Combinatorial Methods: Redundancy in Design and Digital Fabrication

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PAPER

Keywords: discrete aggregation, computational design, manufacturing, material assemblies

This paper outlines combinatorial methods in design which empower architects with systematic approaches for producing novel spatial and formal aggregations that allow for sustainable and practical approaches to fabrication and construction. Combinatorial design methodologies differ from parametric approaches in that they explore part to whole relationships, through additive repetition of discrete parts designed to share tectonic relationships in three-dimensional space. This paper outlines two case study projects that appropriate this methodology and describes the formal, material, and manufacturing possibilities of the approach.

INTRODUCTION

"Architecture continually informs and is informed by its modes of representation and construction, perhaps never more so than now, when digital media and merging technologies are rapidly expanding what we conceive to be formally, spatially, and materially possible" (Iwamoto 2009, 3) [1]

Over twenty years ago architects began exploring the possibilities of appropriating digital tools for both the design and actualization of architecture. Yasha Grobman and Eran Neuman describe these early digital explorations of the 90s and early 2000s writing, "Architects who were interested in realizing the potential of computation in design began to explore what were perceived as odd forms, basing them mainly on the outcome of visual properties, on an image, while neglecting to incorporate other aspects of architecture." [2] Today, however, we have reached a point beyond this line of investigation purely for novelty or innovation's sake, where designers are tasked with more carefully considering their exploration of digital design and fabrication processes not solely for a visual and sensual appeal, but also as "being a product of technical utilization."[3] This paper explores this notion of form and performance specifically through the lens of combinatorial processes for design and fabrication. These combinatorial processes explore alternative computational methods for design and advanced manufacturing by considering the efficient use of materials along with innovative, yet accessible, methods of construction. The goal of the work is to neither compromise formal study nor efficiency. Instead this research seeks to empower designers with approaches for exploring digital design paradigms that incorporate sustaining ecologies through considerate use of matter and practical manufacturing approaches.

Specifically, this paper outlines two projects that appropriate methods of combinatorial design in an architectural context. The projects interface with a body of research exploring design, material, and fabrication methods which have the possibility to enhance everyday applications for architecture.

PARAMETRIC VS. COMBINATORIAL METHODS

To start, it is important to differentiate between parametric and combinatorial approaches to design. As defined by Jose Sanchez, "Combinatorial design encapsulates notions of both permutation and combinatorics and uses the studies of discrete finite sets of units and their possible arrangements by an algorithmic or intuitive process." [4] In other words, combinatorial design methodologies involve systems for investigating part to whole relationships, through additive repetition of parts designed to share geometric relationships in three-dimensional space. The process involves designing units and their configurations in order to provide a framework for developing alternative formal and spatial opportunities in architecture based on redundant parts. This technique of aggregation differs from traditional parametric design approaches, which boast of continuity and variation from unique parts through mass customization. Conversely, combinatorial design approaches achieve complexity from discrete parts that aggregate and repeat.

While parametric design approaches rely on geometric framework of interdependencies that allow for variation controlled through parameters, combinatorial design relies on redundant parts with limited variations in their arrangement.[5] Giles Retsin likewise describes a similar design process to combinatorics which he calls "digital material organizations", that involve the use of discrete parts developed to aid in enhanced tectonic relationships and efficient assemblies. In Retsin's case discrete computation "has a limited set of connectivity problems [... and] demonstrates how differentiated, complex and heterogeneous spaces can be achieved with just serialized, discrete elements."[6]

An example of the difference between parametric design and combinatorial design approaches is apparent in the comparison

