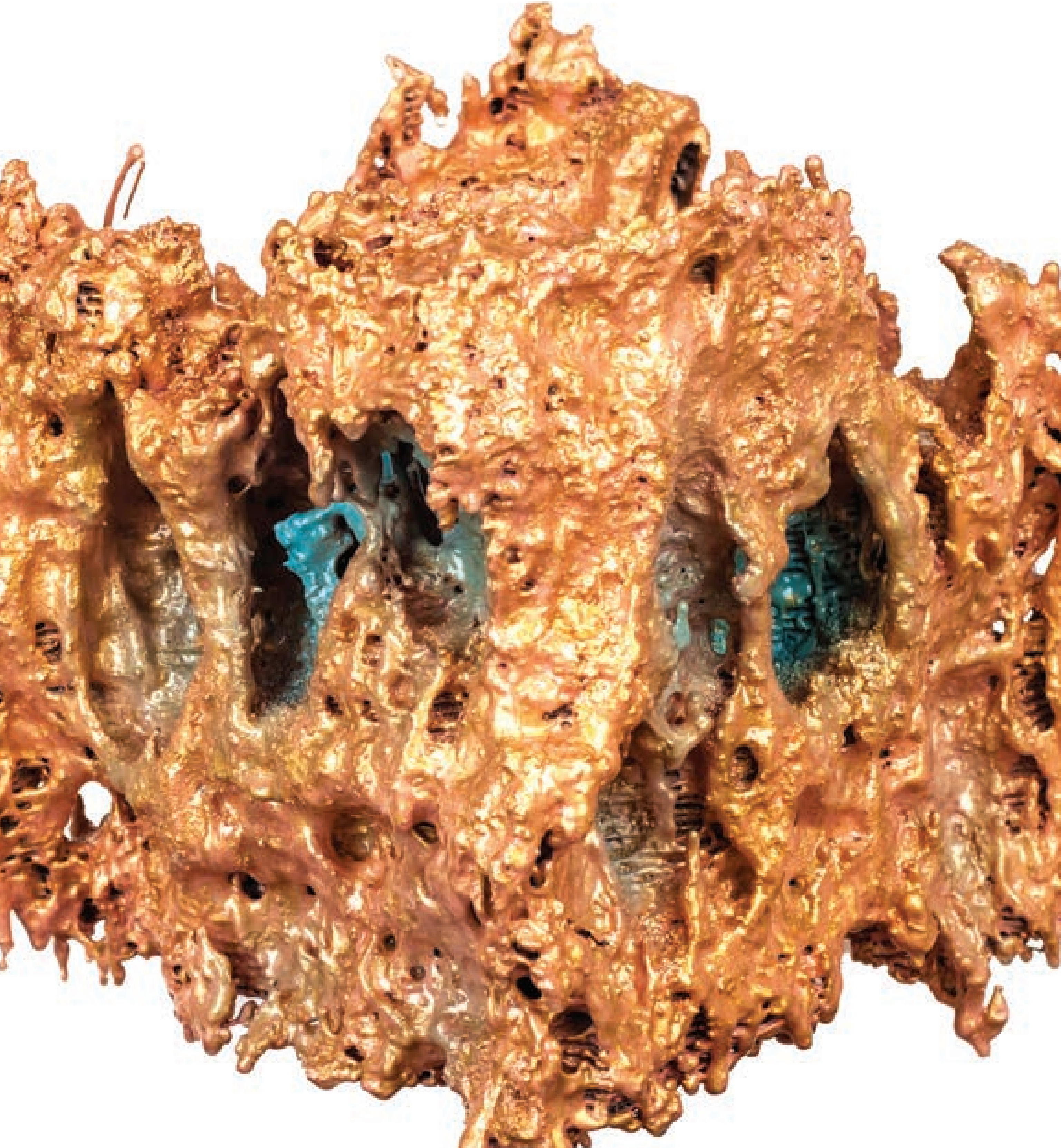


Figure 8: The elements from the Blokhut applied in the design for a museum at the Karlsplatz in Vienna.



Texture Extended: Contemporary Techniques of Architectural Surfacing

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INTRODUCTION

Historically, architectural texture has been identified through properties of materials—the rustication of brick, the patina of copper, or the grain of wood. With the introduction of CNC fabrication into architecture, texture became artificial, a product of machining rather than a quality inherent to materials.[1] This turn to the synthetic has inspired architects to loosen their metaphysical appreciation of materials (the impulse that led Louis Kahn to ask a brick what it wanted to be, for example). Within today's expanded technological milieu designers are devising strange mixtures of digital modeling, material misuse, and inexact fabrication in a bid to radically expand architecture's visual and textural palette and challenge established narratives of the digital and the natural. This paper presents work from two contemporary practices leading these trends, organizing their work into three categories: *textural grafting, textural massing, and excessive finishing*.

ORNAMENT IN DIGITAL FABRICATION

Greg Lynn first theorized synthetic surface articulation in architecture, connecting the artifacts of CNC machine tooling to disciplinary conceptions of ornament.[2] Historically, ornament had been defined in contradistinction to structure, the latter seen as essential to a building and the former as an excessive form of decoration that served a representational role. Lynn saw in CNC fabrication a collapsing of these two categories, as the process of making (or structuring) objects was the same process that left decorative marks. Thus, Lynn circumvented the representational role of ornament by identifying it as integral to the process of making. At the time of these claims, Lynn was part of an influential group of young architects that was attempting to surpass the fraught disciplinary positions of architectural postmodernists while simultaneously theorizing the digital technology entering the field. This group identified with French philosopher Gilles Deleuze, who saw the world in terms of flows and process rather than disjunction and representation.

Lynn's characterization of ornament as non-representational spurred further discourse. In their book, *The Function of Ornament*, Farshid Moussavi and Michael Kubo systematically develop a non-representational account of ornament by creating a taxonomy of building

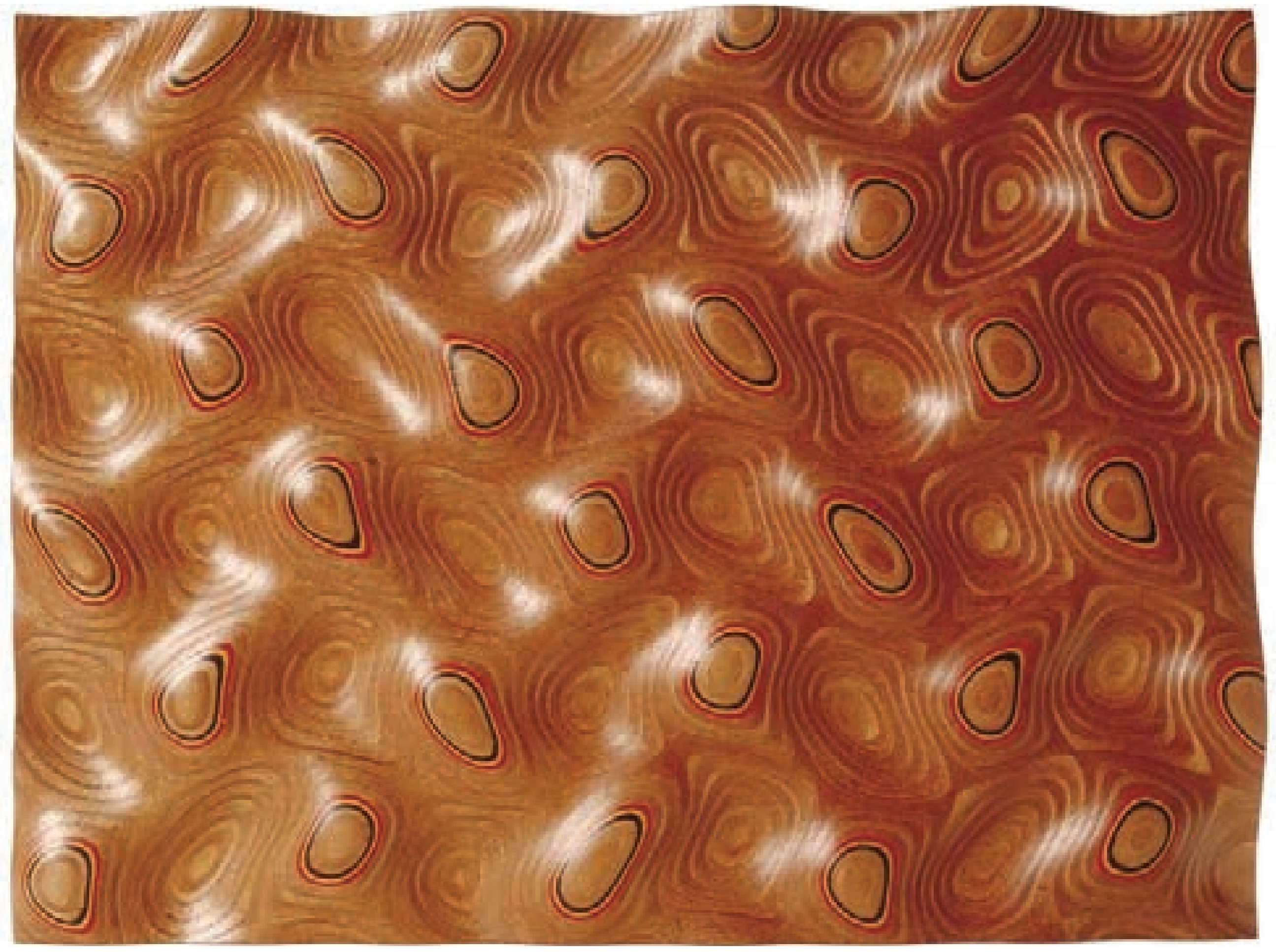


Figure 1: Bernard Cache/Objectile, wooden panel machined by CNC, 1998. - photo courtesy Objectile

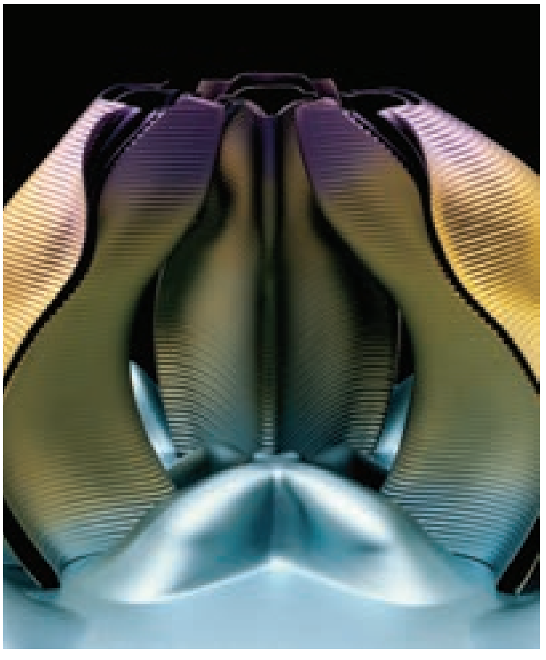


Figure 2: Greg Lynn, Alessi Tea and Coffee Towers, 2003. - photo by Carlo Lavatori, courtesy Greg Lynn

skins.[3] Surveying a wide range of buildings, Moussavi and Kubo apply a two-part categorical system that addresses "material," or the main component of a building that produces ornament, and "affect," which names the dominant quality of the resultant building. Others have refuted this non-representational account of ornament. In his article, "Contemporary Ornament: The Return of the Symbolic Repressed," Robert Levit questions the relevance of ornament as a concept if it is addressing qualities of a building that are devoid of representation, symbolism, or meaning.[4] Levit points out that ornament emerged as a concept in architecture explicitly to speak to the symbolic dimension of form and thus, "can never be reduced to a question of function" or an artifact of construction or craftsmanship.[5] According to his argument, whether architects acknowledge it or not, form is interpreted symbolically and ornament is a primary device of its expression.

In this paper, we will focus on two aspects of this discourse on architectural ornament: one, Lynn's contention that ornament is no longer applied but integral to the fabrication process; and two, Levit's assertion that ornament will always express something other than its material existence—a dimension that people understand symbolically.[6]

TEXTURE VERSUS ORNAMENT

This debate on the nature and purpose of architectural ornament benefits from further parsing the terms in use. If, following Levit, we conclude that ornament cannot exist without symbolic meaning, then surface articulation that is non-representational can be defined simply as texture. Thus, in addition to the inherent qualities of materials—like wood grain or patina—texture can refer to an artifact of construction or fabrication that has lost its representational significance, either because it is ubiquitous or has become cliché. An example of the former would be undulating wall panels carved by CNC routers, such as those by Bernard Cache, which were novel in the 1990s but are now common features of our built environment and are no longer remarkable (fig. 1).[7] Similarly, when Lynn was expressing machined toolpaths on his Alessi Tea and Coffee Towers in the early 2000s it was an entirely new form of surface decoration, but has since become cliché (fig. 2). This new definition of texture—as the artifacts of fabrication that no longer hold representational significance— would encompass what Moussavi and Kubo are referring to as ornament and thus apply to the physical patterning of facades that are the mere result of construction processes.

With texture now referring to non-representational forms of surface articulation, ornament can be reserved for physical qualities that express meaning. Ornament is not a coincidence of construction or fabrication; it is an intentional act of design that seeks to communicate beyond affective experience. Ornament is authored by a designer and intended for an audience—what Antoine Picon calls the "subjectivity" of ornament.[8] In his book *Ornament: The Politics of Architecture and Subjectivity,* Picon identifies three ambitions to ornament: "pleasure and beauty, rank and prestige, communication and knowledge." In his opinion contemporary architecture has only engaged the first of these ambitions, largely through a focus on the pleasures of affective experience, demonstrated by Moussavi and Kubo's inclusion of "affect" as a category in their analysis. For clients funding projects with more elaborate budgets for materials and finishes, often high-end retail stores or museums,

Figure 3: SIFT Studio. Alt Brew panel, 2015.

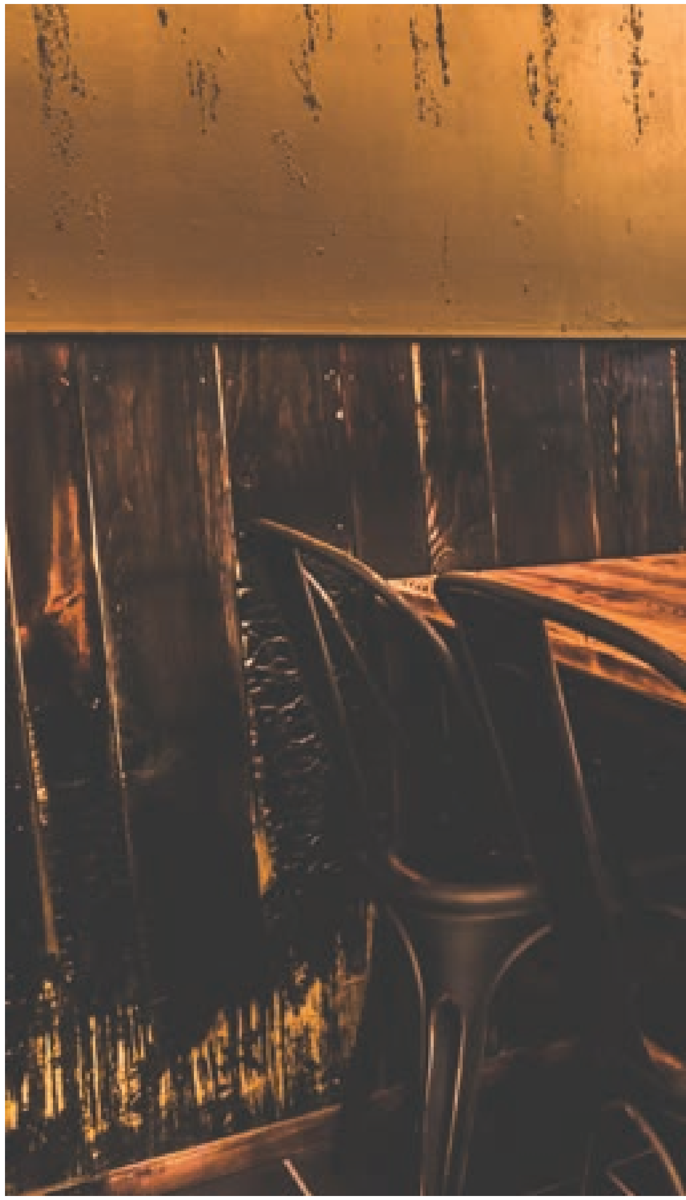


Figure 4: SIFT Studio. Alt Brew wall stencil, 2015.

architects express "rank and prestige" if somewhat unintentionally. The last of the triad, however, that of "communication and knowledge," is problematically absent from the ambitions of contemporary architecture and is precisely where architecture can begin to regain its cultural and political agency through a more ambitious approach to ornament.

Recouping architecture's agency as such has been at the heart of our recent work. We see this as a practice of producing images that alter the political and cultural imaginary through strange materiality and texture. We approach surface articulation as a spectrum from texture to ornament, where texture can become ornamental by taking on additional meaning and ornament can turn textural when it loses its symbolic significance.[9] Our work increases the representational significance of texture by defamiliarizing everyday materials in an attempt to draw people into more subtle yet meaningful forms of engagement and challenge established categories of the digital and the natural.

Focusing on texture as a primary design concern has advantages. First, texture is accessible. From the whitest matte plastic to the craggiest stone, all materials have a set of physical properties that are familiar to a wide range of people. In contrast, the symbolism of ornament requires a cultural intelligence that is more rare. Second, texture is more haptic than visual. Although possessing tactile qualities, ornament is most often

Figure 5: EADO & SIFT. The Marq wall stencil, 2015.

accessed visually at the scale of the building. Thus, the transmission of symbolic content via ornament requires sustained attention, a rare occurrence amongst the average building-goer. Conversely, texture is accessed informally, a casual brush of fingers across a surface, and therefore better suited to the general state of distraction in which architecture is most commonly perceived.[10] Our work is primarily haptic. People connect to it not through visual interpretation, but rather through a tactile familiarity of texture that at some point turns strange.[11] It is in the space of this suspended immediacy of the ordinary where we attempt to establish new meanings.

The following work showcases a series of approaches that seek to defamiliarize texture while speculating on larger disciplinary and cultural implications. Following Lynn, the broader concepts of the work are developed vis-à-vis the techniques and technologies of production.

TEXTURAL GRAFTING

Textural grafting is a process of transferring the texture of one material onto another through both 2D and 3D processes. This technique abstracts and distorts inherent material qualities, pointing them towards alternative applications and producing a tension between one's recognition of material origins and alternative synthetic expressions.

For *Alt Brew*, an interior renovation for a craft brewery, high-resolution polygon modeling software, such

Figure 6: EADO & SIFT. Texture Tectonics, 2015.

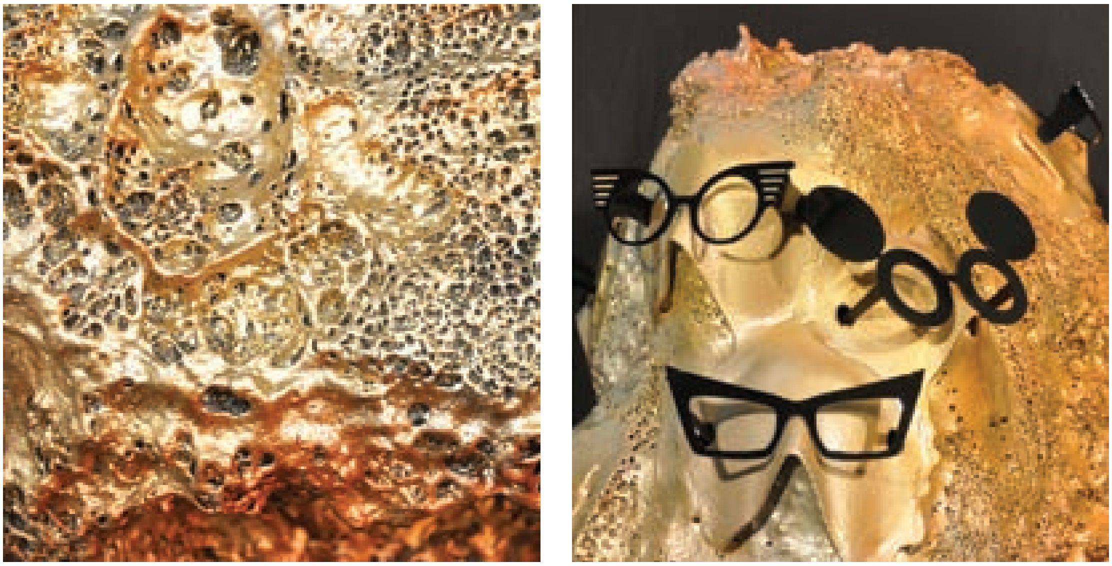


Figure 7: EADO & SIFT. Mirror Mirror, 2013.

as Autodesk Mudbox, is used to sculpt digital models from detailed photographs of material textures, such as wood, rice, or grain. These textures are "painted" onto digital models in a thin layer of 3D relief then CNC routed onto large panels (fig. 3). Elsewhere in the brewery interior, another type of *textural grafting* abstracts detailed material photographs into vector linework that is cut into stencils and used to guide the application of accent paint onto flat walls (fig. 4). These various applications, along with a suspended wood ceiling that is charred, reddened, and highlighted gold, present various expressions of familiar materials, such as wood, yet "natural" wood is absent.

Another interior, a gastro-pub called *The Marq,* uses similar stenciling processes for both the application of paint and an adhesive-aggregate mixture (fig. 5). In both of these projects, natural materials are defamiliarized in a series of abstracted textures that retain some elements of familiarity. Materiality is established through a series of unnatural copies that selectively maintain qualities of an absent original. The play between ordinary/extraordinary, natural/synthetic, and digital/analog challenges common understandings of these categories, and couples haptic experience with broader cultural meanings.

TEXTURAL MASSING

In *textural massing,* objects are derived from specific qualities that are drastically scaled to produce formal ambiguity. Texture is liberated from two-dimensional constraints, amplified and activated to take on issues of formal generation, aggregation, and scalar transformation.

For *Texture Tectonics,* a recent research project and exhibition, formal families are derived from specific material behaviors (such as wrinkly, bumpy, and gummy) and then scaled to produce formal ambiguity. This approach to form and massing is multi-scalar: what appears in one instance as bumps on a surface shows up in another as stand-alone bumps, blurring the distinction between an underlying form and a surface-based texture. Further, these new textural massings inform the way objects aggregate as adjacent textures nest together in a series of loose fits, suggesting an alternative tectonic order that is based on irregular forms and load paths rather than consistent surface-to-surface or point-to-point connections (fig. 6).

EXCESSIVE FINISHING

Excessive finishing involves a mixture of subtractive and additive processes. CNC fabricated objects are intentionally deteriorated by heat or aerosols to produce corroded massings that retain traces of machined form. These objects are then finished with various plastic coatings, resins, powders, and paints to produce ill-formed objects with nuanced gradations of color, iridescence, and finish.

Mirror Mirror, a proposal for a pop-up eyewear store in New York, was conceived as a series of detailed, colorful, rock-like objects suspended in a mirrored container. Baroque-inspired carnival masks are grafted onto the rocks and display individual eyewear frames. The prototype is constructed from a combination of polystyrene forms carved on a 5-axis CNC router and 3d-printed display masks. All traces of the machining are erased through aerosol-induced deterioration and multiple coatings of plastic, resin, and paint. These techniques produce a continuous surface that has both smooth and rough patches with metallic color gradients that move from silver and gold to copper and orange. The finished textures are intentionally ambiguous: they produce associations with geologic forms but are clearly not natural formations (fig. 7).

Another project, *Artifacts,* employs similar methods of making yet pushes the deterioration further. Here layers of polyester felt are excessively melted to produce an eroded mass that loosely resembles its initial cubic shape. Finishing techniques similar to those used in *Mirror Mirror* are applied: plastic coatings, paint, glazes, and resin (fig. 8). In both *Artifacts* and *Mirror Mirror,* the excessive layering of finishes produces objects full of qualities, on par with the most exotic geological specimens, but entirely artificially produced.

At an architectural scale, similar methods are deployed for *The Marq.* Here, numerous techniques are developed to abstract and confuse the image of traditional wood. One such technique extends from *Artifacts* and *Mirror Mirror,* where the bottom edge of the wainscoting is carved and burned, then coated in metallic glaze and resin—a process of initial deterioration and alteration followed by the build-up of new qualities (fig. 9).

These three projects establish a range of qualities that confuse distinctions between natural and artificial materials. This happens in two opposing directions: one, the agglomeration of synthetic materials—foam, plastic, paint, resin—to produce a natural looking artifact and two, the alteration of natural materials, such as wood, with layers of synthetic finishes, such as metallic flecks, paint, and resin, to distort the reading of inherent material qualities.

CONCLUSION

The work shown here demonstrates an expanded approach to architectural texture where the blurring of natural and artificial qualities combines with both digital and analog processes to produce artifacts of ambiguous materiality and origin. Working simultaneously with and against ordinary materials creates a tension between the everyday and the unknown, requiring prolonged attention in order to fully comprehend a thing's physicality. This suspended immediacy is where architecture can produce new meanings (and layer multiple meanings) and derive cultural agency through engaging and creating its audience while challenging established cultural and technological norms.

ENDNOTES

1. It could be argued that this shift to artificial texture arises with the advent of manufactured materials, but here we are primarily interested in a more radical form of artificiality that cleaves a space between a material and its perceived texture. While plywood is a manufactured building material, it still primarily exhibits the textural qualities of wood. A similar assessment could be made of concrete masonry units (CMUs), medium density fiberboard (MDF) sheets, or other similarly manufactured materials.

2. See Neil Leach's conversation with Greg Lynn, "The Structure of Ornament," in *Digital Tectonics,* eds.

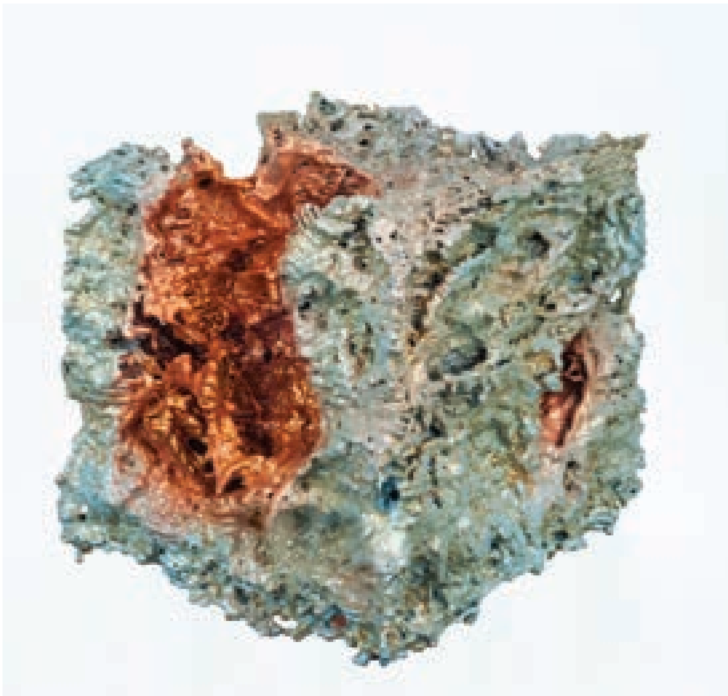


Figure 8: SIFT Studio. Artifacts, 2013.

Figure 9: EADO & SIFT. The Marq, 2015.

Neil Leach, David Turnbull, and Chris Williams (Chichester, UK: Wiley-Academy, 2004), 63–68.

3. Farshid Moussavi and Michael Kubo, eds., *The Function of Ornament* (Barcelona, Spain: Actar, 2006).

4. Robert Levit, "Contemporary Ornament: Return of the Symbolic Repressed," *Harvard Design Magazine,* Spring/Summer 2008, no. 28.

5. Levit, "Contemporary Ornament," 3.

6. These two facts echo the position of Antoine Picon in his book *Ornament: The Politics of Architecture and Subjectivity* (Chichester, UK: John Wiley & Sons, 2013).

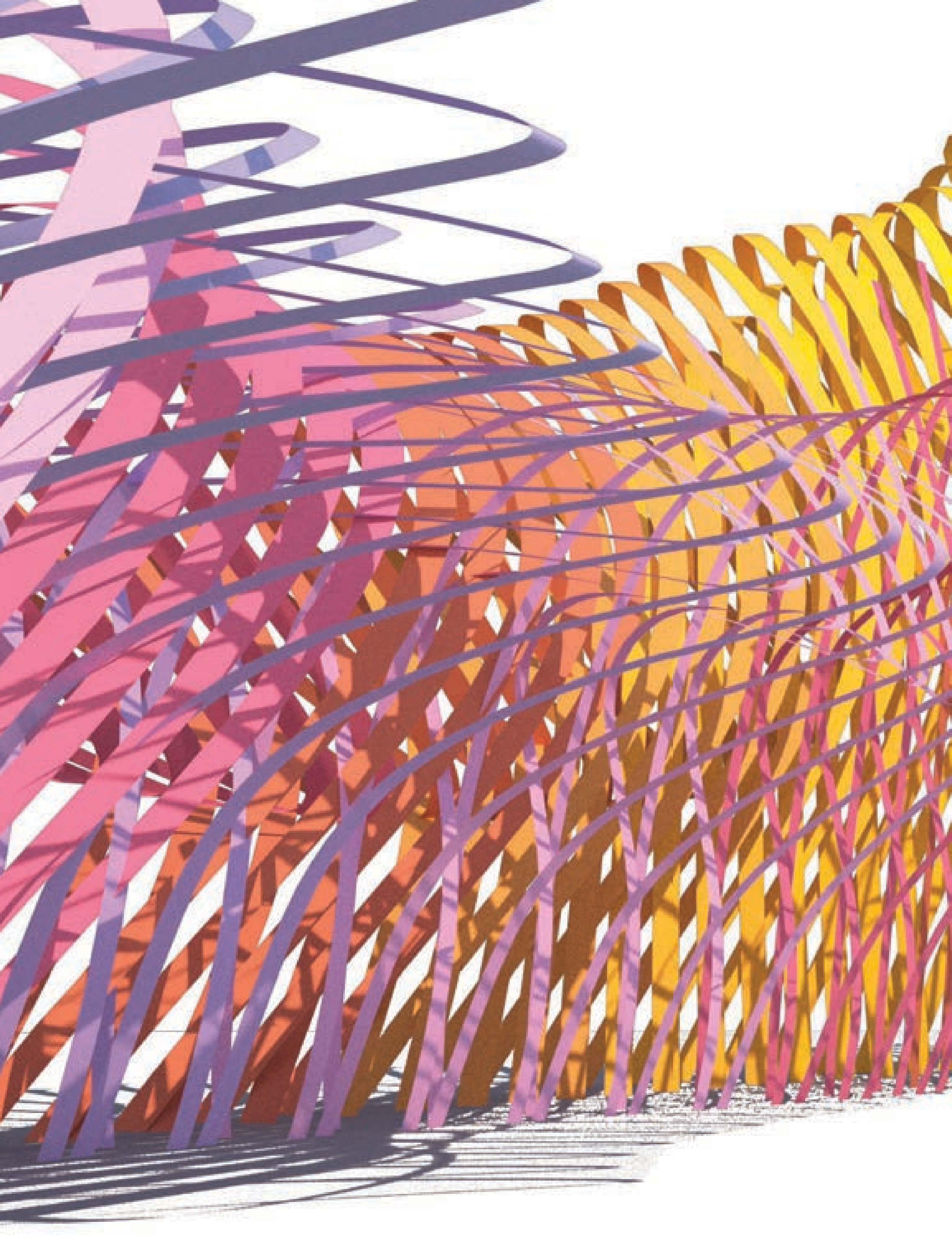
7. Lynn recently referenced Cache's work in the call for his guest-edited issue of *Log*: "...derivatives of Cache's panels can be seen inside museum galleries, on hotel facades, and in steakhouse interiors and elevator lobbies." Accessed October 28, 2015, http://www.anycorp.com/log/submissions.

8. Picon, *Ornament.*

9. The latter condition speaks to architecture's problematic relationship with the market. In the past two decades, architectural research has entered into an arms race with the commercial sector where architects attempt to produce novelty at a rate that outpaces their work's migration into the built environment. If ornament is to "speak," then it must stand out from the background of commercial building products, which is itself quite diverse, colorful, and patterned. This produces a situation where the only end game is more technological virtuosity: more intricate patterns, more sinuous curves, fewer seams, and so on. Ultimately, virtuosic work creates audience—and thus gains agency—through the shocking and spectacular image of the new.

10. See Clement Greenberg, "Avant-garde and Kitsch," in *Art and Culture: Critical Essays* (Boston: Beacon Press, 1961), 3–21.

11. This notion of defamiliarization is similar to that described by Viktor Shklovsky in his essay "Art as Technique," in *Russian Formalist Criticism: Four Essays* (Lincoln: University of Nebraska Press, 1965), 3–24.



Point Clouds, Constellations, Coordinates, and Other Lists

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Architecture has a complicated relationship with shape. Our discipline has loved shape, hated shape, trusted and mistrusted shape, sometimes violently destroyed shape.[1] Shape has been understood as a discrete entity—defined either by a two-dimensional profile or a three-dimensional envelope—or, in recent times, as a shifting figure we glimpse in aggregations of varying intensity, heretofore known as "fields."[2] Let's face it: fields are alluring. They are often visually rich and intricate and can even register movement. But they are problematic, too, because of their ill-defined limits and lack of hierarchy. Some recent tendencies in design attempt to reconcile figure and field and manage the relationships between them. In this paper, I will describe my methods for organizing and visualizing data in efforts to mediate between figure and field, part and whole, system and component.

In developing some recent projects, I find I have a particular interest in various descriptions of points in space-point clouds and their coordinates- and I have started to present them to myself as sets of constellations. In astronomy, constellations are collections of stars that describe the shape of a person or animal. Each is based on a configuration of discrete points in space and a shared mythology about the character, but constellations also rely heavily on the power of the imagination to complete suggested figures in our minds. I am interested in the potential for discrete sets of information (whether stars in the sky or points in space) to suggest nuanced and evocative figures. In the case of celestial constellations, the figures are often human and animal. In architectural constellations, this is less often so.

The role of constellations in my work is to represent partial information—it is complete enough to be suggestive (of shapes, trajectories, etc.) but not so complete as to define an envelope or a closed perimeter. It is a way of limiting control so that design decisions may be made with more reflection. Seeing work as a group of points in space, or constellations suggestive of shapes, and alternately as defined figures allows me to oscillate between what a project is and what a project could be. This is especially useful in digital processes, when the tools themselves can be somewhat tyrannical over design.

There are several related questions guiding my research. What kinds of organizations can yield shapes that have the visual allure of part-based systems (fields)

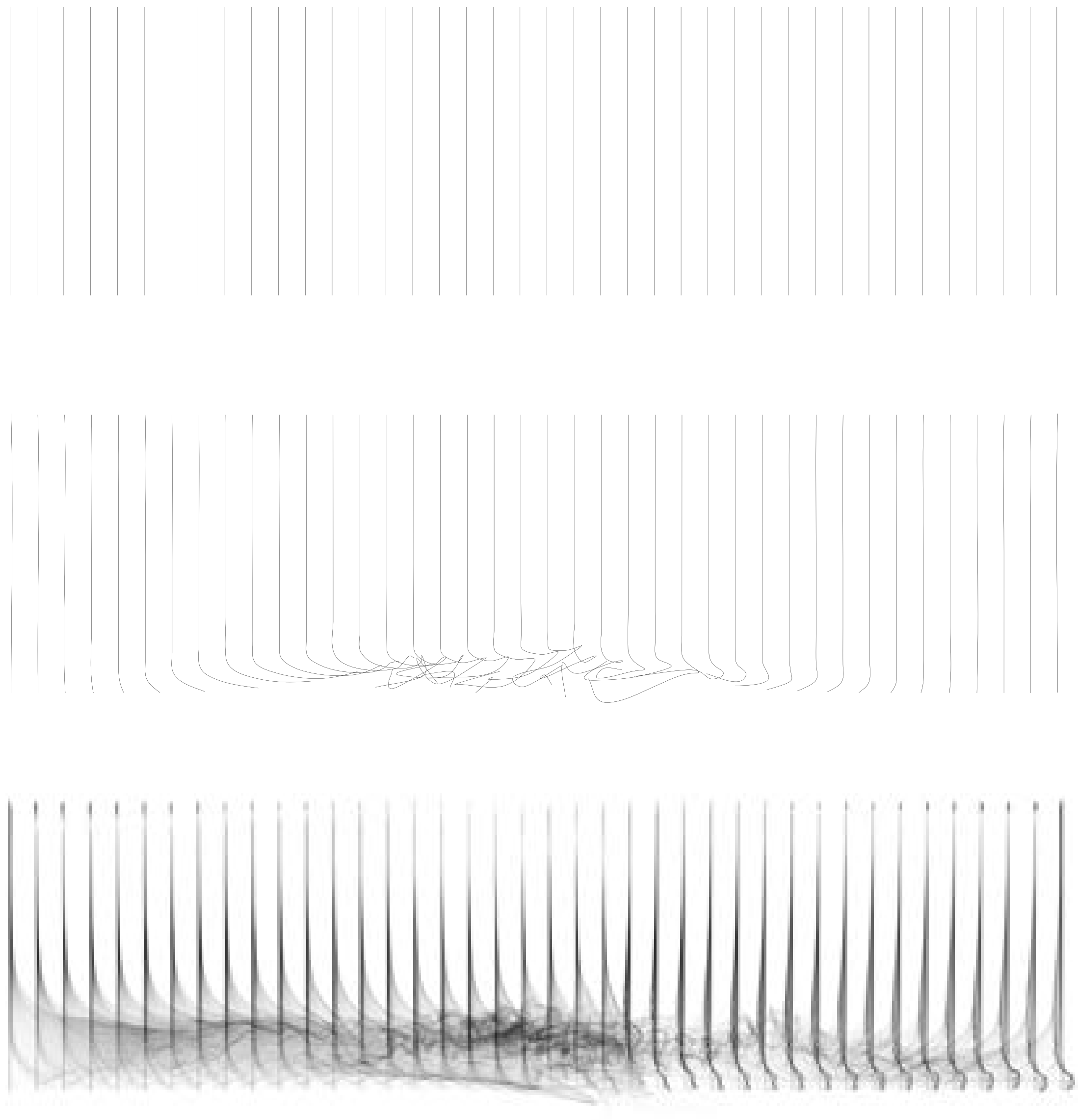


Figure 1: Emily White, Long Piano (drawing and diagrams), 2009.

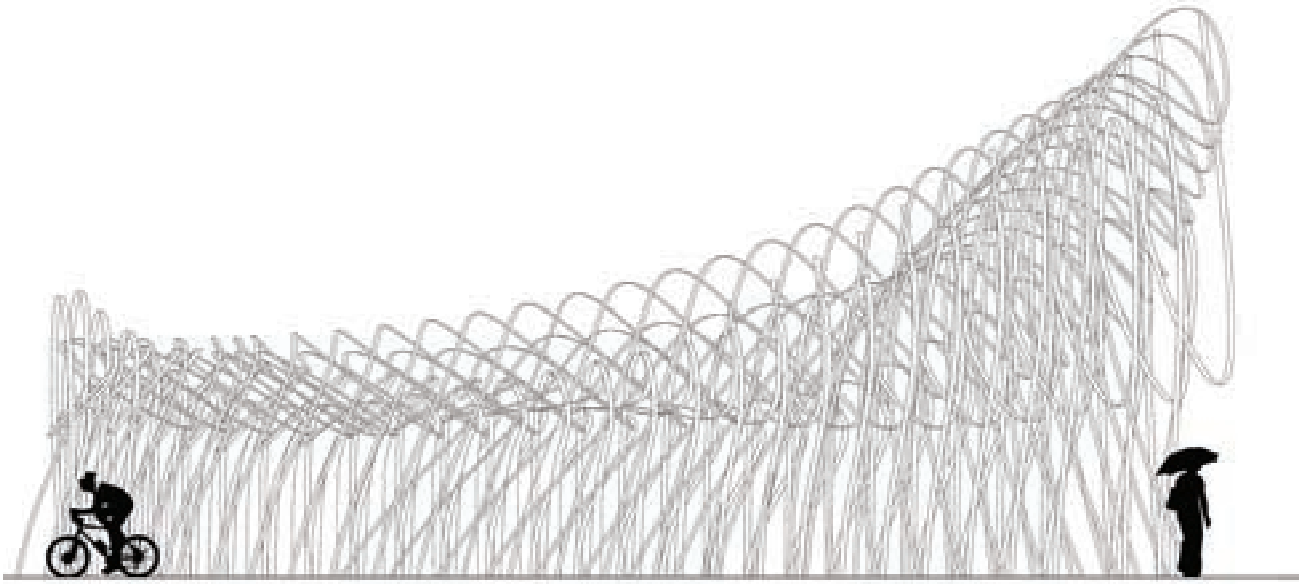


Figure 2: Emily White, Masonic Zoom (elevation), 2014.

and are also bounded, manageable and constructible? When working with points in space, are Cartesian frameworks necessary? Are they limiting? What degree of control is productive in design? When does too much control make a project predictable?

I will use three related projects to examine the implications of constellation-based organizations. Two are speculative, and the third is currently in development. This series of projects started with an interest in how drawings can be expanded into volumetric constructions and how visualizing information can influence that process. In each case, line is more important (and more legible) than shape because lines can belong to multiple shapes simultaneously.

The first project I will describe is a drawing that uses simulated physics to shape curves in two dimensional space. It has no material. The second is a proposal for an urban installation that is translated out of a drawing and designed as a series of extruded lines. It was proposed as a sheet metal structure. The third project is a suspended ceiling installation for the Fort Lauderdale International Airport, to be fabricated in sheet metal. In each case my tendency is to use points (a group of which is called a point cloud) to suggest lines, and lines in turn to suggest volume.

LINES MADE FROM POINTS: DEFINING CONSTRAINTS AND CONTROLS

The first project is useful to layout some terms and concepts, the most important of which is the difference between constraints and controls. I made the drawing with the software Processing, using the Traer physics engine plug-in to simulate physical forces of particles in space.[3]

The code assigns gravity and drag to particles as they move around based on forces applied as the code is executed in real time. I used those particles to draw curves, assigning some as anchors, or end points, and some as inflection points. The anchors are static, and the inflection points are dynamic, moving according to the "physics" written into the code (fig. 1). The dynamic information (moving points) allows the project and its form to be controlled, whereas the static information (properties of "physics") constrains movement. Constraints are set first; controls are manipulated over time. Controls can be manipulated according to an evolving aesthetic or formal agenda.

Of course, working in two-dimensional digital space

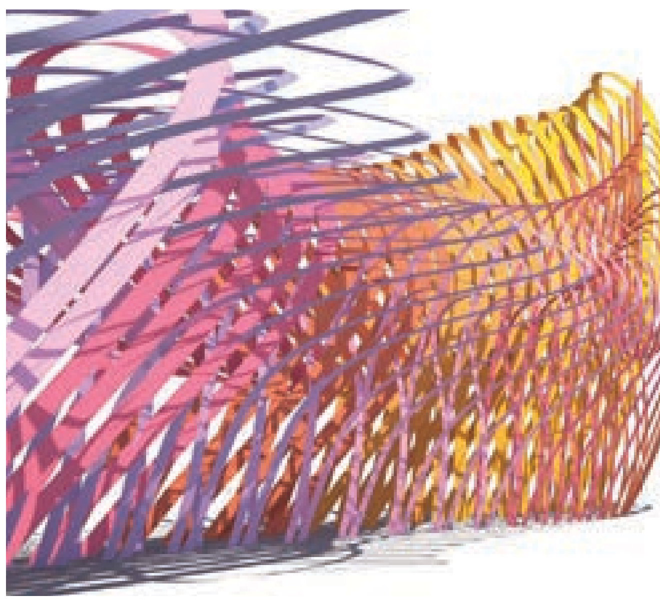
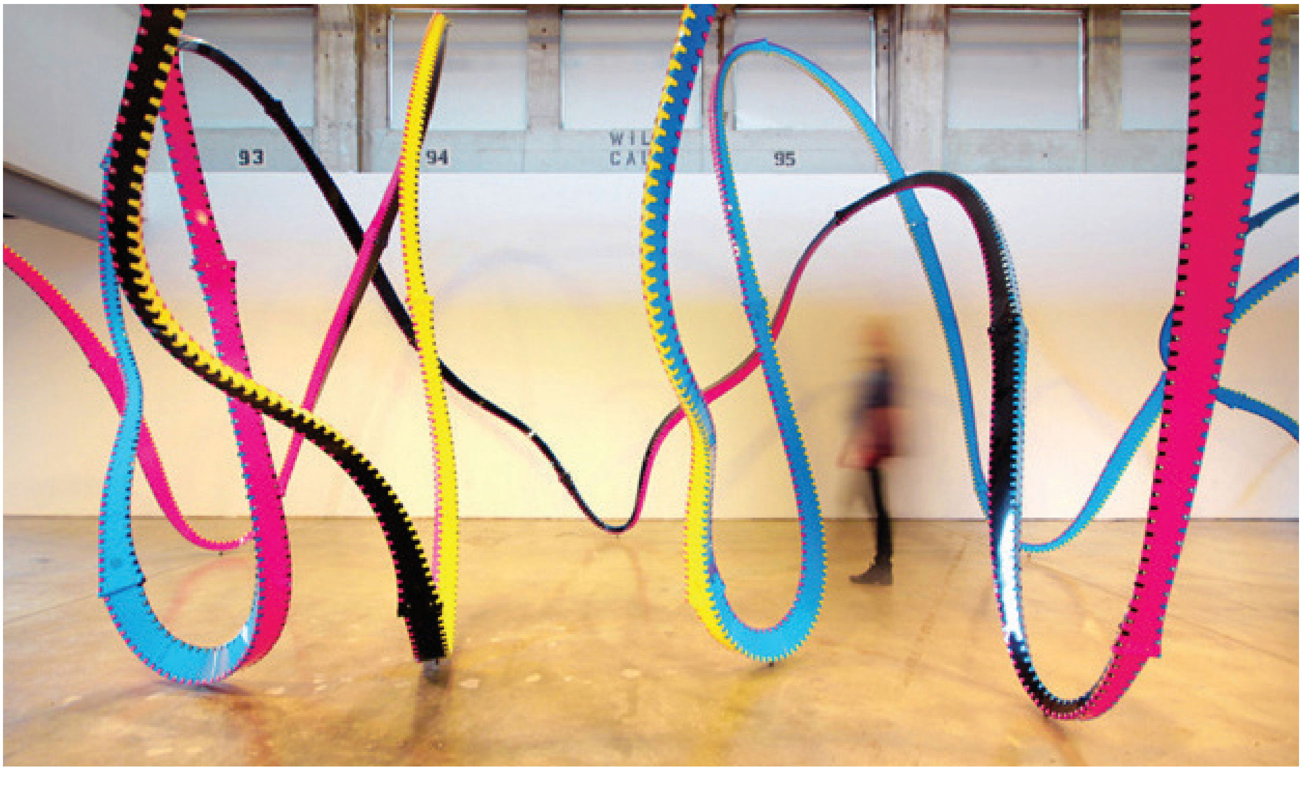


Figure 3: Emily White, Masonic Zoom, 2014.

Figure 4: Ramiro Diaz-Granados, Go Figure, 2012. – photo by Josh White

Figure 5: Ramiro Diaz-Granados, Go Figure (detail), 2012. – photo by Ryan Martinez



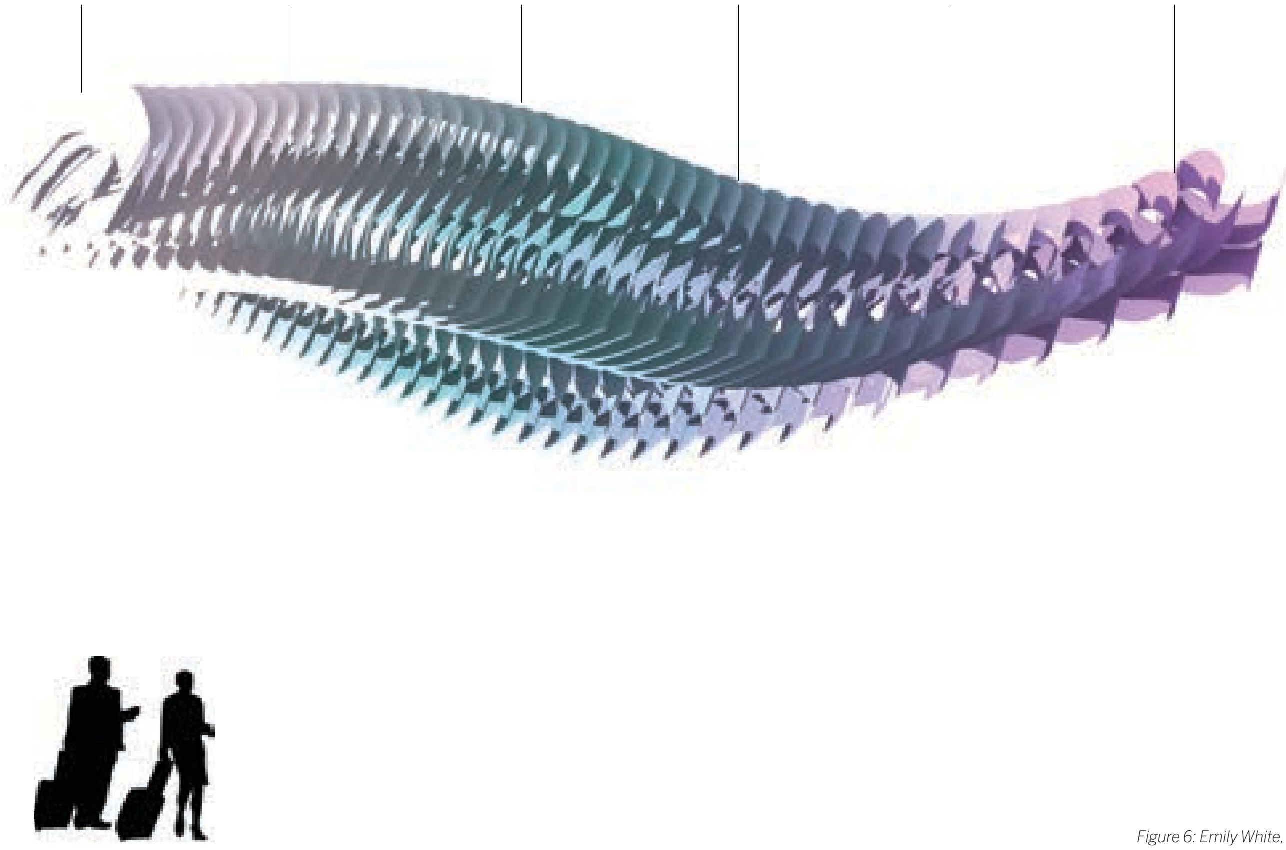


Figure 6: Emily White, Wavelength (sketch model), 2015.

removes a lot of physical and material constraints that might influence a project. Processing is a great design tool for exploring isolated formal relationships. I was interested in questions like: At what point did these big curve networks take on figural characteristics? Was there ever a defined perimeter? I looked at these issues in the next project.

LINE INTO VOLUME: THE QUESTION OF ENVELOPE

The second project involves translations from drawing into volume, which necessitates an envelope, or at least an implied envelope. It is a proposal for a structure marking the beginning of a new section of San Francisco's growing network of bike paths. [4] It started from a drawing that alluded to textile operations with strands knitted together in varying densities (fig. 2). As the project developed from drawing to model in digital space, it maintained a loose, strand-like quality (fig. 3). But of course, as we began to model it in physical space, the issue of stiffness came up. Stiffness, the ability to hold shape, is essential to managing the relationship between figure and field. Without stiffness, there is no figure.

Folding is a tactic that designers often employ to stiffen sheet metal. I was interested in a couple of other projects of roughly similar scale that shared a vocabulary of line rendered in metal and had clever approaches to stiffness. Some of the installation-scale work of Oyler Wu Collaborative maintains the lightness and looseness of drawings, and I was particularly interested in the project Go Figure by Ramiro Diaz-Granados, installed in the SCI-Arc Gallery in 2012, which is explicitly about the spatial figures latent in line drawings (figs. 4 and 5).

Diaz-Granados created a triangular section from three faces of aluminum that were thin enough to read as curves, meandering loosely around the gallery. There was a friction-fit finger joint running along each of the three seams. Each side was powder coated with a different color so the thin sweeps derived from his design drawings—the figure—could be more legible.