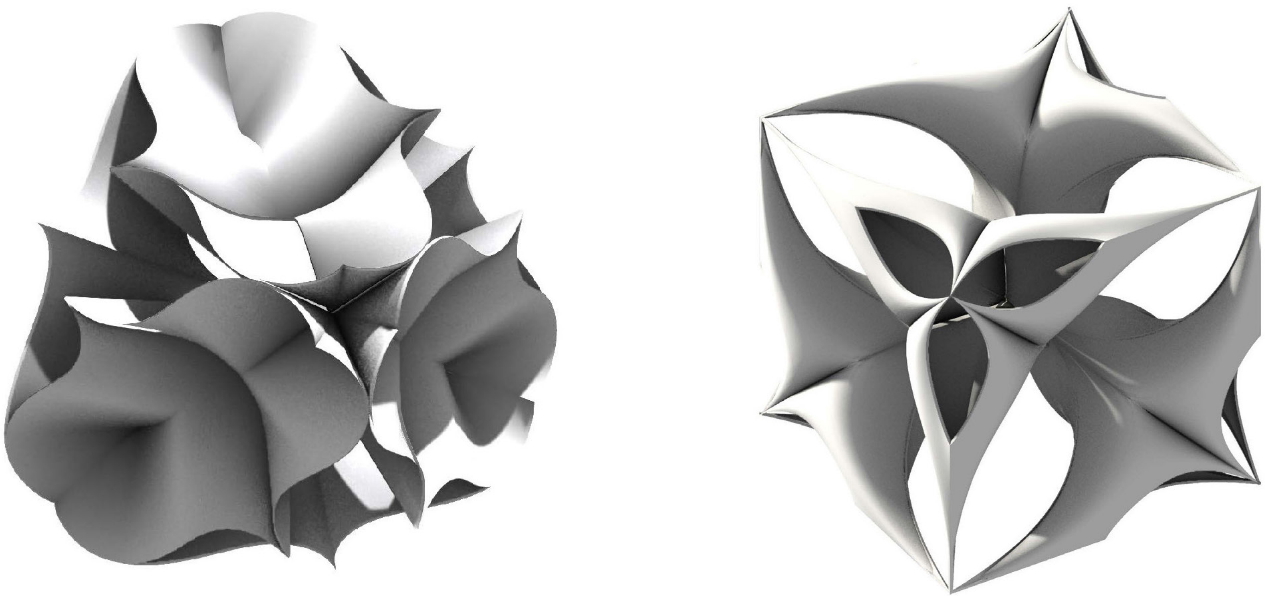

Figure 1. Panels redundantly designed to produce shared edges and nodes based on the subdivision of a cube..