In Masonic Zoom, too, we did not want to make our lines bulky by folding for stiffness. We set up a system

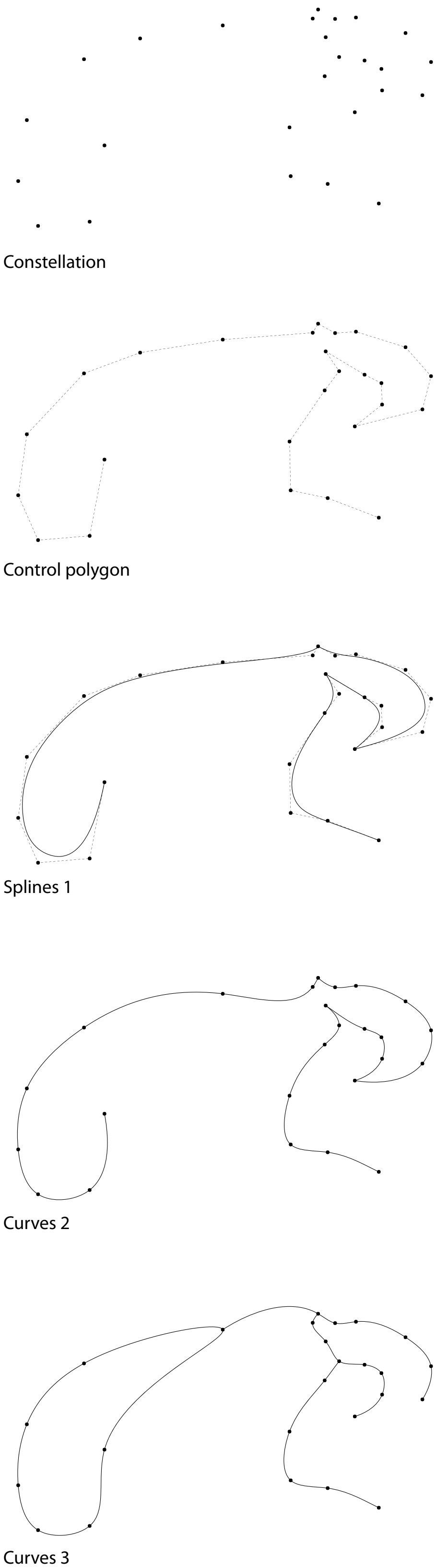


Figure 7: Emily White, Wavelength (diagrams), 2015.

of lamination and mechanical fastening that would allow the sheets to be connected into one large network. We tested this system in paper models and believed it would allow the project to maintain characteristics of expansion and even fluffiness without becoming totally floppy. Masonic Zoom didn't go beyond proposal form, but I am now working with many of the same issues in a project that will be fabricated and tested full scale in the field.

MATERIALIZED LINE

My current project, Wavelength, has a simple organization that describes shifts in form and color over a series of curved sections. What is (purposefully) less straightforward is the development of each of the curved sections, and the process by which I have been moving between part and whole. My interest here is the balance between the implied envelope—the project's figure—and the internal dynamics among the serial sections. I am using constellations as a way to visualize possible alternative shapes at the local level even as I am moving toward a particular global figural ambition (fig. 6).

In this project, there are constraints and controls, but unlike previous drawing projects where physics was a graphic representation, this project will be fabricated and installed in a real site, so it is important that it is accountable to real physics. I am using constraints and controls to develop the shape, and I am also ascribing certain physical characteristics to them, like span and bending radii. The project will be fabricated in 0.1-in thick aluminum. I am working with a structural engineer to define a set of properties that act as constraints, like ranges of possible bending given the material thickness and possible lengths of unsupported spans.

When described in terms of digital modeling, these constraints are approximations of material and structural performance, or parameters, that are represented by nodes in a grasshopper definition. The controls, by contrast, are the modifications to these initial conditions. They can by manipulated either by number sliders, in the case of increasing the length of an arc, or just by altering the shape of a curve or moving a point in space. Because constraints are fixed and controls are dynamic, there are areas within the project which are non-negotiable, and other areas that are in nearly perpetual formal flux.

Figure 7 shows one of the profiles in the series represented as a constellation (at the top, the points that constitute its control polygon) and various profiles drawn among the points of the constellation that allow me to imagine alternative shapes. In this project, I have been working with the control points (constellations) visible in digital space as I develop the model. In past projects, I have usually left control polygons and control points as background information that I only make visible when adjusting the shape of a curve or drawing an interpolated curve using edit points.

On one hand, this makes for some clutter on the screen. On the other hand, it allows me to imagine deviations form, and disruptions to, the overall figure caused by formal negotiations at the local level, among a small group of consecutive profiles, for example. In the case of a serial section project such as this one, these local level dynamics are essential; a project comprised simply from a contoured object—no matter how intricate the object—is totally monotonous. There is potential for a more nuanced relationship between section and envelope when the sections are allowed to exert some influence on the overall form by way of local level interactions. There ought to be some turbulence in the waveform, in other words.

The project can be read at various levels of resolution. It can be described in narrative or metaphoric form (i.e. turbulence in the wave), as constellations that suggest shapes, as point clouds before they are organized into constellations, and, simply, as lists of numbers that represent these points as Cartesian coordinates. It is the oscillation amongst these representations that allows me to manage the relationship between the envelope and the section, or the field (of profiles) and the figure (their implied envelope.)

Oscillation among representational means has another benefit to the work that concerns time. It makes the work go more slowly, and therefore more deliberately. Especially when working with digital tools that enable designers to turn out many quick iterations, it is important to make time to reflect. One way of reflecting is to see and un-see the project. Frameworks that allow partial control privilege the design decisions that occur in translation. This depends on setting up processes that are non-linear and in which the same information can be seen in many different ways.

ENDNOTES

1. A very tiny spectrum of attitudes toward shape could be constructed from two poles of twentieth century architectural discourse. It would include, on one end, Louis Sullivan's position in his 1896 article "The Tall Office Building Aesthetically Reconsidered" that "whether it be the sweeping eagle in his flight, or the open apple-blossom…form ever follows function," and at the other end, Robert Venturi, Denise Scott Brown and Steven Izenour's description in *Learning From Las Vegas* (Cambridge: MIT Press, 1977) of the concept of a "duck" in opposition to a "decorated shed."

2. See Stan Allen, "From Object to Field," in AD Profile 127 (Architecture After Geometry), *Architectural Design,* vol. 67, no. 5/6 (1997): 24–31.

3. The Traer physics engine for processing was developed by Jeffrey Traer Bernstein. His code and a more detailed description of its functions can be found at Bernstein's website, http://murderandcreate.com/physics/. Processing is an open source software and "software sketchbook" for designing with code. It is most commonly used by visual artists. More information and code can be found at the Processing website, http://processing.org.

4. The proposal for Masonic Zoom was a collaboration with Jenna Didier and structural engineer Roel Schierbeek.

Sharing Design: The Columbia Building Intelligence Project

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In a short editorial in *Wired* magazine just after the crash of 2008, "The New Economy: More Startups, Fewer Giants, Infinite Opportunity," Chris Anderson suggested that what led up to the latest economic crash was not just another dip in the ebb and flow of reliable past economic cycles, but rather the last gasp of big-business models that were struggling to adapt to the new pace of change. They were being challenged by more agile, creative and innovative small firms with new models of scalability that would allow them to be competitive in large markets. This was not to say that large firms in all business sectors would cease to exist, but it did hint at a trend that has only accelerated since this claim was made seven years ago: that much of the innovation and new ideas that are making big changes and disruptive shifts in how industries operate are being generated from small start-up firms. This is being largely facilitated by how these firms leverage digital communication technologies as the foundation of their business models along with their full embrace of a new social and cultural dynamic that in only 10 years has developed into an entirely new structure for the exchange of goods and services referred to as the Sharing Economy.

What does this mean for the architecture, engineering, and construction (AEC) industry, and architectural education in particular? Architectural education used to be about preparing students to proceed with their internship upon graduation in preparation for professional registration and a stable job in an architectural firm. No more. There are indications that business as usual is getting short circuited by an impatient, eager, tech-savvy, and network-minded generation who see alternative career tracks that are faster, more interesting, and capable of having a greater impact on industry. This new attitude is partly due to the memory of the recent economic slump and challenging job market that awaited recent graduates, but it is also the result of a hunch that this generation has that the future design and construction industry can and should be much different than it is now. The entrenched silo structure of the current AEC industry, which continues to undermine the sharing of information and ideas that is the foundation of meaningful collaboration among architects, engineers, fabricators, and contractors, seems alien to a new generation who grew up with the open information exchange of the internet and who see sharing as a natural way to gain knowledge and be productive.

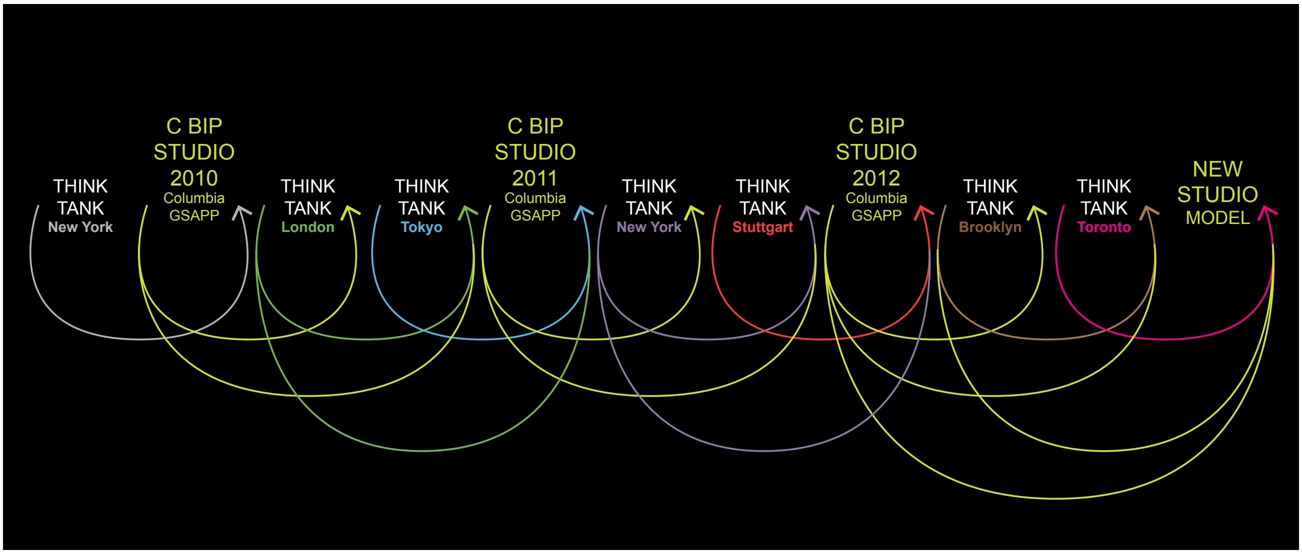


Figure 1: C BIP Diagram

THE COLUMBIA BUILDING INTELLIGENCE PROJECT

This hunch was at the core of the Columbia Building Intelligence Project (C BIP), which was launched at the Graduate School of Architecture, Planning and Preservation (GSAPP) at Columbia University in the fall of 2009. C BIP was initiated as a three-year pilot research project designed to explore new forms of technology-enabled collaboration within and between the various sectors of the AEC industry. The project grew out of an interest in using emerging digital design and communication technologies and the increasing trends toward more integrated forms of practice to address the entrenched adversarial atmosphere that has inhibited the progress of our industry for many years. In addition, C BIP was based on the premise that changing the future of our industry depends on transforming the education of our future leaders, which begins with a renewed engagement between academia and industry.

C BIP was comprised of local and international think tanks and the C BIP Studio. The think tanks brought together leading industry experts including architects, engineers, builders, owners, fabricators, research scientists, software developers, and educators in an open dialogue about current projects, working processes, and research that form the most technologically progressive industry practices. Each year, one of think tanks was held in New York and was more directly related to the work of the C BIP Studio, allowing an exchange of ideas between GSAPP students, faculty, and the think tank participants. In response to the global dynamics of the AEC industry, the other think tanks took place in major regional centers around the world to better understand how the topics around design, technology, and collaboration shift in different cultural and economic contexts. The think tanks uncovered key questions and issues that established a broad foundation to position and evolve the C BIP Studio (fig. 1).

The C BIP Studio was the anchor of the Columbia Building Intelligence Project, which was conceived as a new studio model that responded to the increasing complexity of contemporary design problems. As an evolution of the typical studio model of 12 students working on individual projects and guided by a single instructor, the C BIP Studio was a highly integrated model in which 36 students worked interactively on specific parts of a larger problem, guided by three critics and several technical consultants and guest advisers from the industry who served as experts on key issues relating to the studio topic. The primary objective of this new structure was to encourage the sharing of information, the open exchange of ideas, and a deep understanding among the students of the potential of collective teamwork. The students produced design work that was shared and combined through structured parametric modeling allowing the individual work of each student to contribute to the entire studio. The C BIP Studio took place in the fourth semester of the Master of Architecture Program, when students transitioned from core to advanced studios. At this point in their education, students had enough background to make informed contributions to a team project, while also having another year after completing C BIP to integrate their new findings into future work at the GSAPP (fig. 2).

THE STATE OF INDUSTRY – THE CONTEXT FOR C BIP

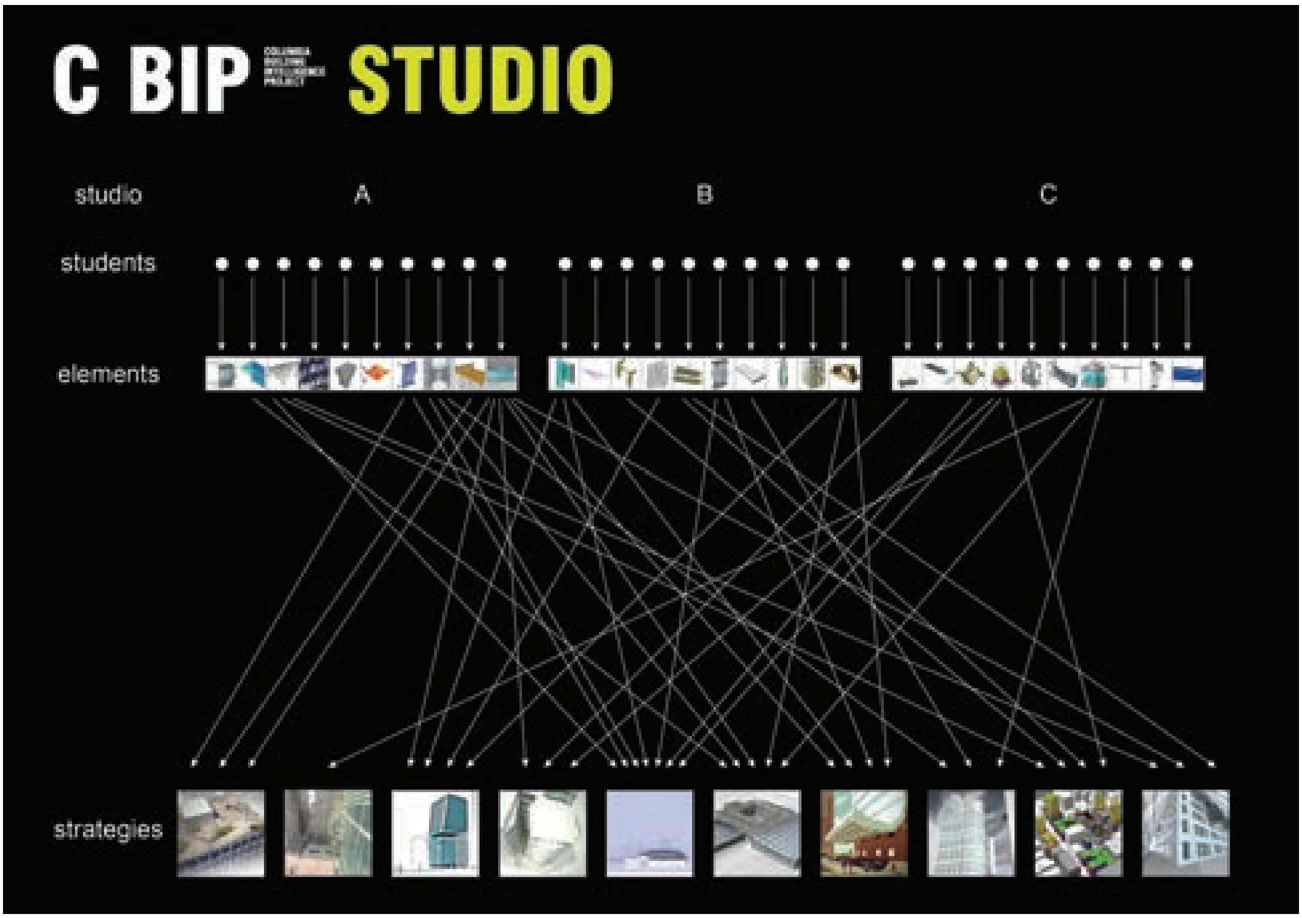
The practice of architecture has always been about managing information. Architects produce drawings that coordinate the efforts of multiple constituents with the goal of producing buildings. However, the amount of relevant and available information that is useful for any given architectural project today has expanded faster than the development of integrated and synthetic working methods. The amount of expertise required to design, fabricate, and construct a new building has lead to multidisciplinary teams that expand far beyond the traditional architect, engineer, and contractor model. This has simultaneously led to more collaboration between individual people, specialized teams, and a fragmentation of information that often inhibits the full benefits of a collective workflow. This is largely due to the lack of effective means to organize and coordinate the efforts of the multiple team members. While this is certainly a *logistics* issue, it is also a *design* issue in that any organizational system has inherent biases that either support or obstruct the potential of creative work.

With the availability of ubiquitous digital communication technologies, the rapid transformation of industry through these technologies, and a new entrepreneurial spirit among a younger generation, architects are now able to leverage their position so that they have the potential to *design the organization of a project*—to creatively and strategically assemble new alliances and relationships among owners, clients, builders, fabricators, consultants, etc., that lay the groundwork for innovative architecture. The C BIP Studio addressed this new working environment with the goal of preparing the next generation of architects to lead in the development of new modes of practice.

Acknowledging that the industry is already moving toward a restructuring with new developments like Building Information Modeling (BIM) and Integrated Project Delivery (IPD), which promise to address many of the procedural inefficiencies in design and construction, C BIP attempted to build on this restructuring while also critically addressing some of the difficult questions beginning to emerge for architects. For example, what is the relationship between BIM and design? At what point does the degree of integration that is the basis of both BIM and IPD become a deterrent for design, innovation, and risk taking (which goes hand in hand with innovation)? Is the degree of integration inversely proportionate to the degree of flexibility for more open-ended design? Are BIM and IPD only for managing workflow, or can they evolve to support more effective design methodologies?

One aspect of the studio methodology borrowed from the concepts of *collective intelligence* and how it

Figure 2: C BIP Workflow



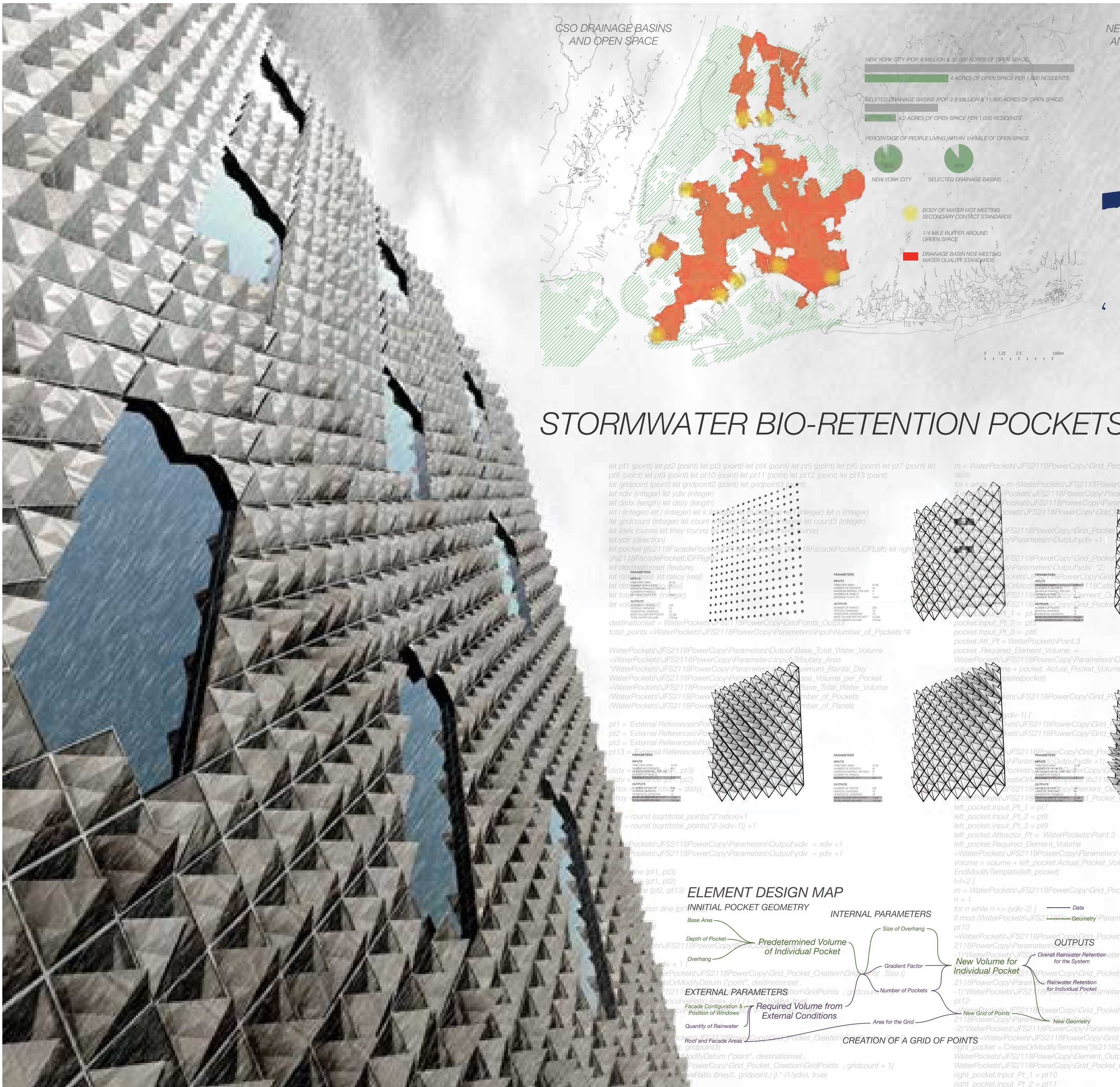
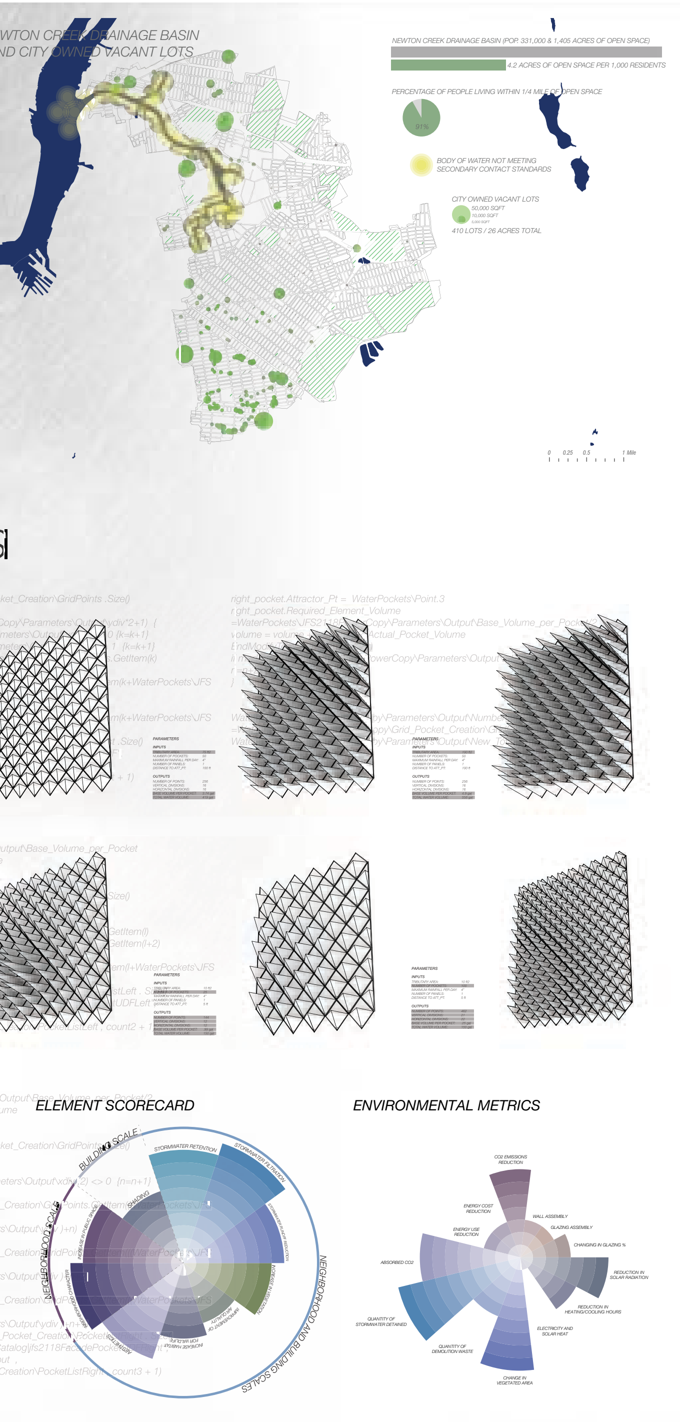


Figure 3: Sample Element



might be applied to architecture. As individual projects evolve to include more and more information, as well as more and more stakeholders, how might diverse and decentralized groups make intelligent design decisions? In architecture, is it possible to leverage "the wisdom of crowds," as theorized by business writer James Surowiecki?[1] Is there a way for design teams to take advantage of "crowd sourcing," the contribution of many distributed users toward a collective product?

Another aspect explored how *open source*—a design method pioneered for software development—might be reformulated for architectural design and how multiple independent parties might build successive versions of a part toward the goal of a single deliverable.[2] Could modules of buildings and 3D files be "checked out," revised, and "checked in" by different architects, fabricators, and contractors over time durations that exceed a single project? How would discrepancies between versions be handled? If complex building parts could be designed, documented, and released into a broad architectural community, how would intellectual property be handled? Might an open source model start to change the one-off nature of buildings and reduce inefficiencies in the construction industry?

The C BIP Studio also explored how cooperation and sharing could change the process of design to realign the motivations and incentives that drive design decisions.[3] "Shared risk, shared reward" is a cooperative structure at the core of IPD intended to align the priorities between design teams, contractors, and owners around financial incentives. This structure is less beneficial for architects due to the value of their services, in financial terms, in relation to overall project costs. What other value structures could encourage people to move towards collaborative work? Can the silo structure that defines current practice be overcome in a highly litigious working environment? If so, how can the next generation accomplish this and put legal structures at the service of design instead of vice versa. Can the next generation transfer the deeply rooted culture of sharing that defines their daily social life into a sustainable business model for design?

The C BIP Studio engaged these more speculative questions backed with an understanding of the current state of the industry to develop new design workflows that might contribute to meaningful change to the practice of architecture and its future position within the AEC industry.

ENERGY + ADAPTATION – THE C BIP PROGRAM

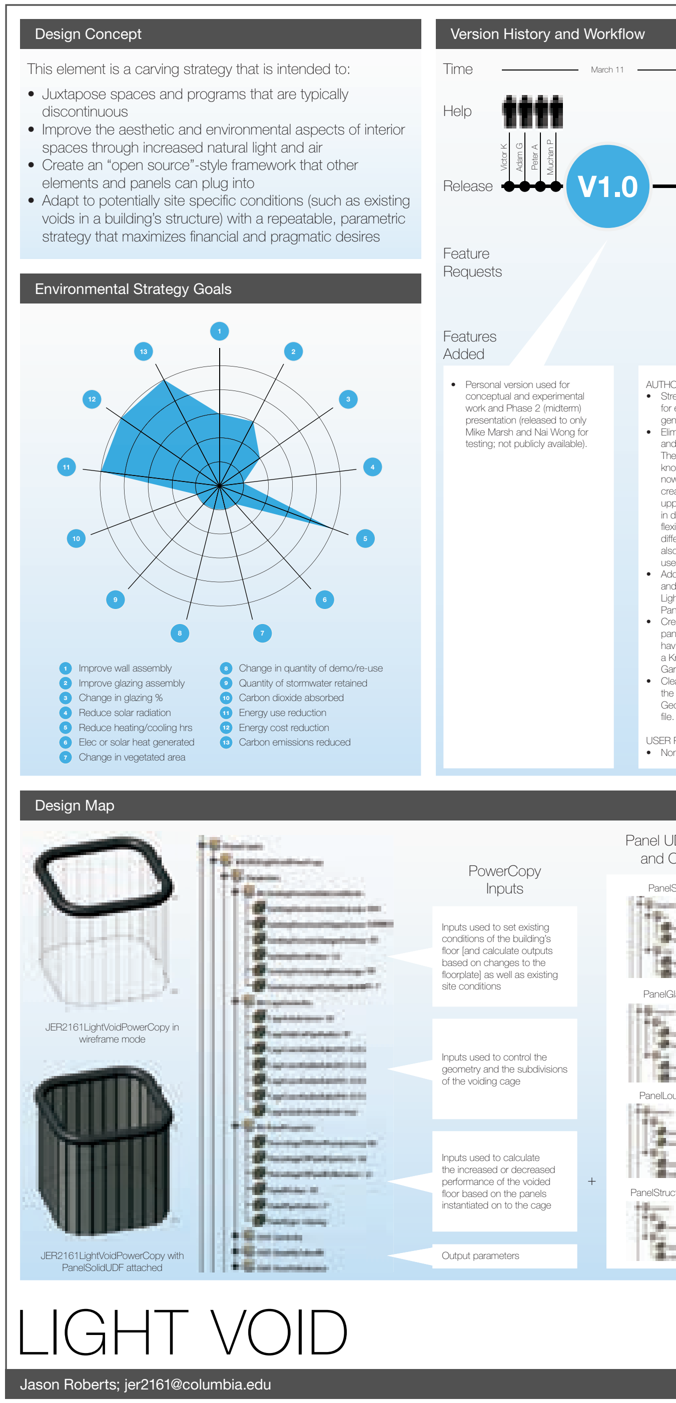
Cities around the world have begun developing ambitious programs with specific goals and timeframes to make tangible progress in addressing global climate change. As one example, PlaNYC was initiated in 2007 with the target of reducing carbon dioxide emissions in New York City by 30% by the year 2030. Because of the density of NYC, buildings make up 75% of the city's overall carbon emissions. The advances made in high-performance design and engineering will keep new buildings from compounding this problem. However, 85% of the buildings that will exist in NYC in the year 2030 already exist today, so as in most cities, the greater challenge is not the design of new buildings but how to adapt the existing building stock to current standards. This challenge was the program topic of research for the C BIP Studio.

As a systematic approach to addressing energy mitigation and in order to address the greatest number of low performing buildings in the city, representative building types were determined through an urban analysis using numerous relational data sets and parameters taken from the PlaNYC program. These parameters included buildings larger than 50,000 square feet (SF) and buildings built before 1990, the time period when energy performance became a more important design concern. This analysis resulted in six building types that collectively represented just over 37% of the total building SF in New York City, but more importantly, these six types represented 87% of the building SF of buildings within our targeted building profile. These types included glass towers, schools, lofts, mid-rise residential, high-rise residential, and public housing. A representative building was chosen from each of these types as a case study site for the studio.

Much of the building adaptation work to address energy mitigation occurs with little or no architectural or urban effect—upgrading building systems, increased insulation on perimeter walls, window replacement, etc. Students were made aware of this but were also asked to explore how to leverage the resources that would be dedicated to this effort to design adaptation strategies that would affect the urban landscape. The following environmental metrics were used to direct this effort: increased daylighting, reduced heat gain or heat loss, quantity of water stored and re-used, change in vegetated area, electricity or solar heat generated, improved ventilation, and reduction in construction waste.

DESIGN AND RELEASE – THE C BIP STUDIO WORKFLOW

Unlike a typical studio in which students work alone and produce one-off designs, the C BIP Studio employed a *design-and-release* model based on sharing. Over the course of the semester, each student authored a building Element (addressing a building part) that would be combined with Elements authored by other students to create a building Strategy (addressing an entire building). A single student designed the Elements in the first phase of the semester, and the Strategies were designed by a group of 3–5 students in the second phase. As the semester progressed, students would be simultaneously refining the design of their Elements while also working in a group to develop a Strategy.



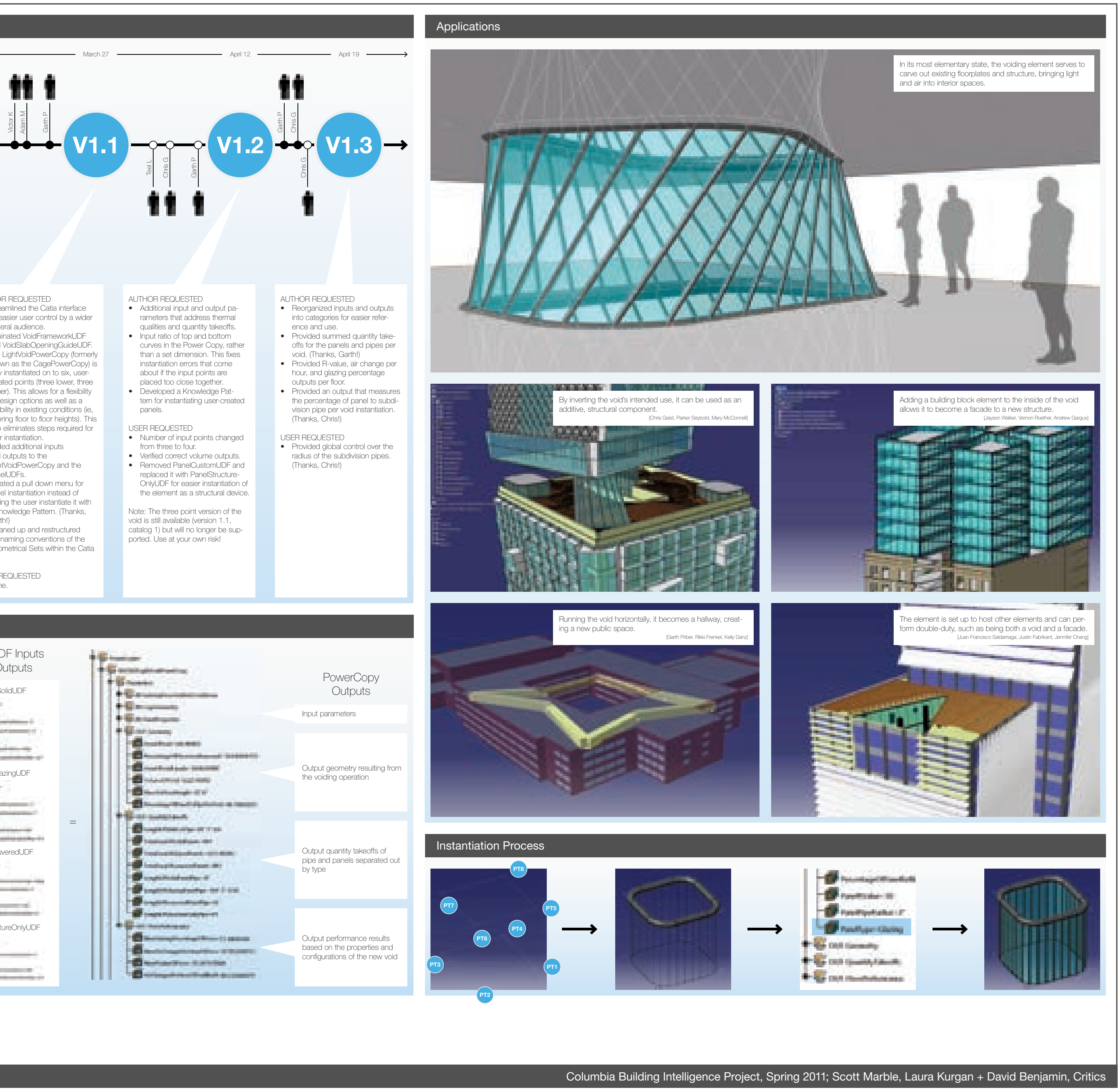


Figure 4: Sample Element

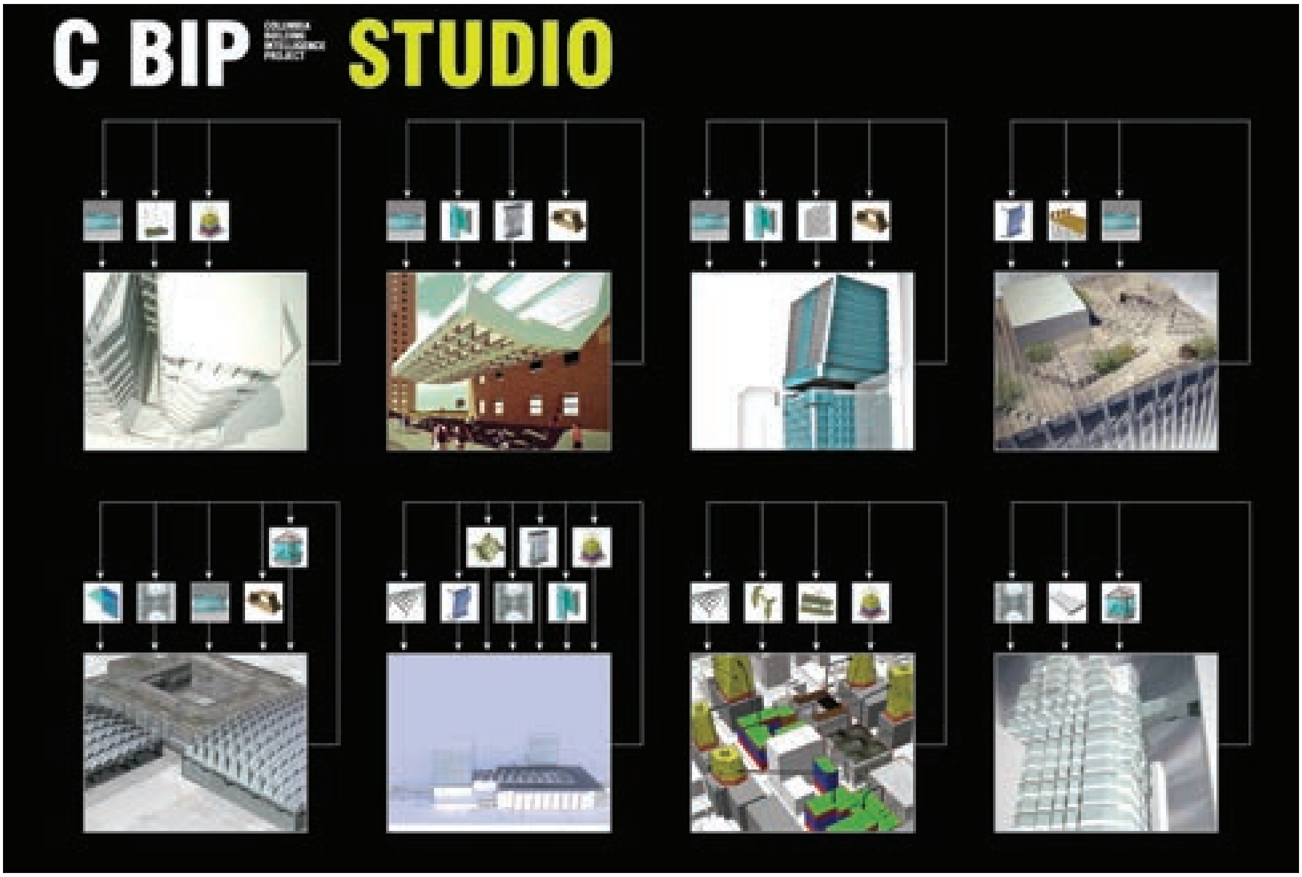


Figure 5: Element Updates

For the design of their Elements and Strategies, students utilized design, analysis, and production software currently used by the building industry for its most advanced projects. Taking advantage of the unique opportunities of academia, students explored BIM practices and parametric modeling techniques in novel and experimental ways to contribute to the broader research and development of new integrated and collaborative design workflows. The core software of the studio workflow was CATIA, a powerful parametric modeling platform originally developed for design and manufacturing in the aerospace industries by large distributed teams of engineers and now being used to design and construct complex architecture projects.

In addition to the three design critics, the teaching team consisted of several technical experts from local architecture, engineering, and consulting firms who developed and managed the digital workflow for the studio. These outside consultants also brought industry expertise in other areas including architectural detailing, structural engineering, environmental engineering, and software interoperability. Over the course of the semester, students became fluent in CATIA as the common platform for structuring the exchange of design ideas with others in the studio through shared parametric models. Students also learned to use SVN (a version-control system for managing and sharing current and past versions of files) and SBA (an arbitration system for resolving conflicts in design goals), along with multiple methods for building simulation (including finite element analysis, computational fluid dynamics, and environmental analysis) for evaluating the performance of design iterations. By utilizing these new advanced modeling tools and structured design workflows, students were able to create robust, adaptive parametric models that set the foundation for the most important objective of the C BIP studio: *sharing design intelligence*

PHASE 1: ELEMENTS

Elements were designed by each student in CATIA in response to their research on energy use and the particular NYC building type selected as a site. In this first phase, Elements were designed as prototypical, based on generic building conditions with maximum flexibility to adapt to more specific building conditions during the Strategy phase. The studio took two approaches toward energy-related building adaptation: the mitigation of energy use and the harvesting of energy. To focus the work students chose one of three building conditions to address: facades, roofs, and courtyards. Beginning with the design of generic building components, the students adapted their designs to each other's and to a series of selected buildings, urban conditions, infrastructures, and scales. The goal was to invent architectural solutions to energy mitigation and harvesting in existing buildings that were at once speculative, experimental, innovative, and technically feasible (fig. 3).

As parametric models, Elements were structured with specific inputs and outputs that were an essential part of the author's design intent. Inputs had to give users sufficient flexibility to explore many design options without being too open-ended. Outputs had to provide users with useful information to be able to assess results. Outputs consisted of both geometry (visual images that architects typically use to qualitatively evaluate results) and numbers (metrics that give quantitative aspects of the results).

In anticipation of Phase 2, where Elements would be combined to form integrated Strategies, students (as Element authors) were asked to exchange early versions of their Element design with at least two other students (Element users) to get feedback on usability and overall design capacity. Users were encouraged test the limits of the Elements to get unexpected outputs and even to "break" the Elements if possible. This step proved valuable in making sure the Elements were designed to be robust, and in providing authors with new ideas about how to expand the functionality of their designs. As part of the exchange, students were also required to combine two Elements together so the numeric outputs from one served as the inputs to another. This was the initial step in understanding how Elements could link together to form a Strategy. It also emphasized the point that, by definition, Elements should be conceived as "incomplete" and reliant upon other Elements to realize greater design potential.

At the conclusion of this phase, v1 Elements were packaged and uploaded into an Element Library for use in the next phase. These early versions became referred to as "low-res" and often emphasized the overall functionality to generate useful numeric outputs over fully developed geometry, with the understanding that users would want more control over geometry and appearance. User guides were attached to each Element explaining the authors design intent and providing users with step-by-step instructions on using inputs and outputs (fig. 4).

PHASE 2: STRATEGIES

In the second phase of the studio, students formed into small groups, selected a NYC building type based on research from PlaNYC as a "site," and began developing ideas for a building Strategy. As the student groups were developing concepts, they would search the Element Library for Elements that related to their design intent. As groups would start to test Elements on their sites, they would discover limitations in an Elements functionality that would require updates in order to develop their design. Two important rules of the studio structured this process—the first was *that updates to Elements could only be done by the original author; the second was that groups could not use an Element authored by one of its group members.* These rules greatly expanded the exchange of Elements and overall sharing of ideas, as each student would be working with their own group to develop their Strategy while also working indirectly with several other groups who had selected their Element for use in the design of their group's Strategy. Following techniques of open source software development, student groups were able to experiment with and suggest specific updates to any Element they might want to use in their Strategy, but were required to follow mutually agreeable protocols in getting these updates executed (fig. 5).

The objective of designing Strategies instead of solutions was to encourage students to exploit the parametric capacity of their work so they could be applied to the greatest number of buildings within their chosen type. For instance, the inputs for the Strategies were variable and could adjust to the specific conditions of different buildings, allowing the Strategies to be reusable beyond a single site. With this approach, a limited number of Strategies could be applied to the greatest number of buildings, resulting in a more significant impact on the PlaNYC goal of a 30% reduction in carbon emissions by 2030 (fig. 6).

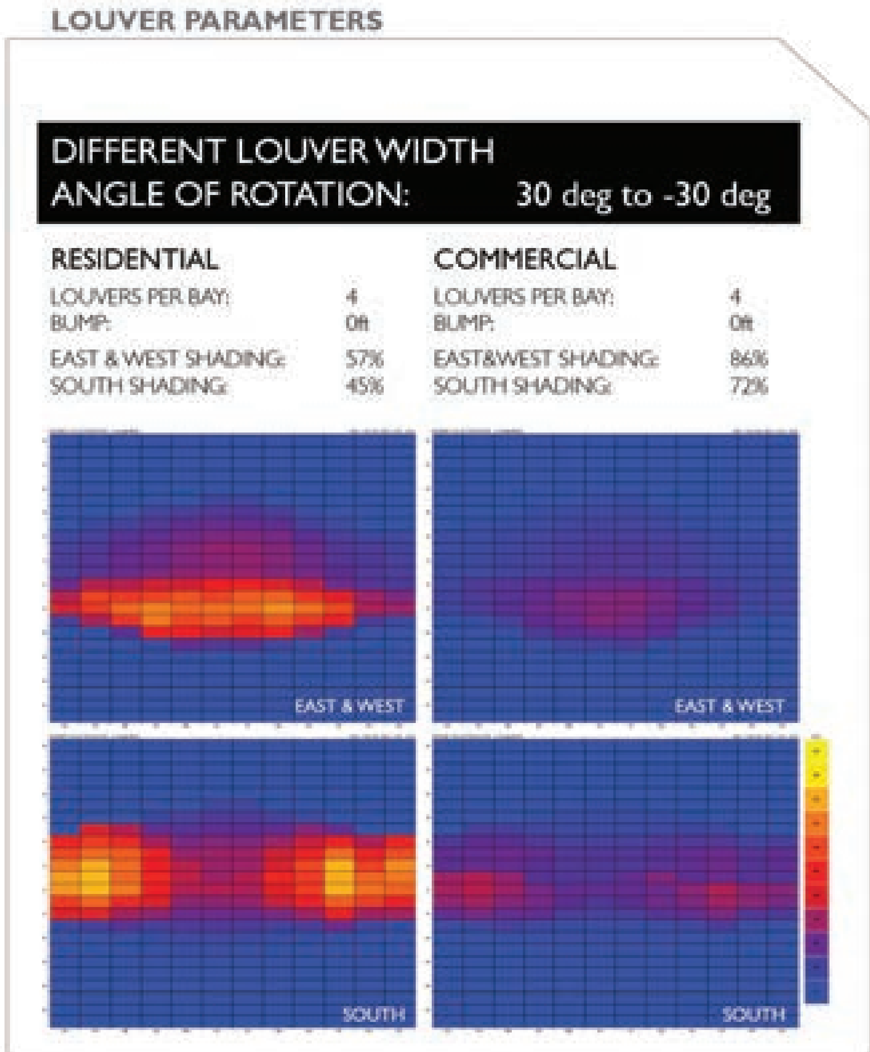
The most successful Strategies were able to get multiple Elements linked together in a fully integrated model where the fewest number of inputs could generate the widest range of design outputs. These outputs were presented as dashboards that included visual images along with numeric and graphic readings of quantitative information about the design. For both Elements and Strategies, results were iterative, meaning that there was no single solution, but rather multiple iterations based on different inputs (fig. 7).

At the conclusion of the three-year pilot period, the C BIP Library contained over 100 individual Building Elements and over a dozen integrated Building Strategies.

SHARING AS A NEW MODEL OF DESIGN STUDIO

The technical protocols of the C BIP Studio created a powerful incentive for students to understand the structure of collaborative work. Students quickly realized that *the success of their own work relied on the success of their peer's work.* This created a unique social dynamic that added unfamiliar factors into their typical design process. For instance, during the Strategy phase of the studio, students would have to manage their time and their aspirations between contributing to their own group Strategy and updating their Elements from feature requests from other Strategy groups.

TRIAL 4: +TWIST



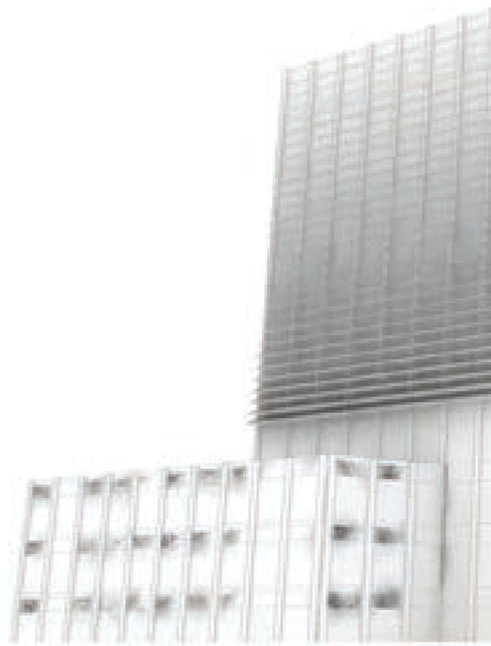
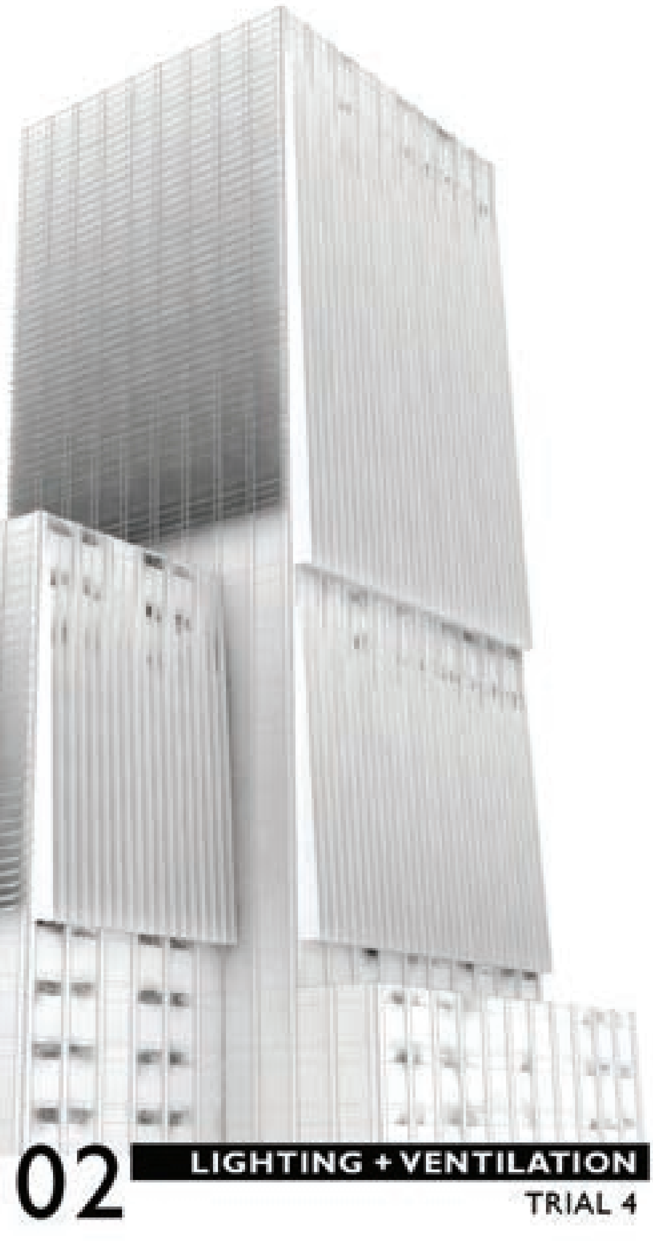


Figure 6: Sample Strategies

The incentive for focusing on the later was that if their Elements were being used by several groups, their impact on the total studio output would be greater as they would indirectly be part of several groups instead of just one. This was especially the case for students who had very popular Elements. On the other extreme, when an Element was not being used by any group, the author would have to decide whether to put more of their time into their group Strategy or try to revise their Element on their own to be more appealing to users. In general, Elements that were more formally generic and functionally robust were more popular among groups. Some of the most popular Elements over the three-year period were those that were purely operations. For instance, one of the most popular Elements, *Light Void*, simply created slab cutouts in existing floor plates, which could be utilized by groups in multiple ways for different programs.

In the second and third year of the studio, when students could choose Elements authored by students from previous years as well as those authored by their current studio mates, they tended to use Elements



from their current studio. This reinforced the importance of face-to-face exchange when engaging in a creative process like design, even when everything is online. The previous year's Elements, however, did have a cumulative impact on subsequent studios in that students started to be more ambitious with the design of their Elements because they realized that they had to build upon past work and not repeat Elements that already existed in the Library. This awareness of the Elements from previous years indirectly encouraged better design.

CONCLUSION

Design studio is deeply entrenched in architectural education. Entire curricula revolve around the structure and content of studio, and it is the cultural and creative anchor of architectural schools. It is a teaching model that is the envy of educators in its ability to be both structured and open-ended, where students learn as much from each other as they do from an instructor. The challenge for educators is how to evolve studio so it not only stays current with, but stays ahead of, the profession that it serves. Exploring the full potential of digital design and communication technology and how it can expand the design capacity of our students is one part of addressing this challenge. It is a missed opportunity to casually position digital technology as just tools. Technical skills and design skills are becoming intertwined as part of a complex workflow requiring a new mental agility among designers to move fluidly between qualitative and quantitative thinking. One does not enable the other, but rather, they work in tandem.