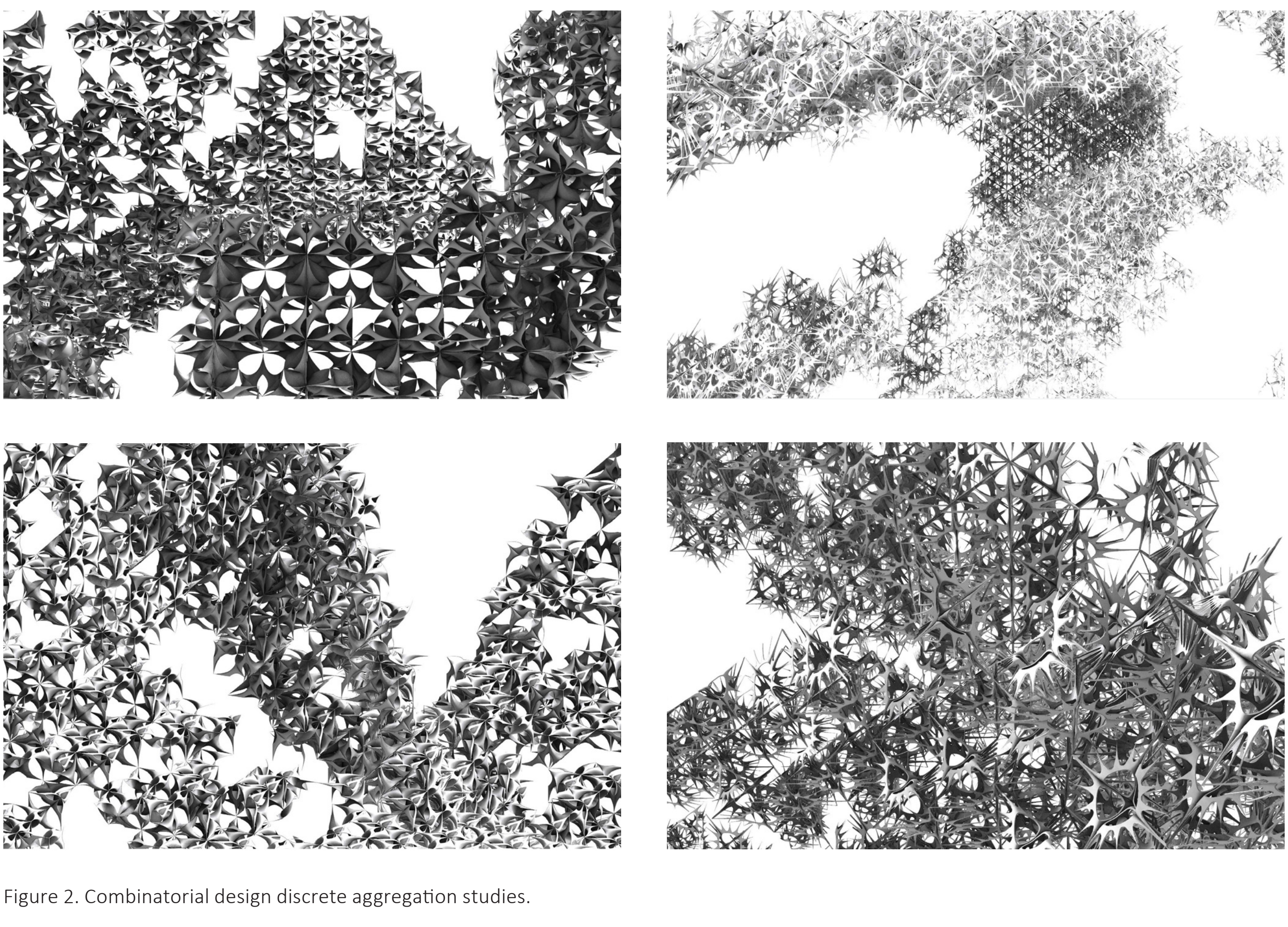

Figure 2. Combinatorial design discrete aggregation studies.

between the Blobwall (2007), a collaborative project between Greg Lynn and Panelite and the robotically assembled brick walls by Gramazio Kohler. In the case of the Blobwall, the blob unit reimagines the unit of the brick as a repeated interlocking curvilinear unit which has limited connection possibilities and allows for a tectonic nesting between units in their aggregation, exemplifying traits of combinatorial design. [7] Gramazio Kohler's robot assembled brick wall, however, is an example of parametric design. Although the brick is a discrete element, every brick has a unique position and "infinite connection possibilities" where the parameters of the wall are defined by the rotating of the brick in three-dimensional space creating infinite design variations.[8] The blobwall focuses on the design of the discrete module and its aggregations, while the Gramazio Kholer project focuses on the design of rotational parameters and the multiplicity of variations.

Combinatorial design starts with the design of individual repeatable modules; the design criteria for these modules is driven by the capacity of their aggregation to provide formal and spatial results and by their potential for tectonic relationships to aid in assembly. Rules of tilling and tessellation come into play to study how the pieces fit together sharing edges, nodes, and faces. Aggregation patterns or tiling strategies allow for a range of configuration designs which leads to extensive strategies for making complex forms. To summarize combinatorial design is modular, tectonic, additive, and repetitive.

Both parametric and combinatorial processes draw upon computational logics to inform ways of making through decomposition, pattern recognition, abstraction and algorithmic thinking, "by developing a step by step process to solve a problem which is repeatable." [9] Nick Dunn explains how computation has impacted ways of thinking about design and production when he writes, "From conceptual design to manufacturing and on-site assembly, computers and digital technologies, have transformed not only the way we represent our ideas, but also the means through which we generate them." [10] As Dunn points out, the use of the computer has impacted ways of thinking and generating design ideas that range from early design to manufacturing and construction. The case studies subsequently presented draw upon this notion and present a method for which this way of working impacts design and actualization.

Specifically, the projects outlined in this paper offer somewhat similar design approaches to Giles and Sanchez by focusing on discrete aggregations; however, they differ by applying discrete making to digital fabrication techniques as well. The results include a catalog of designs paired with applicable advanced manufacturing procedures for their production. In contrast to parametric design and digital fabrication approaches involving customizable unique parts and an assembly puzzle for configuring, the fabrication of these projects allow for simple and repeatable actions for both the production of components and their assemblies. Two projects, Discrete Aggregations and the Acoustic Pavilion, explore the potential of combinatorial design through the development of repetitive modules with tectonic aggregations.