The challenge for the profession of architecture is whether we will take a back seat in the development of these new workflows and remain on the receiving end of a professional infrastructure that will increasingly set the ground rules for how we practice, or alternatively, whether we become proactive in the design of this infrastructure. This covers both the tools that we use to design and the organizational structure of our professional relationships. How this challenge is met will be determined by how architectural education engages with industry and how bold we are as educators in pursuing curricula that prepares students to lead in this long-overdue change.

ENDNOTES

1. James Surowiecki, *The Wisdom of Crowds: Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations* (New York: Doubleday, 2004).

2. Eric S. Raymond, *The Cathedral & the Bazaar: Musings on Linux and Open Source by an Accidental Revolutionary* (Sebastopol, CA: O'Reilly Media, 2001).

3. Robert Axelrod, *The Evolution of Cooperation* (New York: Basic Books, 1984).

C BIP PROJECT CREDITS

C BIP Studio Director: Scott Marble

Design Critics: Scott Marble, David Benjamin, Laura Kurgan, Janette Kim

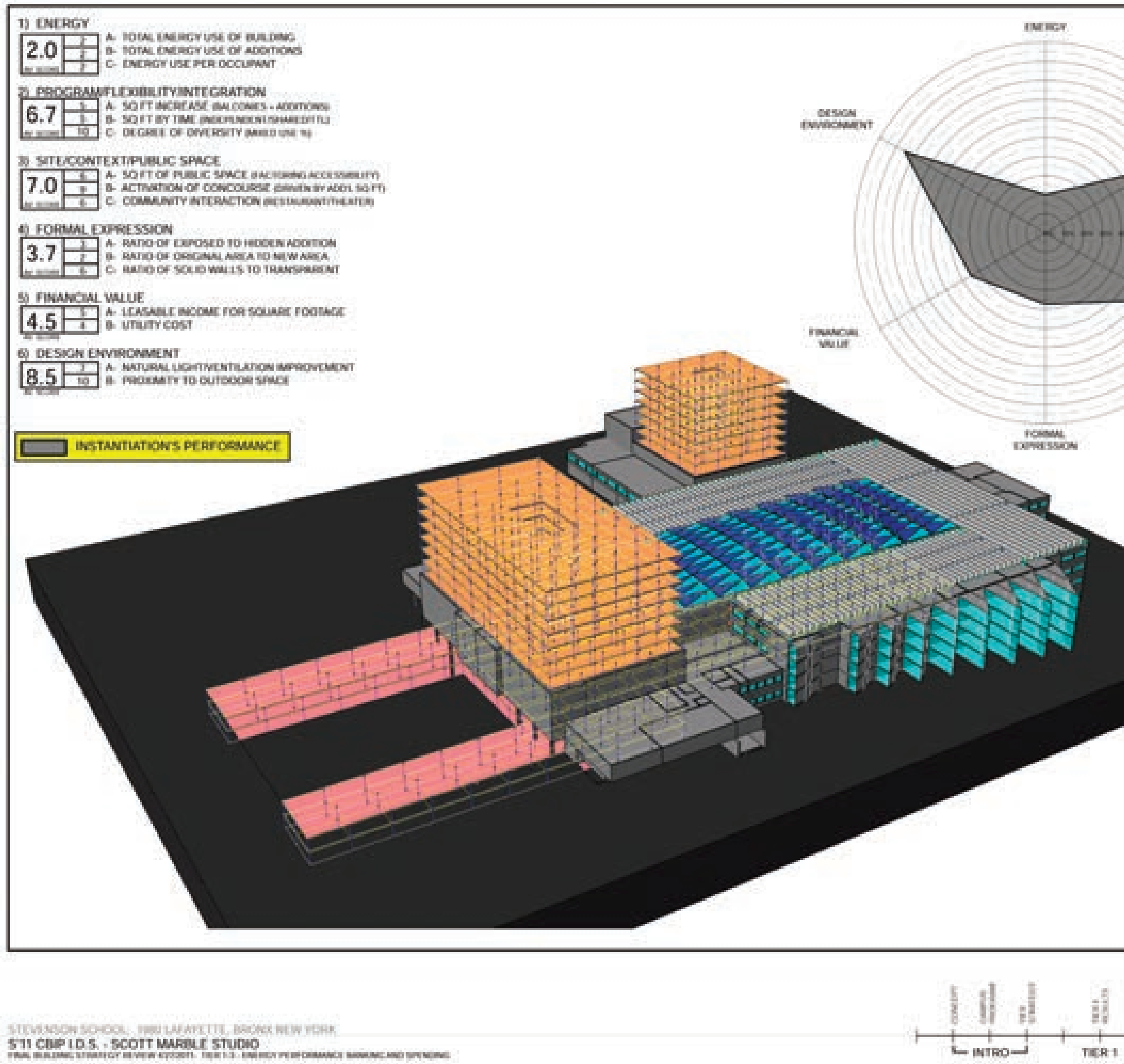


Figure 7: Dashboards

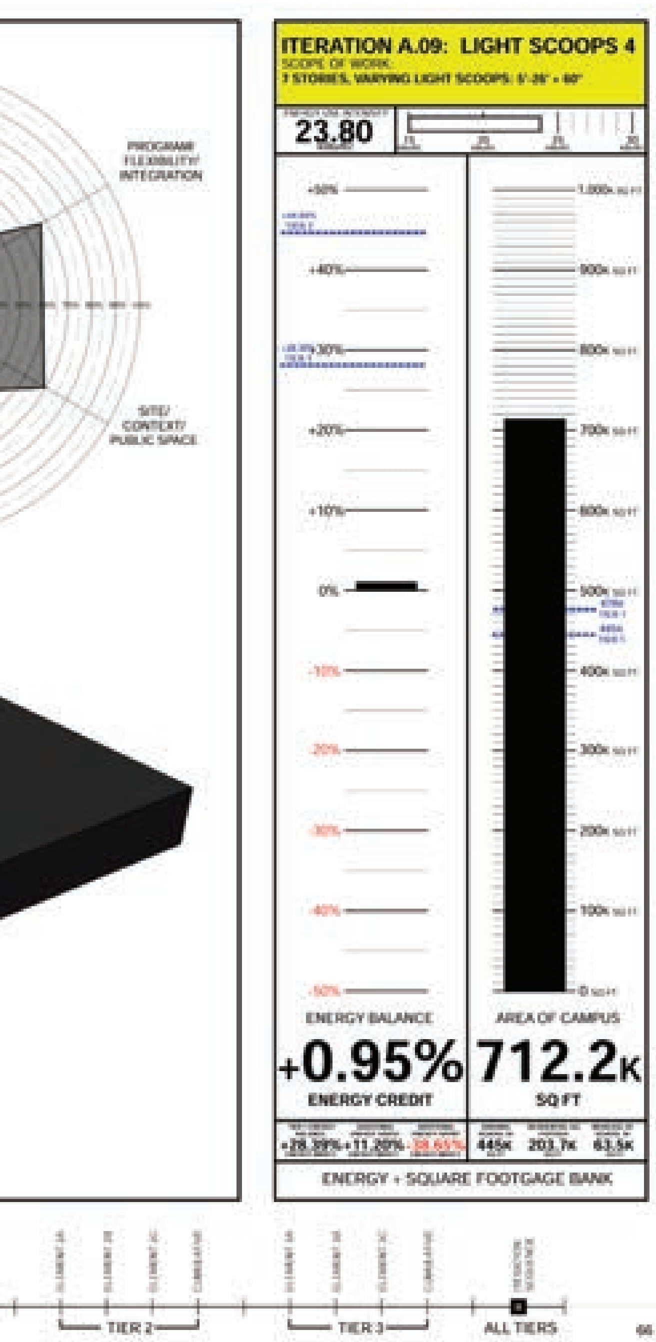


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IMAGE CREDITS

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Image 3: Juan Francisco Saldarriaga

Image 4: Jason Roberts

Image 6: Ardeshir Aliaskari, Jennifer Chang, Justin Fabrikant, and Juan Francisco Saldarriaga

Image 7: Jason Roberts, Nai Wong, Michael Marsh, and Michael Marvin

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MATERIAL

Scye: Material Form Technique

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The project, titled *Scye*, was produced by ISSSStudio as a commission for the 2015 Tallinn Architecture Biennale's main exhibition "Body Building." Curated by Estonian architects Siim Tuksam and Sille Pihlak, the exhibition brought together the work of ten international practices: Atelier Bruno Juricic (Croatia), Tom Wiscombe Architecture (USA), Kokkugia (Australia), Marjan Colletti (Austria), Julia Koerner (Austria/USA), Carlo Ratti Associati (Italy), nformations (Austria), City Form Lab (Estonia/Singapore), Achim Menges/ICD+UTKE (Germany) and ISSSStudio (USA). According to the curators, "Body Building" takes a look at hybrid forms of construction that combine cutting-edge technology with self-driven variability of material systems, thus exploring the balancing acts between the computational and the physical as well as between the unruly and the unpredictable.* Upon the curators' invitation to partake in the exhibition, it became clear that what brings this diverse group of practitioners together is the extensive use of physical objects—prototypes, models, mockups, full-scale fabrications—as integral to all of our digitally driven design methods. Curatorially the exhibition was to reflect this commonality by focusing on such objects, presenting to the broader public a range of possibilities for material output in architecture via digital technology. For ISSSStudio, this was an opportunity to further develop our design work with biodegradable plastics, a stream of research that we have been pursuing in various forms since 2011. Rather than treating the commission as simply an exhibition of artifacts related to other building-scale projects, the aim was to treat it as a project in its own right.

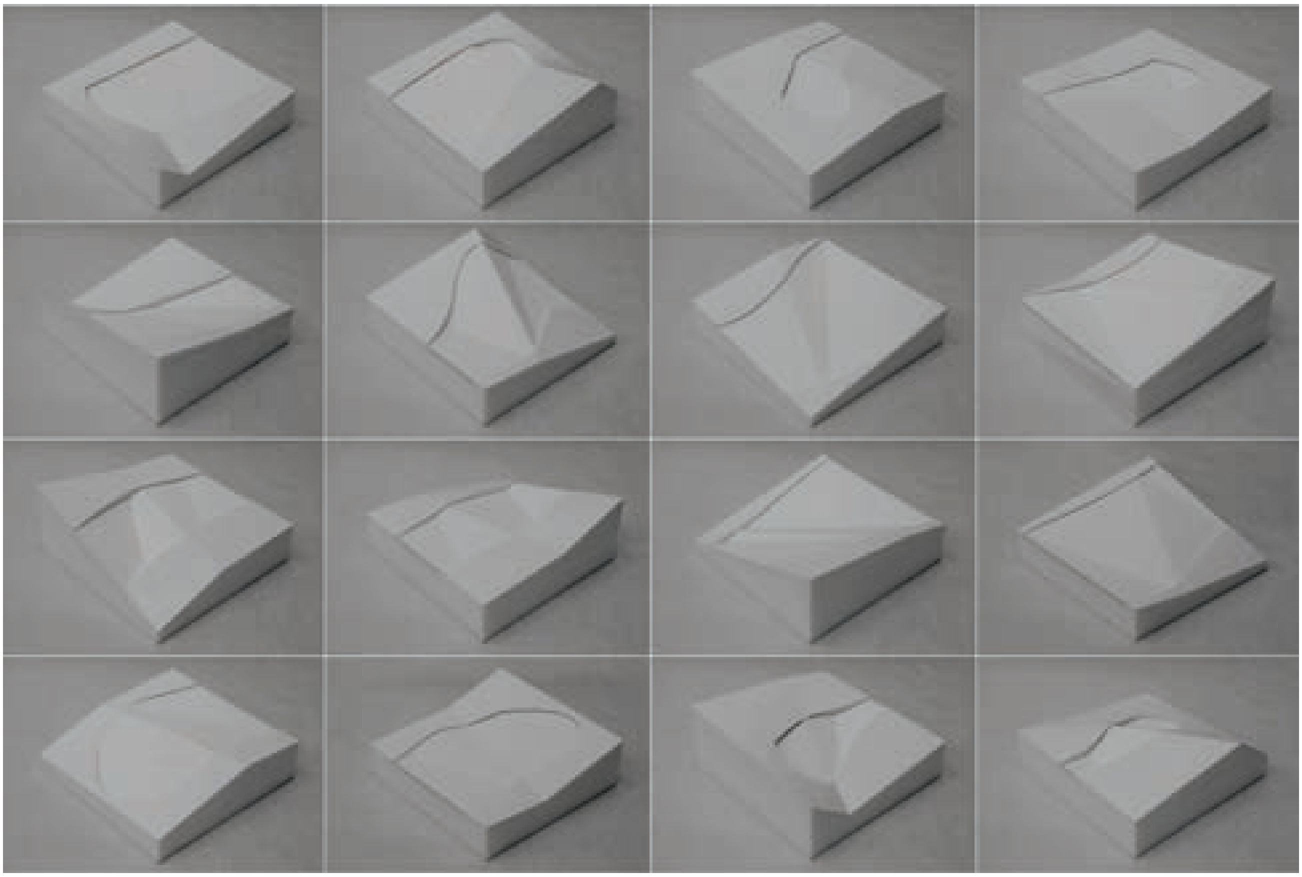
From the outset, we took into account a number of objective considerations that constrained the project and framed those as a reality to which we could respond to through our design. We knew that the project had to travel long-distance on a limited budget, which directly informed its size and weight relative to shipping conventions. We also knew that the installation at the exhibition was temporary, prompting us to engage with the question of the project's lifespan beyond the one-month display at the Estonian Museum of Architecture. These specific conditions—transportation, volume, weight, duration, lifecycle—shaped our design intentions in tandem with the curatorial direction and its relationship to ISSSStudio's larger body of work. Through a fabrication-driven process, the project's intentions coalesced into a design inquiry

Figure 1: Igor Siddiqui/ ISSSStudio, Scye, 2015. View of installation at the Museum of Estonian Architecture during the Tallinn Architecture Biennale.

about the interdependence of material, form, and technique. The outcome is an installation the size of a large architectural model, one that is less representational than it is relational in nature. In that sense it is constrained by size, rather than scale. The project is a three-part system consisting of a three-dimensionally tessellating base, a pair of translucent sleeves, and a series of freestanding objects (fig. 1). Each part considers its own set of specific material conditions investigated through its capacity to yield architectural form under the influence of production techniques. They are parametrically synthesized into a single system, constructing in effect an ecology of objects. As such, *Scye* can formally grow, evolve, and mutate over time through three specific operations: multiplication, extension and densification. The various materials that make up the overall system differentiate the parts in terms of how they may potentially circulate beyond the spatial and temporal footprint of the project. This brings us to the question that frequently preoccupies us in our work:

Where does material go?

The consideration of where material goes is twofold: it addresses the actualization of built form through material distribution, while also alluding to material lifecycles shaped by patterns of use, reuse, and disposal. As advancements in digital technologies continue to expand architects' ability to link design, fabrication, and assembly into new workflows, materials too have acquired a broader range of roles. With technologies like additive manufacturing, materials conform to the rule of data in ways that are evermore fluid, precise, and nonstandard. Meanwhile, increasing capabilities to digitally record, simulate, and reproduce materials' dynamic behavior are yielding new models of organization for architecture across multiple scales. The digitization of the design process has liberated architectural form from standardization, ushering the demand for material customization to the forefront of design innovation. Materials as such enter design not as fixed entities, but rather as pliable variables. Existing materials are remade to reveal latent character; new ones are made from scratch. In other words, materiality is not given but is rather designed, further expanding architecture's engagement with material resources and their circulation. The question of where material goes—but also where it is coming from—links a singular architectural project to the broader ecologies within which it operates. For us, the techniques for distributing materials relative to formal, structural, and



atmospheric demands of a single project have the potential to be expanded to encompass movement across larger territories and wider timeframes.

PART I: BASE

The base is a solid architectural volume with a footprint of 40 sf and thickness that varies from 1 to 10 inches. In plan, it is tiled in a 4-by-4 grid, creating a topography that is sectionally varied but continuous. Each tile, a three-dimensional block of recycled polyethylene, is a one-off and the tessellating pattern does not repeat (fig. 2). However, the tiles are organized into book-matching pairs; each pair nests to make a fully packed orthogonal volume which in turn maximizes the available space determined by the logistics of bringing the project overseas. As such, the base neatly packs into four 20-inch x 20-inch x 20-inch volumes, reflecting the largest permitting dimensions for checked-in luggage on commercial flights (fig. 3). While maximizing the volume, the aim was to minimize weight. For this purpose, we used light but relatively rigid polyethylene foam which commonly serves as packaging material. The digital script that allows for the volumes to nest when the parts sit on top of one another but book-match and tessellate when side-by-side produces a double-curved top surface constrained by a diagonal ridge on each tile. Because the volumes were designed not only to produce the base, but also to contain the other parts of the installation, additional geometries had to be carved into each block. Along the top surface of the base, a series of secondary, ruled surfaces is recessed into the blocks to contain folded out bioplastic sheets that make up the second part of the overall system, while eight of the blocks also contain pockets to hold the 3D-printed objects that constitute the third part (these pockets are cut into the underside of the base and are not visible when the project is on display). The blocks were fabricated using a 3-axis router, though a CNC-foam cutter would yield even more materially efficient results. The fabrication technique produces a satisfactory finished surface, but because we were limited to laminated material rather than solid blocks the top surface benefitted from another finished layer. We applied pliable white silicone sheeting to the double-curved areas; the developable parts of the surface were finished using rigid cotton board, laser-perforated at each interior seam for precision. All laminations between different materials were made using removable adhesive, so the layers could be separated for recycling. While this particular combination of the script with these material and fabrication techniques effectively yielded

Figure 2: Igor Siddiqui/ ISSSStudio, Scye, 2015. The series of nesting, book-matching, and tessellating blocks that together form the base of the installation.

Figure 3: Igor Siddiqui/ ISSSStudio, Scye, 2015. A diagram of packing procedures.

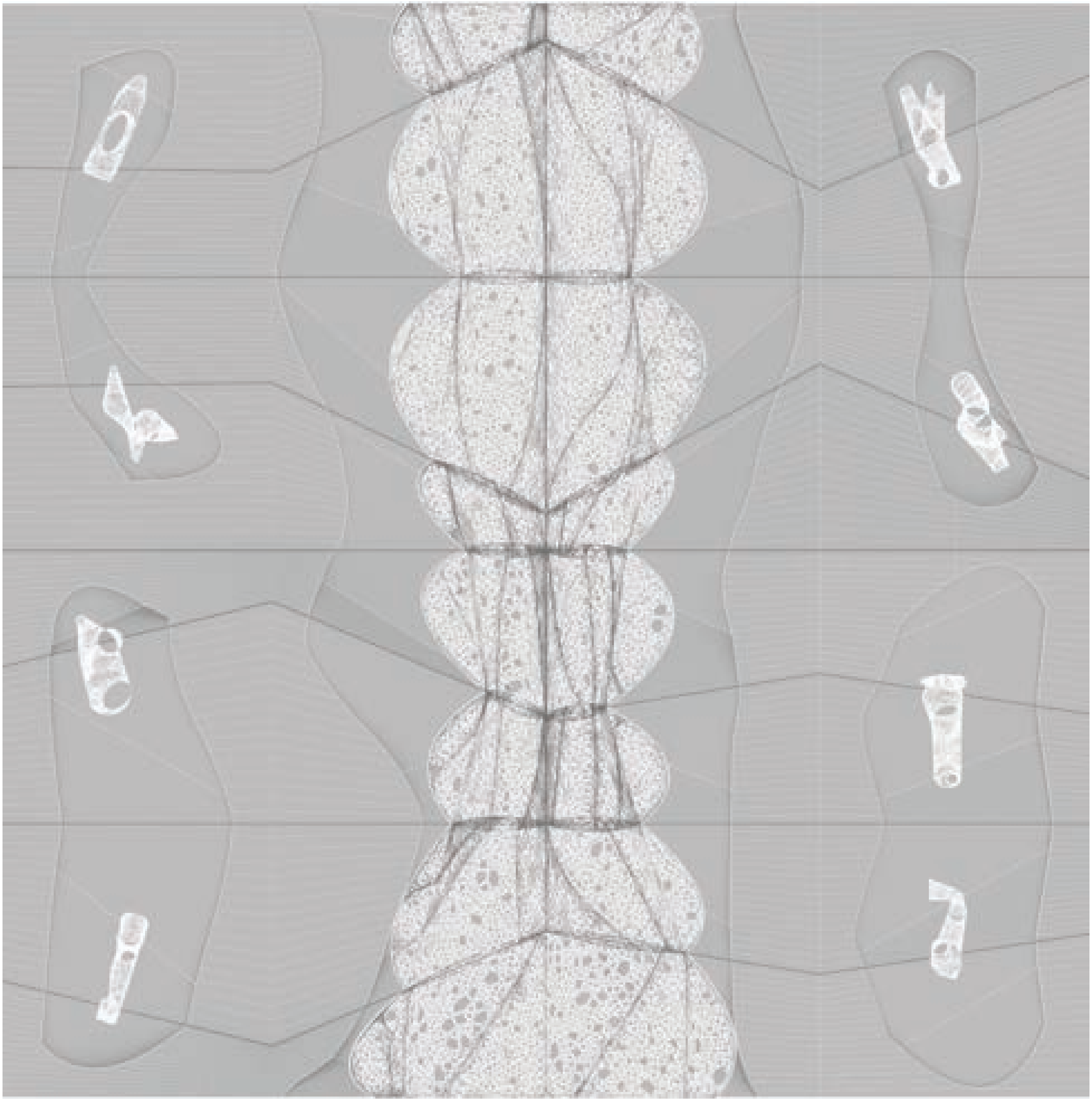
a ground condition, the process could easily be tailored for the design of a vertical system, such as customized masonry.

PART II: SLEEVES

Book-matching as a strategy also informs the arrangement of the 16 translucent bioplastic surfaces into two parallel architectural volumes that we refer to as sleeves. Organized along one of the center axes of the base, the sleeves are symmetrical in plan but not in section, a result of their relationship to the geometry of the ground (fig. 4). They are subdivided into overlapping surfaces, the seams of which align with those of the blocks beneath. In section the surfaces were generated as catenary curves with equal lengths; the range of profile geometries in controlled by the distances between their end points on the ground, from the center axis and out. The geometry was scripted to respond to the changing geometries of base and tested through different iterations. Because the surfaces were cast and shipped flat, the lofted catenary profiles had to be designed as developable, the process enabled by the D.LOFT plugin for Grasshopper. The outlines of the flat components were mapped back onto the surfaces of the base to create recessed pockets for storage, while the creases introduced in the blocks in order to make those surfaces developable were mapped back onto the translucent sheets. These vectors influence the propagation of the surface pattern developed for the project—the closer to the vector the denser the pattern. The patterns serves as a device for distributing the material throughout the casting process, resulting in both structural and atmospheric effects. As in several of our previous projects, these surfaces were fabricated from entirely custom-made biodegradable plastic cast in bas-relief formwork. We use a combination of animal and vegetable-based polymers to make thermoplastic, allowing us to control material properties that include rigidity, thickness, transparency, and biodegradability (fig. 5). While the plastic is designed to be entirely compostable, it is chemically stable, anti-microbial and, when used in combination with other biopolymers, water-resistant. Through the design of the material itself we are able to increasingly calibrate and control not only its architectural properties, but also its lifespan beyond the project itself. Because the fabrication process is based on casting, we are currently investigating multiple ways in which formwork can be engaged as an asset to the overall ecology of a project rather than as redundant and wasteful.

PART III: OBJECT SERIES

The series of eight objects situated at the sides of the base parallel to the bioplastic sleeves leverage the volumetric constraints of the project with the potential of the surface pattern as structural. Each object is constrained by the geometry of an envelope shaped by three distinct

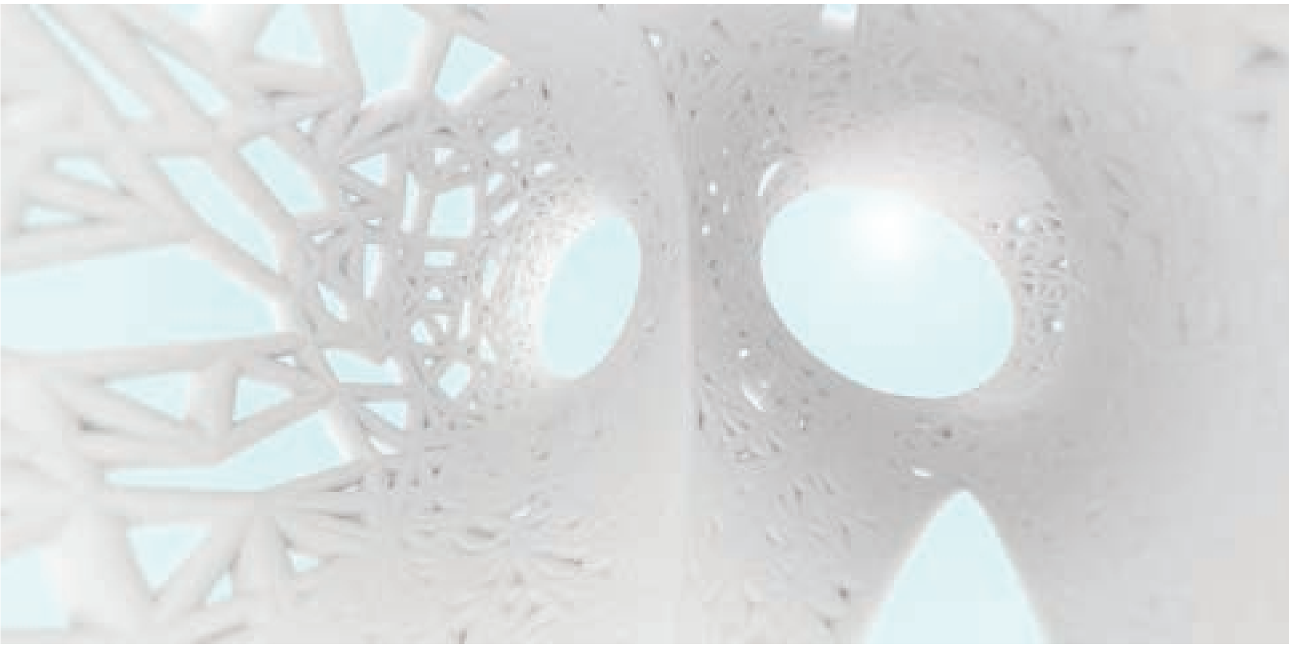


conditions: 1) the amount of volume available for its nesting within the base block beneath; 2) the size of the 3D-printing bed; and 3) the geometry of the topographic surface that it sits on. Within this volume, each object is an investigation into the morphology of sleeves produced not through pliable sheets, but rather through rigid tubes (fig. 6). The shift from surface to volume utilizes the pattern not as an entity inscribed topically, but rather as a generator for the architectural thickness itself. As with the two other parts of the system, the articulation of seams is specific to the interrelated conditions of material, form, and technique. How the material is distributed to yield each micro-structure is specific to the logic of layering inherent to the fused deposition modeling (FDM) method of 3D-printing, allowing for a structural mesh based on the interaction of strands in the pattern. Although designed as full-scale objects, the series alludes to its potential realization as building much like the way more conventional scaled models in architecture typically do (fig. 7). For us, considering them as scaleless

Figure 4: Igor Siddiqui/ ISSSStudio, Scye, 2015. Plan.

Figure 5: Igor Siddiqui / ISSSStudio, Scye, 2015. Detail view of bioplastic sleeves.

Figure 6: Igor Siddiqui / ISSSStudio, Scye, 2015. Detail view of 3D-printed objects.



but scalable allows us to speculate upon how such morphologies may be further developed through our future endeavors. While the other two parts of the systems are designed to be recycled and composted, the object series was designed as a collectible edition.

CONCLUSION

About the name: the project is titled after a term specific to the craft of tailoring, resonating thematically with the exhibition title, "Body Building." A scye is the seam that connects the top edge of a sleeve to the rest of the garment. As closed curves that circumscribe the area between the shoulder and the underarm, scyes—or armholes—are both joints and apertures. This condition resonates in architecture as it negotiates flatness with volume and dynamic movement with material. Both garments and buildings are membranes that surround us, yet to make a sleeve in architecture may not be the same as making a sleeve for the body. As far as tailoring is concerned, body is to clothing what ground is to architecture. The conjoined translucent sleeve in the *Scye* installation is defined by a series of parametrically differentiated sectional profiles tailored not to the vertical body, but rather to the horizontal ground plane. Like a scye's position relative to the body's hinge between the arm and the torso, these profiles coincide with the location of topographic shifts in the ground, articulated as expansion joints that register the movement underneath. In architecture materials appear static, whereas in practice they are always moved around and moving. As architects, we choreograph where materials go: perhaps more than ever we are now capable of shaping their trajectories in ways that are innovative, impactful, and otherwise significant.

ENDNOTE

* For further reference, see the exhibition catalog: Sille Pihlak and Siim Tuksam, eds., *Keha Ehitus/Body Building* (Tallinn: Estonian Centre of Architecture, 2015).

PROJECT CREDITS

Igor Siddiqui (Principal); Mitchell Peterson (Project Designer); Alex Wu and Heather Sutherland (Project Assistants).

Figure 7: Igor Siddiqui/ ISSSStudio, Scye, 2015. Rendering of object interior.

Almost Natural Things: Production and Aesthetics

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College of Architecture Art and Design

I would feel more optimistic about a bright future for man if he spent less time proving that he can outwit Nature and more time tasting her sweetness and respecting her seniority.[1]

–E.B White

INTRODUCTION

At the beginning of the 21st century, the chemist and Nobel laureate Paul Crutzen made popular what had been floating around within the study of geologic epochs for the latter quarter of the 20th century.[2] Crutzen indicated that the Holocene, the geologic era that had existed for almost 12,000 years has transformed into the Anthropocene. Aptly named, the Anthropocene has emerged out of the unprecedented influence of the human race on the planet's ecology. Crutzen also indicates that the Anthropocene is not as one might think, a 20th century phenomena, but it has its beginnings in the 18th century, propagated by the Western industrial revolution and the invention of the steam engine. In fact, scientists as early as the 1870s have begun to raise these issues with little success.[3]

The emergence of the Anthropocene and its unprecedented effects on the planet's ecology has forced the industries concerned with the built environment to confront what seems like a fundamental ethical responsibility. Examples of this relatively newly established attitude include the establishing of U.S. Green Building Council in 1993 with a mission to raise awareness about sustainable practices in the construction industry. This has been followed by the establishing of LEED in 2000, which is essentially a certification programme for the construction industry.[4]

This essay does not aim to expose the sins nor highlight the virtues of such practices; critics and supporters of LEED are spread the world over. The aim of this essay is to present an attitude towards environmental ethics and aesthetics vis-à-vis computational design technologies and non-linear fabrication workflows. More specifically, it describes a framework for an alternative and nebulous relationship between natural and synthetic things that can be just as relevant to the conversation surrounding architecture in the Anthropocene as mainstream green building practices are. This is also illustrated through describing a non-linear digital and material workflow that produces *almost natural things.*

Figure 1: New Information Centre of the CTU in AIR House on CTU Campus, Prague.

THE CODIFICATION OF SUSTAINABLE PRACTICES

Architecture, and the energy consumption that occurs during its construction and well into occupancy, should be held partly culpable for the environmental crisis.[5] This reality has led towards a reactionary stance from within the practice towards a search for an ethical consciousness through an obsession with issues of the environment. This has directly led to an emerging focus on *Sustainable Architecture.* Sustainable architecture has become a codified practice through the pervasiveness of certification programs such as LEED and off-the-shelf software that allow designers to predict many aspects of building performance early in the design stages. Pioneering figures in the movement such as William McDonough have praised the codification of sustainable practices in construction but noted that on its own, this cannot usher paradigm shifts.[6] While a paradigm shift of how we might build in the Anthropocene is absolutely and undeniably required, contemporary environmental ethics within large parts of the practice have transformed into aesthetic drivers, commercially driven marketing strategies, and a space from which other architects and designers not explicitly dealing with issues of sustainable design, energy consumption, efficiency and optimization are branded as unethical.

Almost two decades after the emergence of these issues, architecture must now *look green.* It has become more commercially viable for *looking green.* Apparently, it is the only right thing to do; looking green is ethically better.[7] This is not surprising given the popularity of the

relatively new field of study of environmental ethics, where the questions of how the public must conduct its relationship with things non-human has extended from an anthropocentric view point towards a more encompassing relationship between human beings and nature.[8]

Amongst a sea of grey, of which many architecturally innovative solutions are produced, contemporary architecture that can be said to have responded to this crisis head on falls into two radically different modes of practice. What this essay aims to expose is that both practices share two common problems when viewed within the lens of computation, digital fabrication and a post-Fordist globalized economy. Firstly, both practices continue to produce and propagate Modernist ideas of space conception.[9] An environmental crisis in an era of pervasive computation and ease of access to post-Fordist workflows has the potential to revolutionize the way we conceive of space and manifest it physically. Secondly, as ethicist Patrick Curry points out, these practices are simply *Light Green* or shallow. Adopting the idea of sustainability is in of itself is highly problematic because it implies a false desire to both exploit natural resources but do it in an *ethical* way that prolongs the problem in itself.[10] As of late, McDonough himself has begun to accept this fallacy through his conversations that revolve around the ideas *Beyond Sustainability.*[11] Due to its architectural outlook, this essay aims to explore the first issue of space conception in the Anthropocene.

CUSTODIANS

The first attitude in which architects have responded to the environmental crisis can be said to characterize what ethicist Patrick Curry identifies as Western culture's "faith in modern techno-science."[12] This practice adopts a highly codified and highly technical attitude towards sustainable practices which is geared towards efficiency, optimization and articulate tectonics in the form of off-the-shelf unit-to-whole assemblies; sometimes there is also a green roof. This results in an aesthetic that takes its cues from the high-tech movement of the 1980s and 1990s. Contemporary examples of this world-view include the U.S. Department of Energy's Solar Decathlon biennial student competition (fig. 1). The competition brief asks for projects that are environmentally friendly in innovative and positive ways (to produce net-gain energy), but also ones that are "attractive."[13] The question of attractiveness is highly problematic and one that is highly cultured and reveals the role of aesthetics within globalized power structures and economies. Specifically, the question of attractiveness has been transformed into a techno-fetishistic homogenous aesthetic agenda that is driven by the kind of materials that allow for positive energy production and their particular assembly processes. For example, the use of PV panels is abundant in these projects.

This attitude is undeniably anthropocentric. Its spreadsheet-fulfilling attitude, it highlights man-nature power structures, positioning human beings in the position of custodians of nature. That human beings can save the environment through the same power structure of domestication and custodianship that has led to this crisis is simply ironic. In their essay "The Future is Hairy,"[14] Jeremy Till and Sarah Wigglesworth have argued that architects can be hopelessly misguided in their aspirations and in their sense of morality, and perhaps more importantly, their sense of self-importance through writing that "the project to provide society's salvation through recourse to architectural honesty,

Figure 2: Digital images of early digital explorations.

Figure 3: 3D prints of early digital explorations.

Figure 4: Sit.1, resin-cast chair.

Figure 5: Photographs of the excavation process, post-curing.

truth, economy of means and precise tectonics appears deeply flawed and delusional."[15] More relevant to this essay is that this custodianship attitude fails in delivering a desperately needed new space conceptions given the emergence of the Anthropocene. Modernist space conceptions that blur interiorities with exteriorities into a continuous synthetic whole have to be transformed into a space conception that is *of* nature, and not simply an extension of it.

SCAVENGERS

The second practice avoids the Western model of techno-fetishism towards an immediate and direct reliance on natural and un-engineered materials driven by reclamation and repurposing. Architects and designers within this model scavenge their environments for materials that can be repurposed without much processing towards the construction of the built environment. Images of the scavenging Jawa from Star Wars' Tatooine come to mind. Where this practice of scavenging fails in relation to the practice of architects as custodians is its scalability factor. These exercises have tended to exist on the very manageable scale of the housing unit. Contemporary globalized economies and the housing and commerce requirements that come from that cannot be held captive to this slow and circumstantial practice.

As with the earlier custodian model and its consistent *green* aesthetic, this model is not without its aesthetic drivers either. Here, projects on the other end of the spectrum. There is not reference to the high-tech, but rather a very DIY aesthetic of multiple, different, and sometimes unfitting parts coming together to form a unique and unrepeatable whole, such as the Accordion House by 24H Architecture. The *indie* and DIY aesthetic cues of this practice seem to have an affinity with Burning Man events. Here, too, we might find green roofs and some PV panels, albeit less organized.

COLLAPSING ENVIRONMENTAL ETHICS AND AESTHETICS

The solutions to the environmental crisis that come from within architecture must confront the consistent and overarching aesthetic agenda that they produce. That a layman can point to a project and call it *green* indicates the strong visual markers that come with such solutions. Moreover, this subversive collapse of ethics and aesthetics is a very problematic trope as it begins to place aesthetic experiences as ones that have to be measured against an ethical criteria, which has historically not existed, not in the least in the field of environmental aesthetics. To put it in context, environmental aesthetics is a relatively new area of focus within the larger field of aesthetics that attempts to explore the aesthetic nature of things, conditions, and activities that are not art.[16] Essentially, environmental aesthetics began as a way to understand how to appreciate things that are not made by human beings. Lately, as art practices have begun to tackle

Figure 6: Detail of resin-cast chair.

Figure 7: Alternative resin-cast chair without the legs due to the high exothermic reaction.

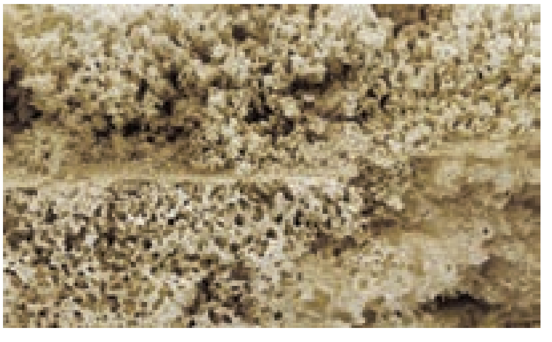

Figure 8: Shelter 0, Faysal Tabbarah with Architecture + Other Things.

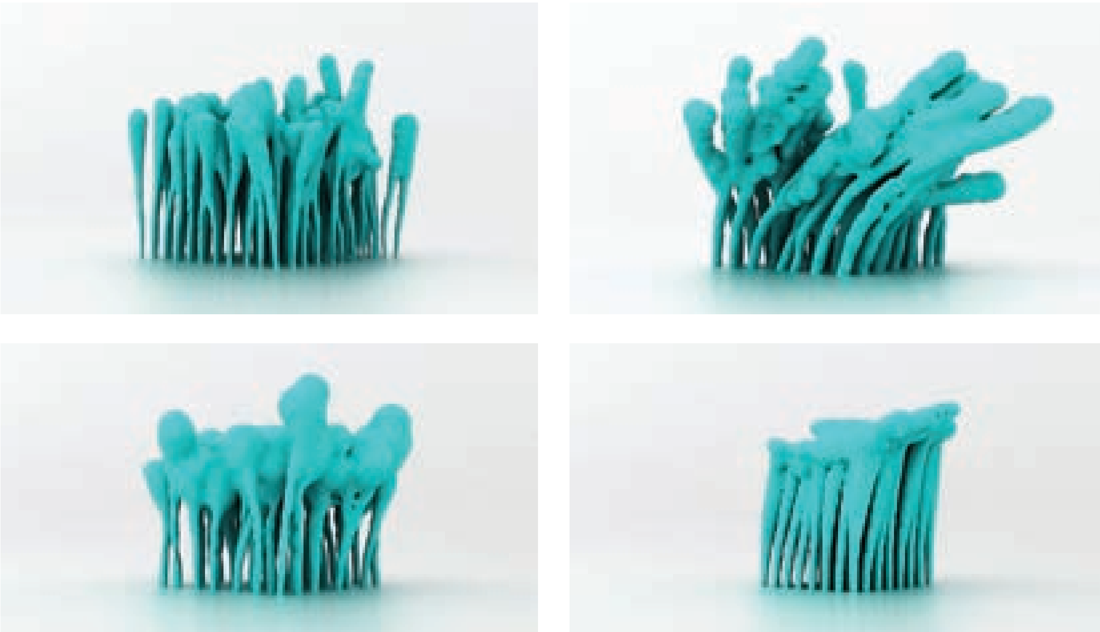

Figure 9: Digital images of early digital explorations.

the Anthropocene, beginning with the Land Art movement and well into the contemporary sphere, environmental aesthetics has also become concerned with "human-influenced" and "human-constructed" environments that are neither art nor possibly architecture.[17] While the emergence and contemporary importance of environmental ethics and aesthetics share an origin, which is the seismic shift from the anthropocentric to the eco-centric, they cannot coexist as they subversively but pervasively do in mainstream sustainable architectural practices.

What is relevant to this essay is the search for a new notion of environmental aesthetic vis-à-vis computation design methodologies and digital fabrication. This notion must move beyond the deployment of off-the-shelf software that more or less accurately predicts building performances within a Fordist assembly line towards an immersion in the possibilities of space within a globalized post-Fordist and big data society that is staring at an environmental crisis in the eye. It's a simple question with many possible answers: What kind of aesthetics must the spaces inhabit today embody?

Historically, there has existed three notions of aesthetics of the environment: The beautiful, the sublime, and the picturesque. Today, neither of these three notions begins to tackle the possibilities of a new and relevant space conception. This is because all three rely on a Kantian experience of nature as something that is *Other*,[18] only to be experienced as audience, and incapable of being truly part of an everyday life. A contemporary aesthetic of the environment must not be viewed, observed or critiqued as an Other thing that needs to be tamed, shut out or extended to. These binaries will force architects into a Modernist space conception that aims at bringing the environment in, or going out into the environment, but never coalesce the natural and the synthetic which is highly possible in an age of eradicated binaries given the new advances in computation, access to big data and post-Fordist manufacturing.

COLLAPSING NATURAL AND SYNTHETIC THINGS

When one experiences human-made art or natural landscapes, one understands the core idea of what is being observed; essentially, one understands whether the observed is natural or synthetic, even when the content is at times elusive, as it is wont to be. We rarely confuse the synthetic from the natural. This essay presents an argument for a new framework of environmental aesthetic experience that overcomes the historical and mainstream framework of the beautiful, the sublime or the picturesque, requiring a collapsing and blurring of the distinction between the natural and the synthetic. Questions like "is this natural?" opens the door for such a framework and aesthetic experience. This has begun to exist in art but is non-existent in architecture, as is it always conceived as the *built* environment.

As early as the 1950s, there has been a push within art to blur this distinction at multiple scales, from large scale Land Art to the traditional scale of the painting. The critique of the irrational difference and value society gives to things is perhaps best embodied by Duchamp's *Fountain,* although he has sought to blur the boundaries between two human-made things (art and ready-mades). What is more relevant to this essay is other extreme conditions, such as Robert

Figure 10: 3D prints of early digital explorations.

Rauschenberg's *Dirt Painting,* where the work of art at the scale of the painting, an endeavor that mixes synthetic and natural materials is constructed out of real dirt, collapsing the natural and the synthetic. How to translate this to a spatial condition is the long-term goal of this essay.

THE PRODUCTION OF ALMOST NATURAL THINGS

And with books I am just the same (just as clumsy and inarticulate) and they do not help me either, as though even they were still too human... Only things speak to me.[19]

–Rainer Maria Rilke

The essay concludes by illustrating the nebulous relationship between the natural and the synthetic through a series of materially produced things made within a non-linear fabrication workflow where computational tools are in constant communication with material science and chemistry. These things aim to express two main ideas: nebulous aesthetics and space conception.

First, the resultant aesthetic of these things moves away from the description of form towards the description of texture and intensities. It also allows for things to be obscure and to lie on the outside of the narrative of mainstream environmental aesthetics. More specifically, these things are not beautiful as they are messy, unwieldy and uncultivated, nothing like the French gardens of Versailles; they are not sublime as they lack the ability to threaten or intimidate as with the Grand Canyon; and they are also not picturesque as they do not attempt to evoke the vivaciousness of nature as in the paintings of Friedrich.

Second, the almost natural things produced within this framework are driven by a critique of Modernist and Fordist part-to-whole relationship that are utilized heavily in the above critiqued custodian model towards a looser idea of assemblages that come together in less linear and fitting ways to create highly textural formations that can be understood as almost natural things.

THE PRODUCTION OF ALMOST NATURAL THINGS: SIT

These almost natural things were first developed through the deployment of branching algorithms that were driven to amplify textural readings within compression-only structures. Early studies were the materialized utilizing 3D printing technologies to better understand their physical qualities. Due to the computational limitations of the process, these explorations lacked an extreme reading of texture over form. Moreover, these tests were initially conceived of as spatial conditions, but it became immediately apparent that they cannot be simply scaled up or made in parts to achieve a larger scale. Therefore, a new fabrication technique was developed that allows for the casting of resin into CNC-routed high density expanded polystyrene foam (figs. 4 and 5). The exothermic reaction that occurs during the curing process has resulted in a highly textured aesthetic that truly blurs the distinction between the reality that this is made synthetically and natural formations.

THE PRODUCTION OF ALMOST NATURAL THINGS: SHELTER 0

Shelter 0, the second of these endeavors, is conceived as an inhabitable shelter that attempts to explore the potential of recycled natural materials, in this case rubber, to create spatial conditions that attempt to redefine vernacular Arish (palm frond) desert shelters that were deployed during the hot summer months and utilized the natural material's qualities for passive cooling and shade. Similar to vernacular spatial conditions, *Shelter 0* defines space through the deployment of high-resolution textures, rejecting the definition of shelter as a solid, monolithic and perceptively stable. Here, the object is defined by the amplification of texture and not through the deployment of a normative attitude towards surface and mass.

Rubber tiles manufactured locally from recycled tires are the primary material system explored in *Shelter 0.* The material comes in 50cm x 50cm tiles and is usually used for exterior playground flooring conditions. These are cut into linear strips that resemble the raw form in which palm-fronds was used to make the vernacular desert houses. The result is a naturalistic and highly textured interior condition that collapses the distinction between the natural and the synthetic. Material tests were first tested and documented to understand the relationship between material dimensions, bending

Figure 11: Sit, Resin-cast chair.

Figure 12: Alternative resin-cast chair without the legs due to the high exothermic reaction.

properties and springiness. This information was built into a physics-based computational model that closely models the behavior of the material in order to design an appropriate material formation.

ENDNOTES

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11. "Beyond Sustainability – Cradle to Cradle: Science, Innovation + Leadership," McDonough Braungart Design Chemistry, http://www.mcdonough.com/wp-content/uploads/2013/10/MBDC-Brochure_4.25sq_130701.pdf.

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13. "The Solar Decathlon 2015 Competition," U.S. Department of Energy, accessed October 10, 2015, http://www.solardecathlon.gov/2015/competition.html.

14. Jeremy Till and Sarah Wigglesworth, "The Future is Hairy" in *Architecture: The Subject is Matter,* ed. Jonathan Hill (London: Routledge, 2001), 6.

15. Till and Wigglesworth, "The Future is Hairy," 15.

16. Allen Carlson, *Nature and Landscape: An Introduction to Environmental Aesthetics* (New York: Columbia University Press, 2008), 1–2.

17. Carlson, *Nature and Landscape,* 1–2.

18. Carlson, *Nature and Landscape,* 3.

19. Rainer Maria Rilke, Jane Bannard Green, and M. D. Herter Norton, *Letters of Rainer Maria Rilke, 1892–1910* (New York: W. W. Norton & Company, 1969) 122.

IMAGE CREDITS

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Figure 1: Photo via Wikimedia Commons: Gampe, CC BY-SA 3.0: https://commons.wikimedia.org/wiki/File:AIR_House_CTU_01.jpg

Figure 8: Photo by Farah Al Amin

Meander: Data Spatialization and the Mississippi River

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Molly Reichert
Dunwoody College of Technology

Daniel Dean
Minneapolis College of Art and Design

INTRODUCTION

Public art exists at the intersection of sculpture, architecture, and landscape, often integrating elements of all three, yet irreducible to any one discipline. The multifaceted nature of public art demands that it address multiple and sometimes competing imperatives, both conceptual and pragmatic, that continue to change over time. In recent years, these imperatives often include a populist dimension—public art is expected to engage a broad audience in accessible and legible ways (Knight 2008)—as well as the frequent mandate for "site specificity" and integration into the artwork's context (Kwon 2002). In addition to these conceptual aspects, public artists face a unique set of pragmatic and practical demands that can exceed those of a typical gallery or museum commission. Works of public art face much higher expectations for durability and longevity, and unlike architects, public artists can be directly responsible for both the design and construction of the work.

This paper explores these complex issues involved in the construction of compelling public art in the urban realm through a detailed case study of *Meander*, a public artwork completed in 2015 by the collaborative Futures North (fig. 1). *Meander* is a permanent piece commissioned for CHS Field, a new baseball stadium in the Lowertown neighborhood of downtown St. Paul, Minnesota. The artwork consists of fifteen sculptural pillars that creatively re-imagine over two hundred years of historical information about the Mississippi River, which runs several blocks from the site. The pillars are fabricated from custom cast glass fiber-reinforced concrete

Figure 1: View of Meander at dusk.

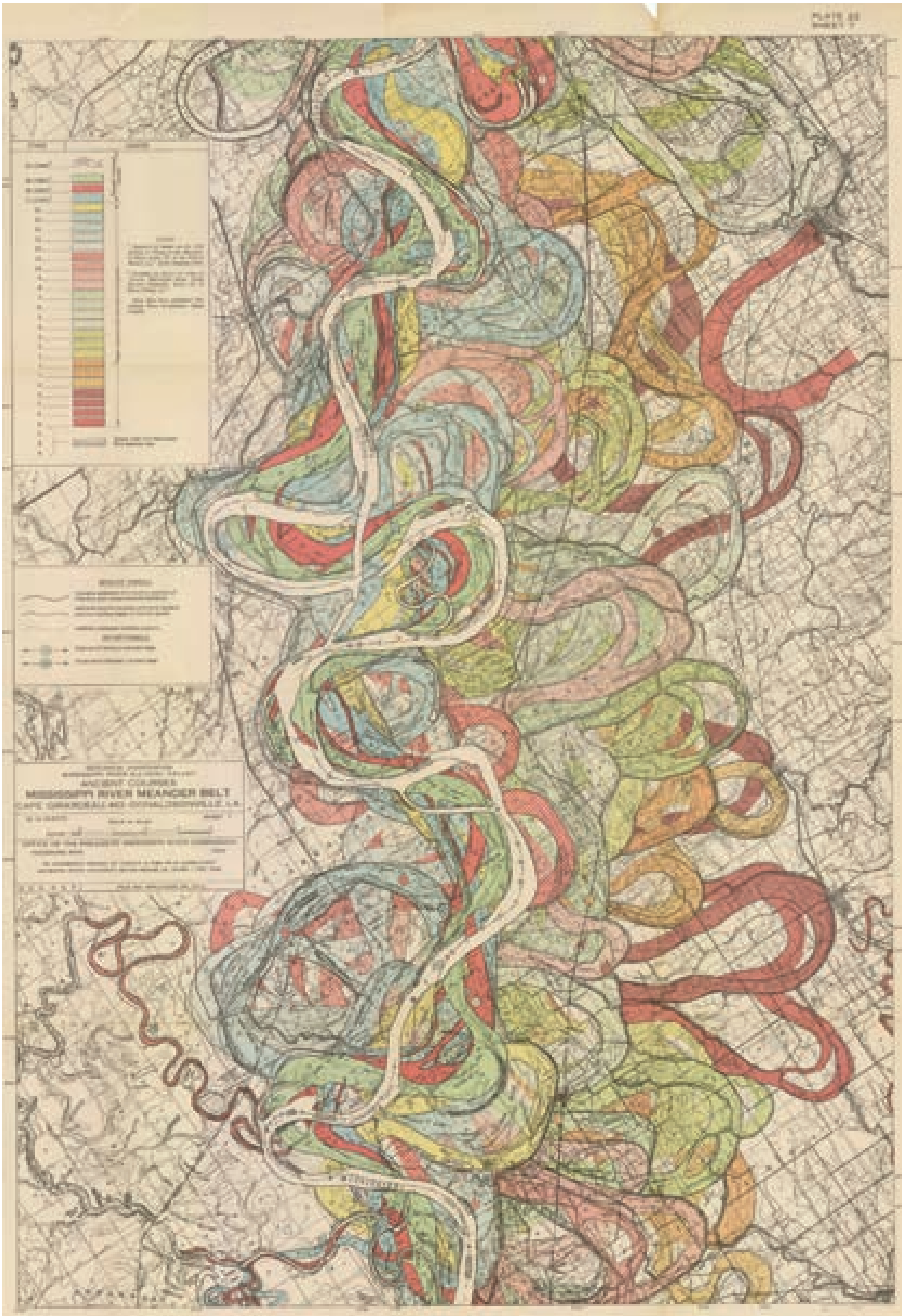


Figure 2: Harold Fisk, Mississippi River Meander Belt, Cape Girardeau, MO–Donaldsonville, LA, 1944.