DISCRETE AGGREGATIONS

The Discrete Aggregations project is a body of design research that seeks to outline a geometric framework for combinatorial design and a catalog of design results. Figure 1 illustrates a combinatorial design approach of aggregating parts by using a design assembly of redundant panels. In this case, the repeated units evolve from the subdivision of a cube which is capable of aggregating more parts by stacking in three-dimensional space (Figure 2). However, other case studies involved other three-dimensional grids and the subdivision of volumes such as triangular prisms and hexagonal prisms capable of multidimensional aggregation. Here parametric strategies support the combinatorial procedures, by building the parameters (i.e., the type of prism and number of subdivisions that produce modules, then tiling pattern and number of times copied or aggregated) within the constraints of the combinatorial system. This importantly adds to the potential for these design methods to produce multiple variations of discrete parts and explore their aggregations with the capacity of the computer to quickly replicate, copy, and aggregate. While the results appear complex, all of the elements are simply based on repeated parts. Thus, the complexity is based on the relationship between parts and rules for their aggregation in multiple axes. Likewise, the parts are not dependent on the whole, but rather suggest flexibility in the design since the parts can vary in quantity and organization.

This design process permits for a range of scalable explorations. For instance, the results could apply to the design of an earring, a wall, a pavilion, a 5-story building, or a megastructure. This notion of flexibility in scale is similar to Buckminister Fuller flexible construction systems which he envisioned to vary from a small dwelling or "could grow to become enormous, high density spatial living structures with cells and capsules." [11] Likewise Sanchez describes how this method allows for range of scale suggesting the "parts will be coupled and aggregated to generate larger assemblies, describing meaning, performance and function at different scales of configuration." [12] The range of scaling potential becomes present within the constraints and possibilities of material and fabrication approaches.

Working at the scale of a wall, the research team developed two physical prototypes of the Discrete Aggregations research. Both prototypes involved scaling the module to a masonry unit for a wall. The fabrication process for the unit involved developing a 3D printed model used to pour a multiple part silicone mold later used for casting gypsum building blocks Thus a single mold at the scale of a masonry unit, procures multiple casts of porous modules that aggregate to define a wall (Figure 3). This work learns from Erwin Hauer's designs which provided similar combinatorial design and fabrication methods. While these prototypes used a gypsum cast they also demonstrate potential for precast systems similar to the Cocoon Club precast wall project.[13] The efficiency of this approach is in the redundant use of a single mold to produce multiple parts. Such methods permit a similar approach to architecture, interior design, and sculpture as those used for advanced manufacturing strategies of automobiles, where complex geometry is efficient due to the quantity of parts produced from a single mold. The physical prototypes produced by the research team illuminate the possibilities centered around a question that asks, what if we could cost effectively design and construct buildings with sophisticated formal characteristics, by drawing on nearly a century of approaches used in automobile manufacturing?

COMBINATORIAL ACOUSTIC PAVILION

The second project involves the development of a pavilion made of repetitive Glass Fiber Reinforced Gypsum (GFRG) panels developed from molds capable of producing up to three hundred casts. Titled the Acoustic Pavilion because it also manipulates the conditions of auditory qualities through surface diffusion and form-based reflection. The production of the GFRG panels for the Heydar Aliyev Centre by Zaha Hadid used a similar mold process; however, the fabrication of each panel required a unique mold and therefore resulted in hundreds of discarded molds after only a single use. This kind of waste was a result of mass customization approaches driven by parametricism. The combinational design research outlined here instead strives to provide unique spatial and formal opportunities that carefully consider and limit waste during construction.

The mold production for the pavilion involves CNC milled foam positives used to produce negative molds with a two-part silicone and fiberglass support shell (Figure 4). The silicon aids in capturing texture on the panel and allows for easy demolding, while the fiberglass shell and plywood ribs support the silicon and map the overall panel form. The design accounts for the carving procedures of the CNC mill and optimizes the amount of time spent removing material by using the resulting step-down surface to inform the design of the diffusive surface texture.