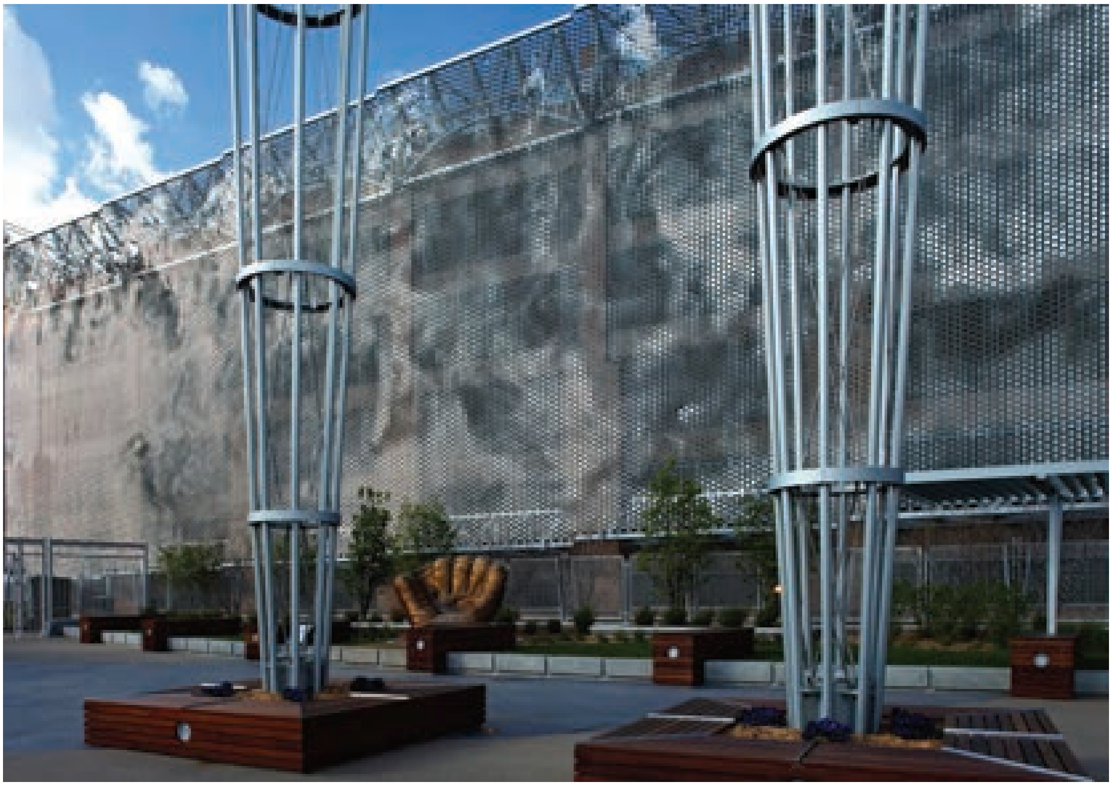


Figure 3: Ned Kahn, The Wave.

Figure 4: The Living, Amphibious Architecture.

Figure 5: Joseph Nicollet, Hydrographical Basin of the Upper Mississippi River, 1843.

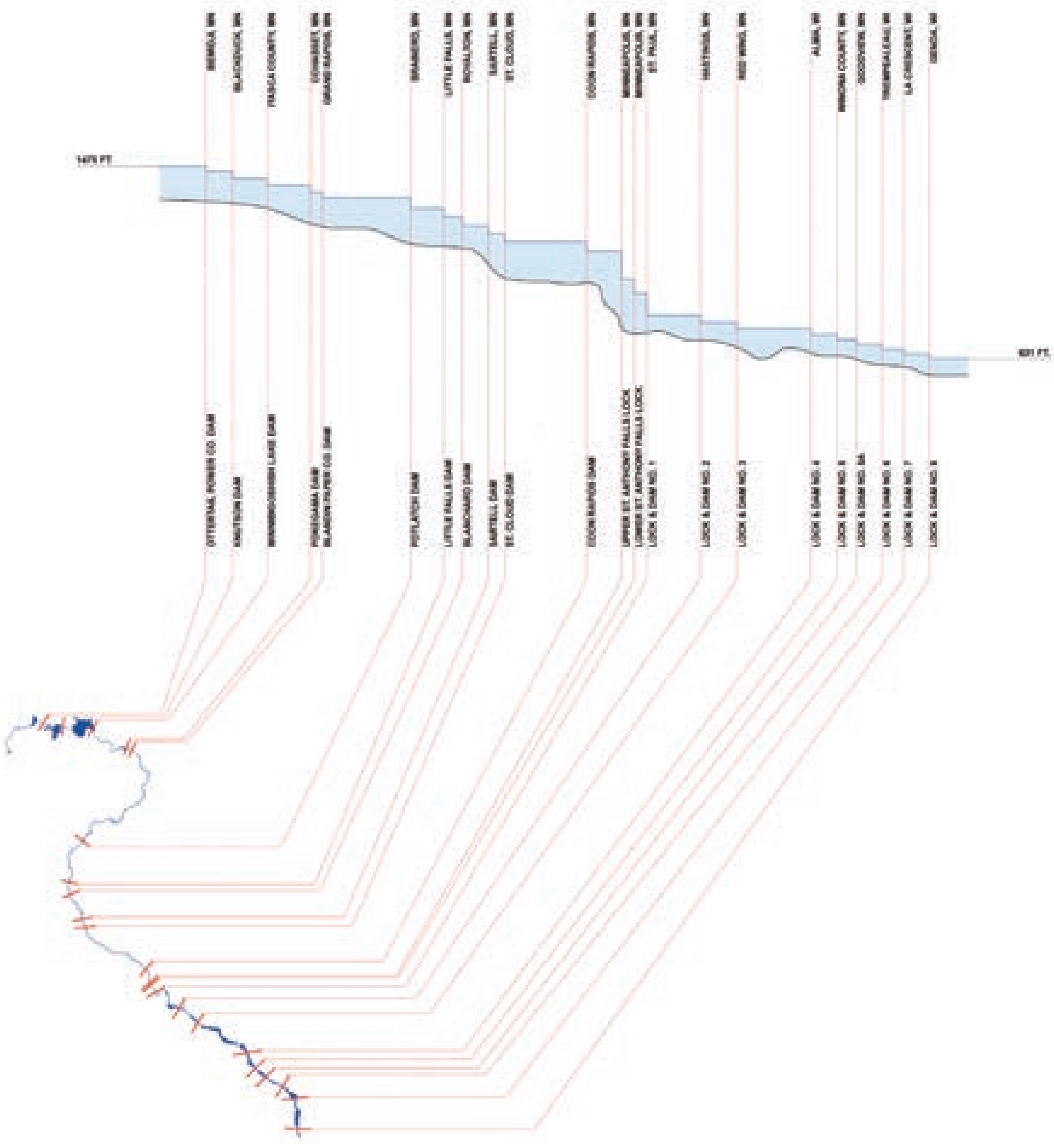
(GFRC) and capped with custom cast glass lanterns containing programmable LED lights that broadcast information about the river.

Through a detailed account of the design and construction of *Meander,* this paper argues that techniques of computational design and digital fabrication can be leveraged to address both the conceptual and pragmatic demands of realizing innovative works of public art. In particular, we discuss how the project is an exploration of what we refer to as *data spatialization:* a technique for mining existing data sets to inspire and design new formal and spatial constructions. Both the artwork's form and its dynamic lighting were designed with parametric modeling software and advanced computational processes that reinterpret the Mississippi River's geometry and environmental behaviors. The

Figure 6: Army Corps of Engineers, Upper Mississippi River, 1963.

Figure 7: Google Maps, 2014.

Figure 8: Section diagram of the Upper Mississippi, showing changes in the river's elevation and depth.



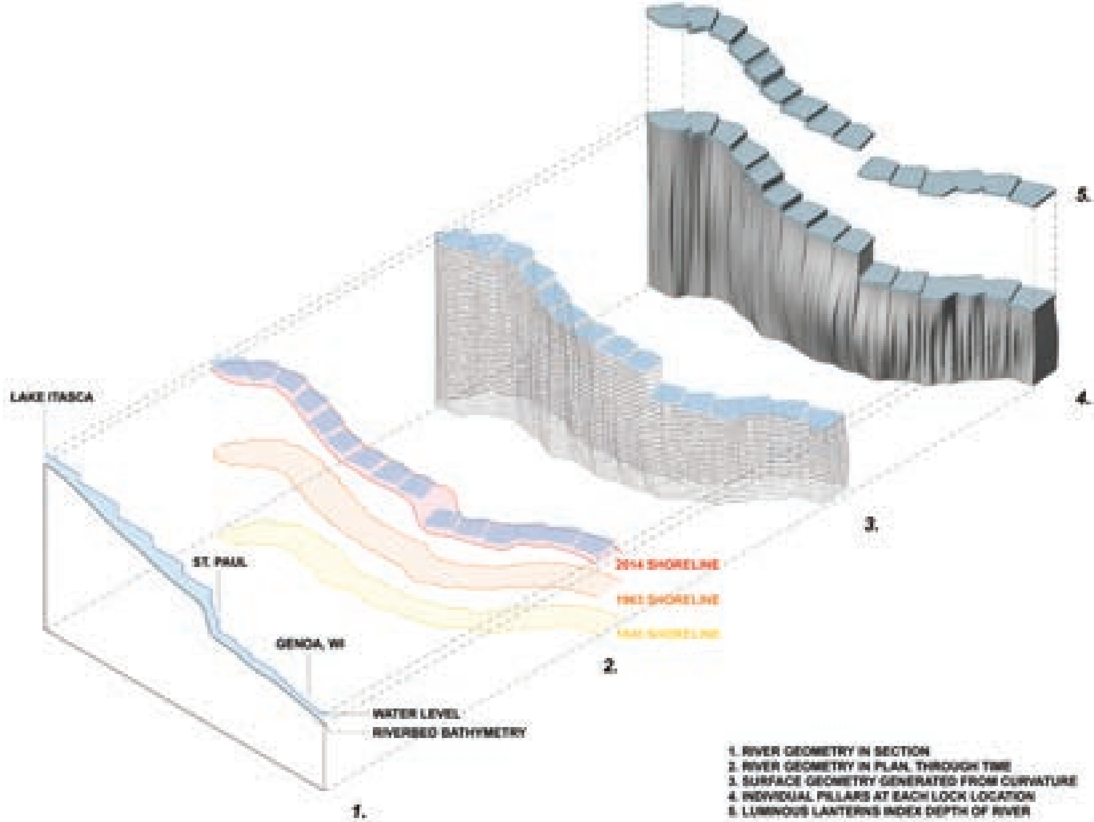


Figure 9: Diagram of design process, showing the translation of river data to sculptural form.

technique of data spatialization embraces a representational capacity while also grounding the project in its local context, thereby rendering the project both accessible and site-specific. And yet, the project's data-driven process paradoxically yields a degree of abstraction that ultimately precludes the artwork's immediate legibility as either a direct re-creation of the Mississippi river, or a fully integrated feature of the ballpark's architecture. In other words, *Meander* is simultaneously referential (it clearly represents the Mississippi and is recognizable as such) and abstract (the piece is not a perfectly accurate representation, because it uses abstracted data as the basis for its design).

Meander also demonstrates how computational fluency in the fabrication stage can enable a streamlined translation from design to construction, mitigating some of the pragmatic challenges of building interactive and complex works of public art. We utilized file-to-fabrication workflows and digital fabrication technologies to achieve complex curvature in both the concrete and glass elements, and we developed custom software to forge a link between the river's environmental data and the lighting controller. Digital processes are combined with the age-old materials of concrete, glass, and light to yield a hybridized materiality that is at once contemporary and rooted in traditional craft. The project leverages advanced technologies to shape raw, earthen materials of concrete and silica into a data-rich artwork that evokes the site's layered geographical and environmental histories.

PRECEDENTS

An initial inspiration for *Meander* was the remarkable set of cartographic drawings produced by Dr. Harold Fisk in the 1940s. These famous "meander maps" of the Mississippi River (fig. 2) were the product of an exhaustive mapping project that Fisk conducted on behalf of the Army Corps of Engineers, which sought to better understand the geological origins and evolution of the alluvial valley of the Lower Mississippi River (Fisk 1944). Fisk painstakingly documented the river's historical geometries through time, using color to code the significant variation of its course throughout its history. His drawings are entirely empiri-

Figure 10: View of Meander along CHS Field entry plaza.

Figure 11: Diagram of the water quality, wind speed, and water temperature datasets used to drive the artwork's light animation.

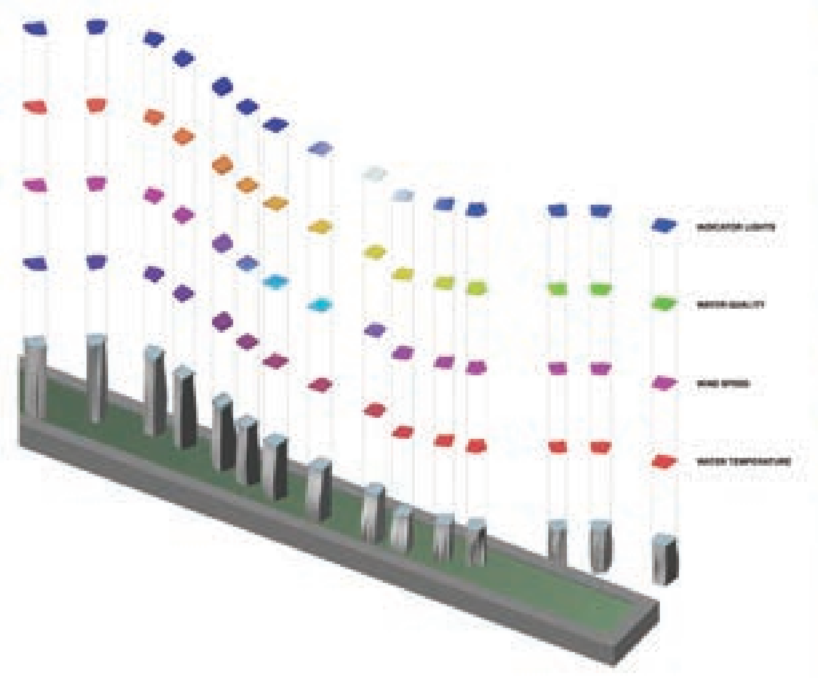


Figure 12: Views of Meander throughout the data animation cycle.

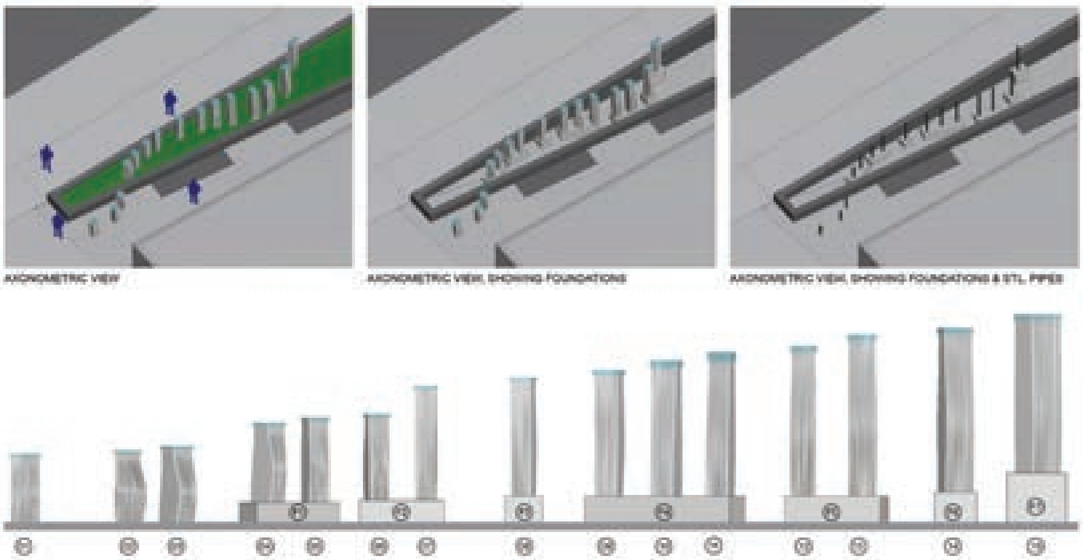


Figure 13: Views of integrated digital model.

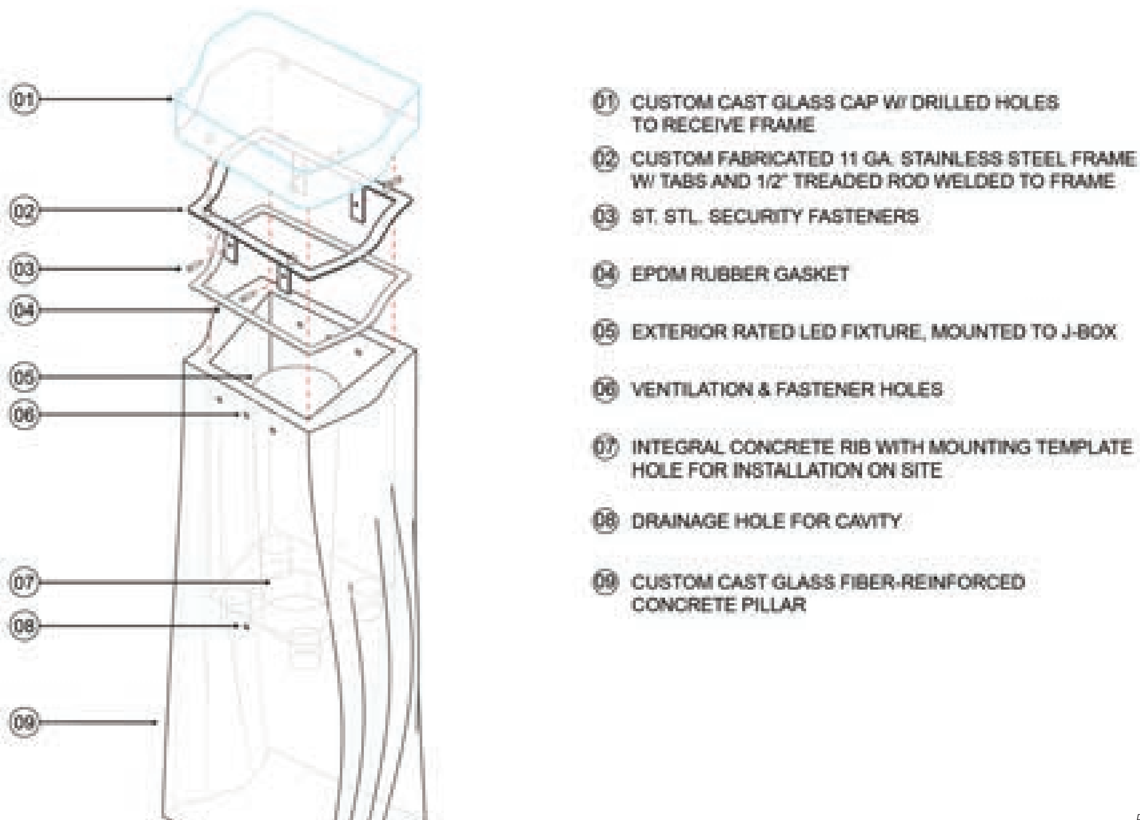
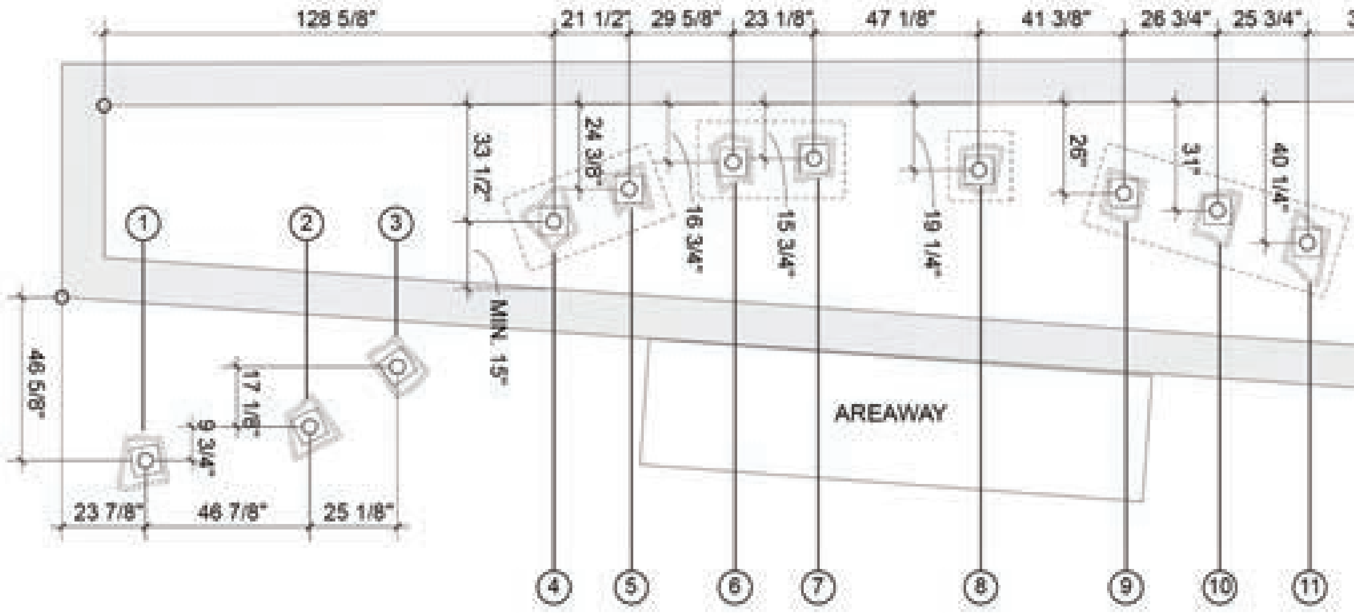
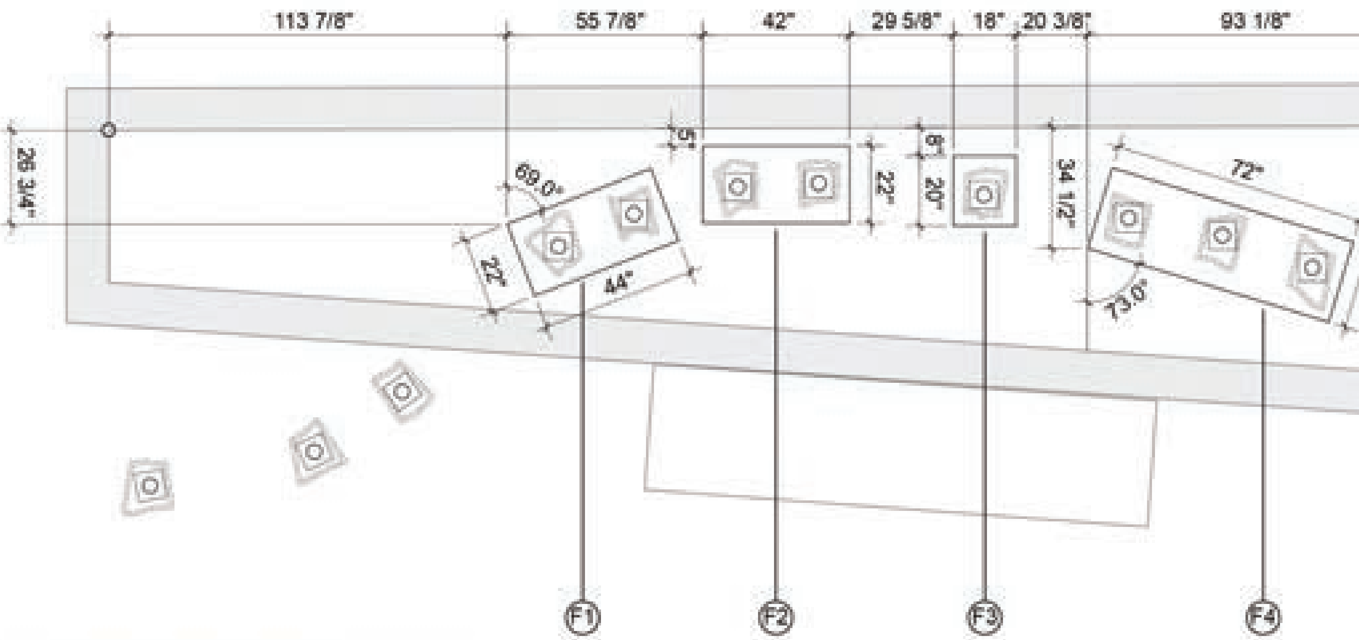


Figure 14: Exploded axonometric diagram, showing the components of each pillar.

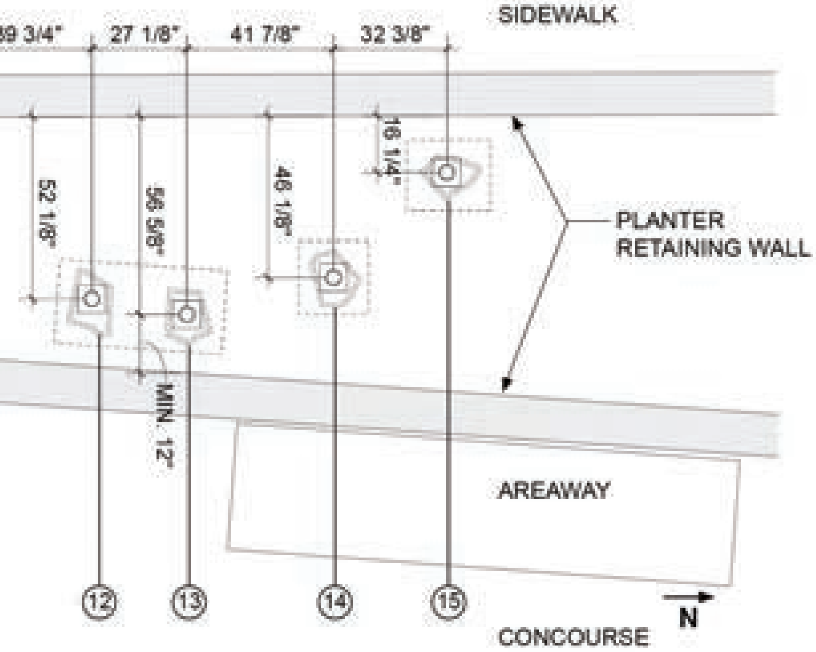


1. STL. POST LAYOUT DRAWING
Scale 1/4" = 1'-0"

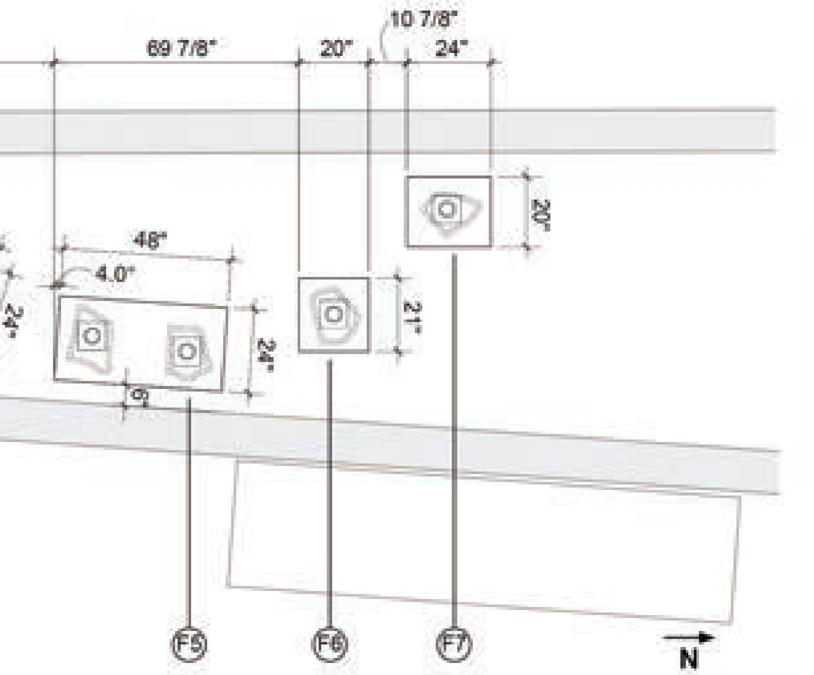


2. CONC. FOOTING LAYOUT DRAWING
Scale 1/4" = 1'-0"

Figure 15: Coordinated drawings used for locating the concrete footings and steel posts.