The pavilion demonstrates the scalability of the design and fabrication approach, while also demonstrating simplified approaches to building complex forms with redundant parts (Figure 5). Unlike mass customization which requires an abundance of labor and sophisticated assemblies, the pavilion has a limited number of parts and shared relationships to simplify assembly. Such redundant tectonic parts allow for prefabrication strategies that allow for faster and more precise construction, making customized forms more accessible, sustainable, and feasible in the discipline of architecture.

In the case of the wall and pavilion prototypes there is a fine tuning of the geometry to accommodate additional overlaps in nodes, edges, and faces to enhance tectonic relationships. In the case of the pavilion integrated aluminum angle connections are reinforced with additional glass fibers. Such methods explore material and fabrication at the early phases of design to provide immediate feedback on changes to form based on tectonic and material performance. [14] Each prototype also explores ways to combine multiple fabrication methods including combinations of additive, subtractive, and molding processes. Scaling up would require changes in materials which would be possible with composite materials or performance fiber reinforced concrete. Such future studies could also explore green concrete that uses waste materials from different industries and requires less energy for its production. Such reinforced materials like glass fiber or textile reinforcement techniques would allow for the modules to operate with multiple functions integrating both structure and cladding.

DESIGN FOR MANUFACTURE AND ASSEMBLY

The Discrete Parts project and the Acoustic Pavilion demonstrate how combinatorial design processes can also relate to design for manufacture strategies. Design for Manufacture and Assembly (DFMA) is an approach used in engineering, design, and manufacturing that promotes the design of components and products for ease of manufacture, reducing time and expense rather than operating with the knowledge of design and not thinking of manufacturing. Rolls Royce outlines the benefits of this approach explaining, “DFMA (1) influences design definition in early stages of product development (2) reduces the number of parts for easing handling and assembly (3) requires cross functional knowledge for idea generation and implementation (4) explores cost effect material and process to ease manufacturing operations.”[15] Such methods involve understanding and engaging material processes early in the design phases.

Paring such DFMA approaches with combinatorial design and digital fabrication permit for a range of formal designs to become economically viable in industry since “serialized repetition of units is still the strongest and most economical form of fabrication.”[16] This argument differs from that of the early digital fabrication arguments centered around the concept of mass customization, where multiple scholars have falsely argued of zero change in time or cost. Some stating, “‘it is just as easy and cost effective for a CNC milling machine to produce 1,000 unique objects as to produce 1,000 identical ones.”[17] Such a statement would only be true if there were no time or expense in programming CNC files for 1,000 unique parts and if the amount of machine time (i.e., the time the machine spends cutting or carving) for the 1,000 unique parts is the same as the 1,000 identical parts (i.e., they are similar size and/or level of geometric intricacy). Such false statements suggest the reasons why mass customizations have not become abundant in everyday architecture, since unique parts may require more time in the design process, while also requiring additional cost for fabrication. Such additional costs evolve from programming multiple unique CNC files and potentially adding additional labor time or skill for assembly of 1,000 unique parts. However, in the case of combinatorial processes, if a design is able to produce a mold from a single CNC milled model, which produces multiple

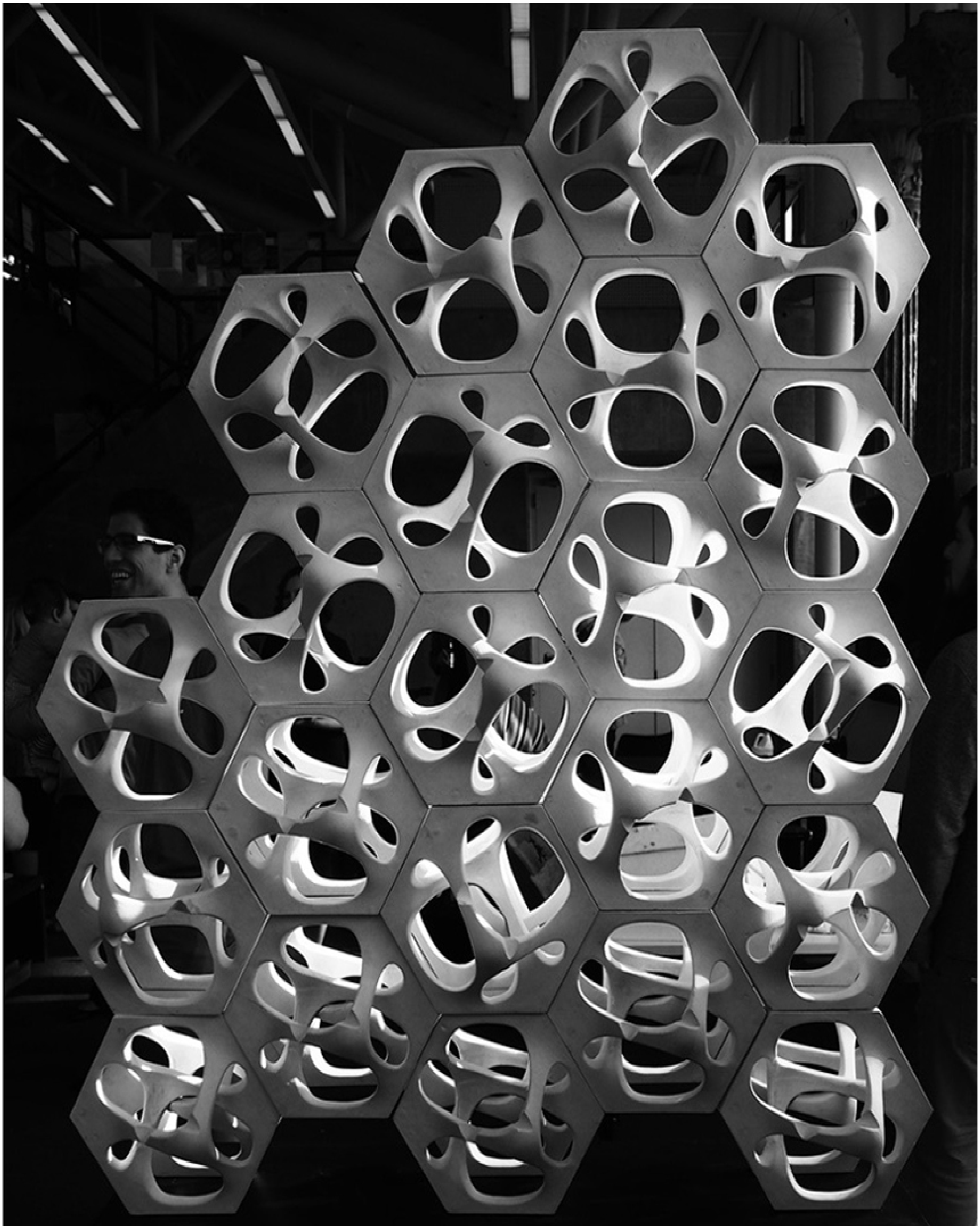

Figure 3. Discrete aggregations wall with all parts fabricated from a silicon mold made from a 3D printed model.