ALL DIMENSIONS TO CENTERLINE OF STL. POST, UNLESS OTHERWISE NOTED.



FOOTING SCHEDULE

FOOTING #	DIMS	HEIGHT
F1	22"x44"	14"
F2	22"x42"	14"
F3	20"x18"	15"
F4	24"x72"	14"
F5	24"x48"	14"
F6	21"x20"	16"
F7	20"x24"	24"

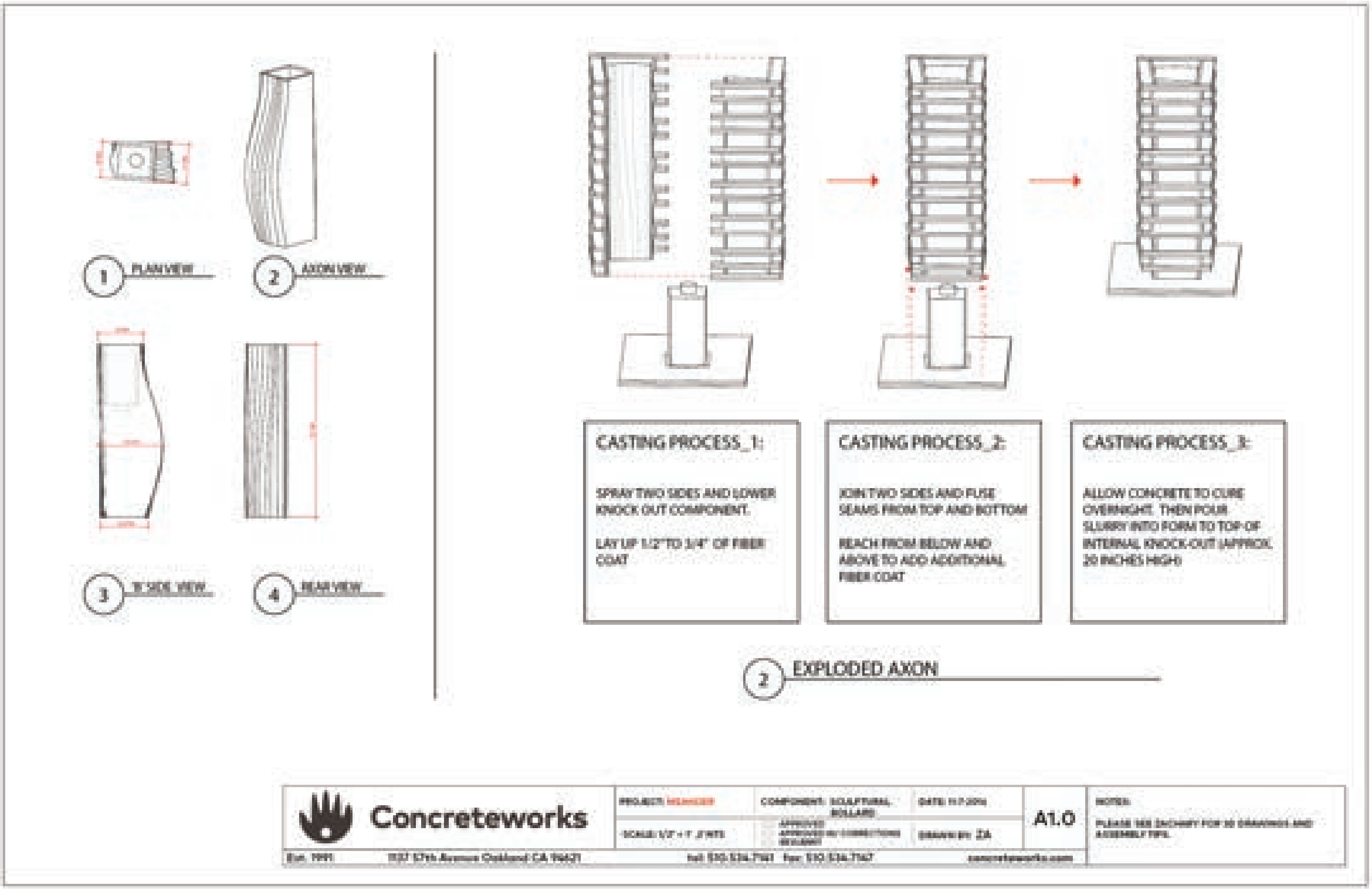


Figure 16: Shop drawings of typical mold for cast concrete pillar.

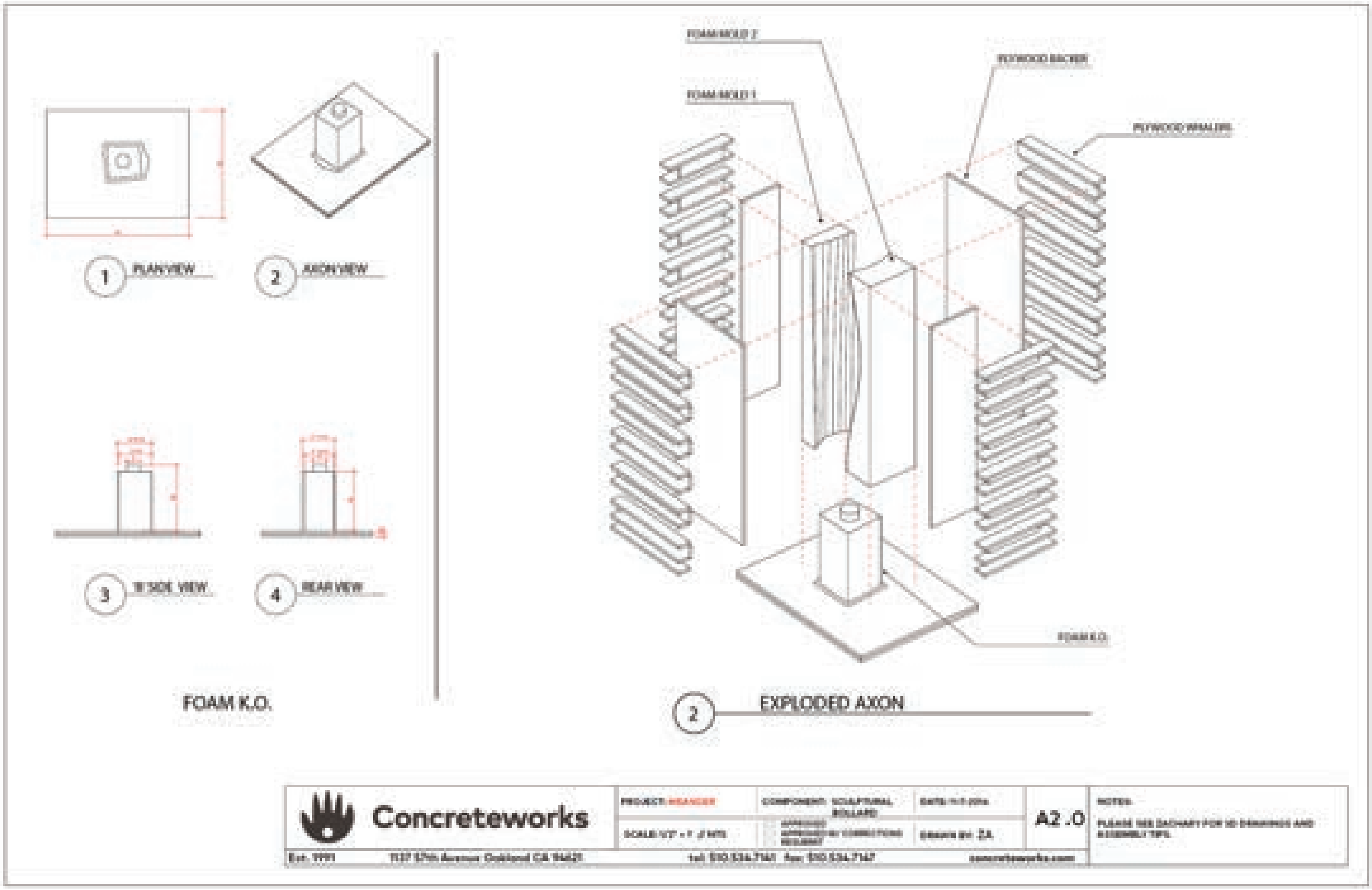
cal—grounded in historical, geological data—and yet the accumulation of the quantitative information yields a highly abstract and evocative result. This oscillation between the representational and the abstract was an inspiration for *Meander's* design.

In addition to its cartographic roots, *Meander* draws inspiration from the broader context and tradition of environmental art—in particular, artworks that aestheticize the quantification of nature through digital processes. This includes precedents such as Maya Lin's *Systematic Landscapes*, a series of large-scale installations that re-present landscape geometry with elegant simplicity, in an abstract yet highly legible way (Lin 2006). Natural and environmental phenomena are also central to the work of Ned Kahn, but in a more immediate and dynamic sense. Kahn's monumental, wall-mounted installation, *The Wave* (fig. 3), consists of thousands of small, kinetic elements that together produce a real-time illustration of the wind's movement across the surface of the structure (Kahn 2010). This sensibility is also present in *Amphibious Architecture* (fig. 4), a work by The Living that utilizes electronic sensors, microcontrollers, and LED lights to visualize water quality in New York's East River in real-time (Geiger 2010, 60-65). With *Meander*, Futures North sought to merge the technological sophistication of this type of work with the capacity of Lin's sculptures to speak to more timeless and ineffable qualities of the natural landscape.

DATA SPATIALIZATION: FORM

The Mississippi is well worth reading about. It is not a commonplace river, but on the contrary is in all ways remarkable... It is the longest river in the world— four thousand three hundred miles. It seems safe to say that it is also the crookedest river in the world, since in one part of its journey it uses up one thousand three hundred miles to cover the same ground that the crow would fly over in six hundred and seventy-five.

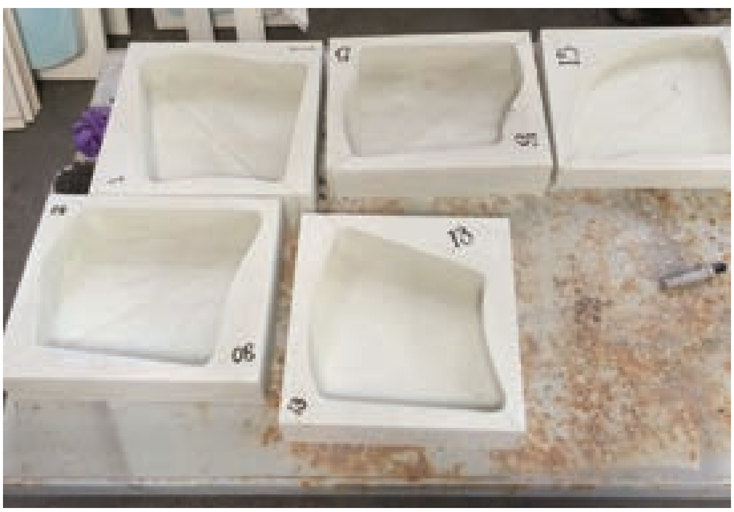
–Mark Twain, Life on the Mississippi (Twain 1883)



Futures North began the design process by researching the Mississippi River, the defining feature of the project's environmental context and, in many ways, the reason for St. Paul's existence as a city. During this research phase, we uncovered a number of historical maps of the upper Mississippi River, from contemporary satellite maps to the less accurate but no less significant maps of early European explorers and settlers of the eighteenth century. We used this information to construct a new, updated "meander map" of the upper Mississippi. In particular, we selected three maps to encompass the full range of the river's cartographic history: the map drawn by French geographer Joseph Nicollet in the 1840s, a survey by the Army Corps of Engineers from 1963, and a satellite map accessed from Google in 2014 (figs. 5–7).

Each of the *Meander* pillars consists of a curvilinear cast concrete base topped with a cast glass lantern. We developed a formal logic for the project through the creation of a digital, parametric model that provided a means to precisely adjust the geometry and iterate through numerous design studies. In the digital, three-dimensional environment, the outlines of the river in each of the three maps were positioned vertically in space to create a volumetric form. With the Nicollet map at the base, the Army Corps map in the center, and the Google satellite map at the top, the resulting volume constitutes a three-dimensional representation of the river's changing geometry over time. This curvilinear form was then divided in fifteen places, which correspond to the locations of locks and dams along the upper Mississippi (fig. 8). At each of these locations, there is a significant change in the elevation of the river's surface, and this sectional variation was used to inform the height of each of the fifteen volumetric segments. Finally, the thickness of the glass lanterns corresponds to the changing depth of the Mississippi river between each lock location (fig. 9). This generative process demonstrates how simple planar and sectional operations can be used to translate geological and hydrological geometries into sculptural form with both abstract and representational capacities.

Figure 17: Images of concrete fabrication process.



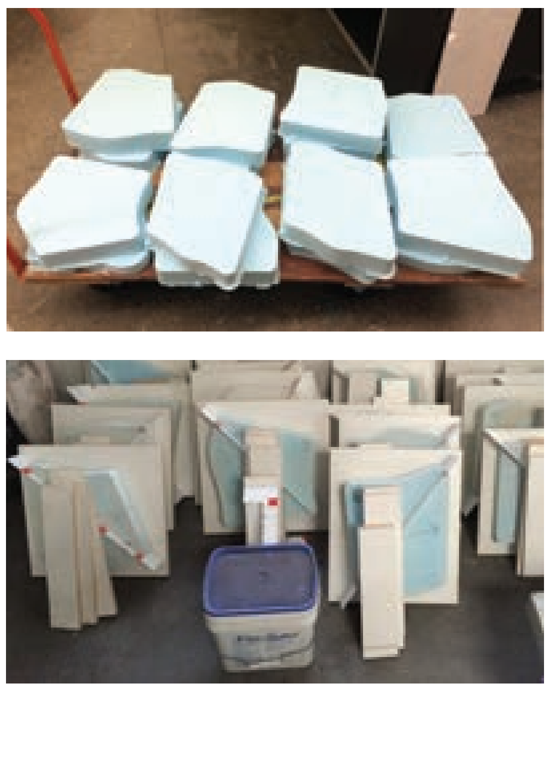


Figure 18: Images of glass mold-making process.

The fifteen resulting volumes are offset in plan to create a meandering line of pillars that weave in and out of a planted berm that defines the edge of the ballpark's entrance plaza. The artwork's orientation matches that of the river, with the northernmost pillar representing the Mississippi River's headwaters in Minnesota at Lake Itasca. We worked closely with the ballpark's landscape architect Bob Close to carefully coordinate the pillars with the design and grading of the planted area. As the pillars decrease in height, they echo the slope of the berm and adjacent sidewalk; pedestrians walking downhill from the north follow the stepped lanterns down to the southernmost pillars, which are sited in the plaza itself and invite visitors to touch them (fig. 10).

DATA SPATIALIZATION: LIGHT

Futures North not only leveraged computational processes in the development of the artwork's form, but also in the design of its dynamic lighting. Each lantern contains

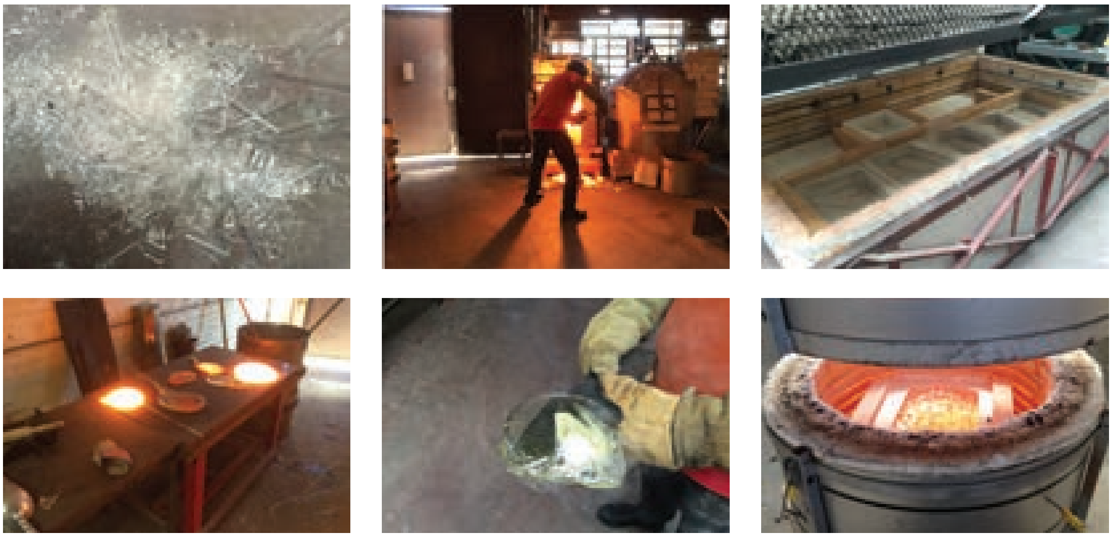


Figure 19: Images of glass casting process.

Figure 20: Images of steel attachment frame fabrication process.

Figure 21: Images of installation process on site.

a programmable LED fixture, and the color, pattern, and intensity of these lights are driven by recorded environmental data about the Mississippi River. In the research phase of the project, the artists screened and analyzed data collected by the Army Corps of Engineers and the University of Minnesota's St. Anthony Falls Research Laboratory to identify information about the Upper Mississippi River that would be most compelling and relevant for a public audience. This process yielded three datasets: the changing water quality (or level of nitrates) over time, the changing wind speed along the river's length over time, and the changing temperature of the water over time.

We used several software platforms to translate the raw data into a light and color animation accessible to a public audience. These included the Grasshopper parametric modeling engine, as well as the TouchDesigner programming interface that ports the quantitative data to RGB instructions for each individual LED fixture. Each dataset is assigned a unique gradient that corresponds to its respective range of quantitative information (fig. 11). For example, the water quality dataset is represented through a green-white-orange gradient that communicates the amount of nitrogen in the water compared to one year previous; green indicates less nitrogen (improved water quality), orange indicates more nitrogen (lower water quality), and white indicates no change.

The three datasets are stitched together to form a single 30-minute program of data-driven light that cycles continuously from dusk to dawn (fig. 12). At any given moment, the color and dynamic behavior is correlated to quantitative data from that section of the river. Although the animation is driven entirely by environmental data, a viewer's experience is not contingent upon understanding the connection to the data; by leveraging quantitative operations for maximal qualitative effect, the artwork's dynamic presence provides an engaging addition to the urban streetscape.

INTEGRATION OF ART + ARCHITECTURE

The project's integration with the ballpark's architecture necessitated a high degree of coordination between Futures North and the building's design/construction team. We maintained an integrated digital model throughout the design process, which interfaced with the ballpark's master BIM model used by the architect and contractor. This digital workflow eliminated the often-complicated back-and-forth of shop and coordination drawings that is common for public artworks built within a large construction project. The digital model that we used accurately communicated the location and orientation of each of the concrete pillars, along with the associated structural steel and electrical infrastructure (fig. 13).

DETAIL & DESIGNED ASSEMBLY

Although *Meander* is a relatively small public art project, its integration of multiple materials and construction trades (steel, concrete, glass, electrical, rigging, landscaping) resulted in a high degree of complexity throughout its fabrication and installation. Futures North anticipated these complexities by front-loading the design process with concerns of tolerance, sequencing, and clear communication between team members. Scott Marble has referred to this approach as "designed assembly":

> *Through CNC technologies, architects can reposition design strategically within fabrication and construction processes, such that design information extends beyond the representational to include highly precise sets of instructions used to drive manufacturing processes. Moreover, these instructions can embed the logic of building assemblies into the manufacturing processes, linking design to a new definition of detail that re-establishes the role of craft in the design process (Marble 2012).*

Several aspects of *Meander* reflect this kind of process. The concrete pillars and glass lanterns were fabricated off-site using CNC-routed formwork, in controlled conditions that allowed for a high degree of precision and craft necessary for realizing the unique and complex forms of each part. The pillars were craned in and grouted on site to galvanized steel posts that anchor them to the building structure and incorporate the electrical conduit for each light; each pillar was fabricated with an integral mounting template in its hollow interior that precisely established its position during installation. Each unique lantern is mechanically fastened to its respective pillar via a custom waterjet-cut eleven-gauge stainless steel frame, with an integrated synthetic rubber gasket (EPDM) to provide a tight weather seal. The frame includes a concealed security fastener, so the lantern can be removed for maintenance of the LED fixture (fig. 14).

The integrated digital model was crucial in managing these aspects of the project, as it allowed for greater flexibility, clarity, and live feedback throughout the design process. The model's parametric functionality—the live connection between the artwork's overall geometry and the fabrication drawings for its constituent parts—allowed the artists to evolve the geometry throughout the design process with immediate feedback on how changes would affect pragmatic concerns of material takeoffs, cost, and installation. For example, with each update of the river mapping data that drives the overall geometry of the *Meander* pillars, the resulting change in form would ripple through the digital model such that the concrete molds and two-dimensional templates for the lantern attachment plates would automatically adjust.

We also used the model to output coordinated two-dimensional drawings for the pouring of the concrete footings and installation of the steel support posts, which, due to construction sequencing of the stadium,

Figure 22: Views of Meander.

were completed six months before the pillars arrived on site (fig. 15). This drawing was coordinated precisely with a hole cast into a concealed, integrated rib in the center of each pillar, providing a means for the riggers to locate precisely each pillar during installation. This ensured the precise position and orientation of each pillar, which is essential for the artwork to be properly experienced. In this regard, the integrated model provided a means to bridge the work of two separate trades—metalworkers and riggers—performed six months apart, while maintaining high precision and preserving the design intent of the artwork.

PROTOTYPING & FABRICATION

Futures North completed a number of full-scale prototypes in order to test and refine the fabrication processes for the concrete pillars and the glass lanterns. This involved close collaboration with fabricators to ensure maximum precision and craft in the final product. File-to-fabrication workflow enabled a streamlined interface with the concrete and glass fabricators, which allowed for a high degree of control and precision with the project's complex geometry.

The pillars were fabricated by Concreteworks, a concrete fabrication shop in Oakland, California that specializes in casting glass fiber-reinforced concrete (GFRC) into complex geometries. The Concreteworks team used a robotic CNC router to fabricate expanded polystyrene (EPS) foam molds for each concrete pillar. Each mold consisted of three parts: two halves that produced the pillar's exterior geometry, and a central "knockout" insert that established the proper depth of the internal cavity for the LED fixture and also located the hole for installation over the steel posts (fig. 16). A custom GFRC mix was applied to the molds via a standard spray applicator until 3/4" of thickness was achieved (fig. 17).

The glass lanterns, fabricated by glass artist David Ruth, were produced using a similar process. We milled EPS foam positives for each of the fifteen unique lanterns using a 3-axis CNC router. Each positive incorporated the unique shape and drainage slope for its respective lantern. David Ruth's studio then cast plaster negative molds around the foam positives (fig. 18). The glass casting process consisted of two stages. The first involved producing large pieces of solid borosilicate glass (commonly known as Pyrex, and notable for its very low coefficient of expansion). The glass casting team crushed unused laboratory equipment from the 1950s (Pyrex beakers and tubes) and placed the fragments in a high-heat furnace to melt them into solid pieces of glass. In the second stage, these parts were arranged in the plaster molds and fired in a kiln. This process melts the Pyrex again and fuses the individual pieces into a single yet highly differentiated glass cast (fig. 19).

We fabricated the stainless steel attachment frames using a CNC waterjet, to ensure that they would match the curved geometry of both the pillars and the lanterns. The Concreteworks team fit each frame to its respective concrete pillar in order to precisely locate the four attachment tabs and coordinate them with the fastener holes cast into the concrete prior to welding them on. Concreteworks also welded 1/2" long stainless steel threaded rods to the top of each frame, to mate with holes drilled in each of the glass lanterns, which were then attached using a high-strength adhesive (fig. 20).

INSTALLATION

Upon completion of fabrication, the concrete pillars and glass lanterns were crated individually and shipped to St. Paul. Upon delivery to the site, the ballpark rigging and concrete subcontractors installed the fifteen pillars over a ten-day period. Each pillar was craned into place, positioned precisely using the integral rib as a template, and grouted in place. The electrical subcontractor then installed and terminated the LED fixtures within the pillar cavities, and the glass lanterns were mounted to the pillars using secure fasteners (fig. 21). The project was completed in advance of the May 2015 Opening Day celebrations for the ballpark.

CONCLUSION

Through its logics of both design and fabrication, *Meander* illustrates how computation and digital fabrication can be leveraged to produce compelling works of public art (fig. 22). Employing these technologies both in the design and fabrication phases enhanced both the conceptual and pragmatic aspects of the project. The use of computational techniques of data spatialization to inform the artwork's sculptural geometry and dynamic lighting behaviors demonstrates how such tools can open up new forms of interactive engagement with public audiences. Employing an integrated parametric model and streamlined file-to-fabrication workflows enabled the artists to execute the project with precision and a level of resolution that otherwise would not have been possible. These aspects of the project demonstrate how emerging technologies can help facilitate the design and construction of long-lasting, conceptually accessible works of public art.

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IMAGE CREDITS

Figure 1, 10, and 22: Stefanie Motta

Figure 2: U.S. Army Corps of Engineers

Figure 3: Ned Kahn

Figure 4: The Living

Figure 5: Obtained from the John R. Borchert Map Library at the University of Minnesota.

Figure 6: U.S. Army Corps of Engineers

Figure 7: Google Maps and its data providers.

Figure 8, 9, 11–15, and 17–21: Futures North

Figure 16: Concreteworks

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