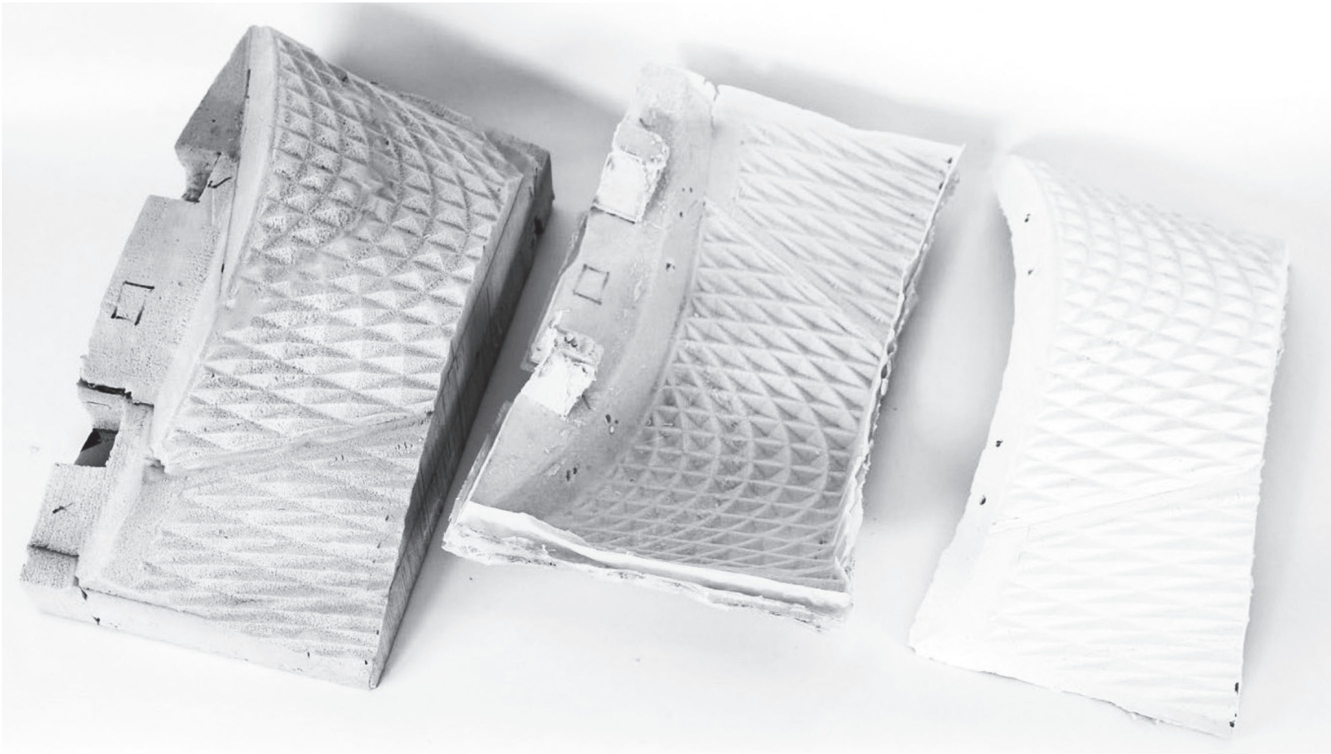

Figure 4. Prototype mold made with CNC milled foam positive model (left) used to produce negative molds with a two-part silicon and fiberglass support shell (middle) which then produces the resulting GFRG cast (right).

casts and complexity from their assembly, then the project has reduced cost, time, and material use.

CUSTOMIZED PREFABRICATION

The combinatorial fabrication methods outlined propose a compromise between mass customization and prefabricated construction techniques, where prefabricated assemblies are customizable. This method provides alternatives to the traditional processes, where architects select materials from catalogs which are then applied to their designs. In the case of combinatorial design, architects can participate in the design of architectural manufactured products and materials rather than pre-made products informing architecture.

Prefabrication building technology acknowledges such possibilities as seen in the Detail Journal of Modular systems exclaiming, “The future of industrial construction lies in the development of computer-based fabrication methods. Building components for geometrically complex structures are already being produced using these techniques; even entire construction systems present unlimited scope for design.[18] Thus the possibilities brought on by digital fabrication can inform modular construction. While buildings have lower technical demands than automobiles, the automotive industry has integrated “digital planning and production methods as a standard procedure” suggesting architecture could likewise take on these ways of design and manufacturing. [19]

Typical concerns about prefabrication building systems are often centered around limited creative possibility within the existing “modularizing, codifying, and repetition.” [20] However, its integration with combinatorial processes liberates those constraints and opens possibilities for customized approaches to prefabrication, empowering architects with methods for modular design and aggregation. Developing processes for prefabrication to interface with combinatorial design allows for variability in designs that have the benefits of prefabricated construction including “quicker construction on site, better ability to build to optimum cost and higher-quality end products due to closer factory control as part of the manufacturing process.[21]

CONCLUSION

Building upon the body of research, future work strives to explore approaches for increasing scale with exploration in material efficiencies, structural optimizations, and design for manufacturing approaches and collaborations. The projects presented articulate a case for a unique architecture not just in terms of design, but also in its production. It expands the ways we, as designers, might think about the appropriation of computational tools and ways of thinking to inform alternatives to everyday approaches to architecture, empowering designers with methodologies and empowering the public with options for accessible innovative design.

Figure 5. Acoustic pavilion designed with repetitive panels with shared edges for assembly.

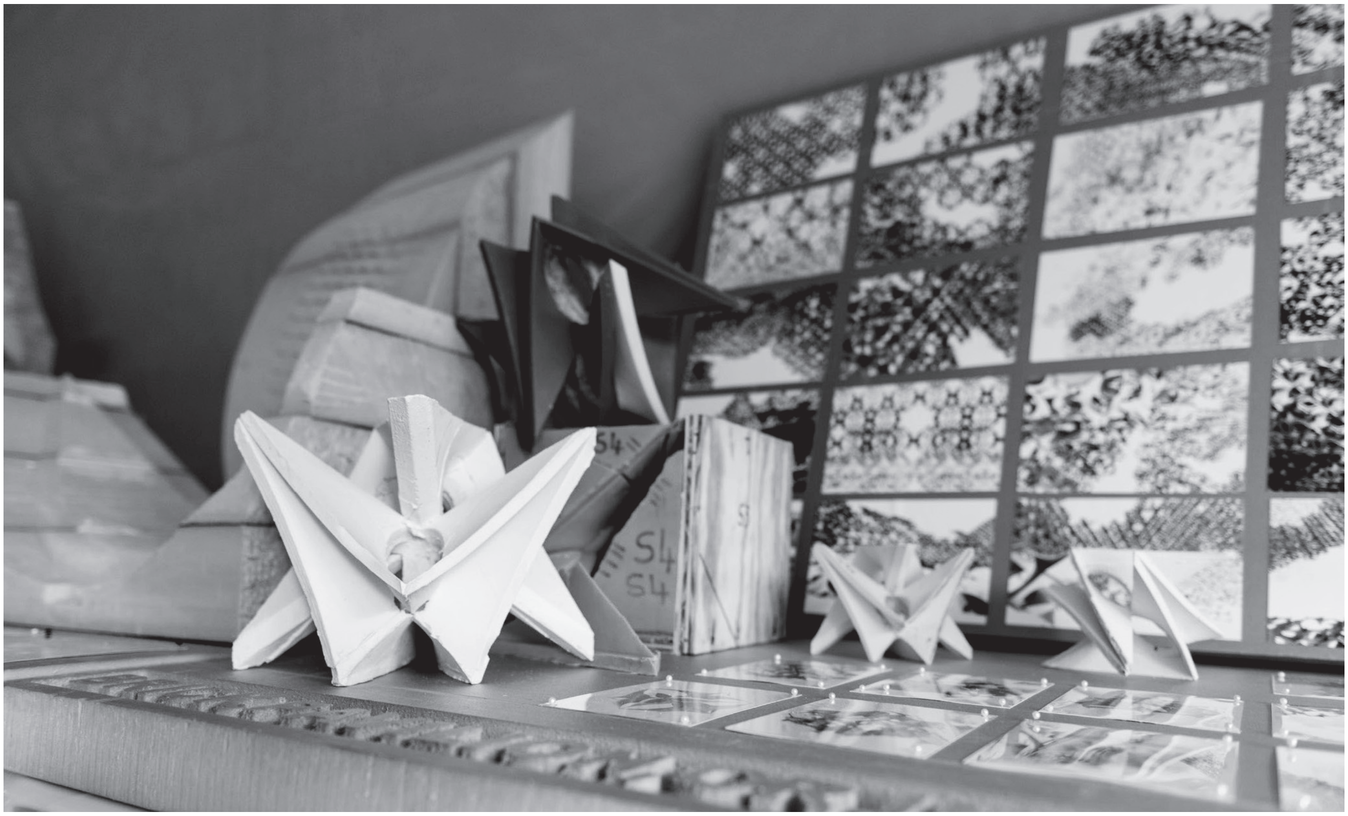

Figure 6. Combinatorial deisgn models, molds, and drawings.

ACKNOWLEDGEMENTS

Discrete aggregation studies (pictured in figures 1 and 2) designed in collaboration with Hana Maleki. Prototype (pictured in figure 3) produced in collaboration with Olga Mesa, Ling-Li Tseng, and Xin Li. Acoustic Pavilion fabricated in collaboration with Alex Cabral, Drake Cecil, Hana Maleki, Margaret Martin, Jarrod Norris, Robby Sachs, and Hunter Sigmon.

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