BREAKING THE MOLD: VARIABLE VACUUM FORMING

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ABSTRACT
Our research explores the growth of surface complexity through careful attention to program and performance criteria. As this complexity emerges, however, we are repeatedly confronted with the realization that its cost compromises any of its performance gains. While the aggregation of repeatable units with variation from one unit to the next is achievable at a low cost through subtractive fabrication technologies (CNC milling, laser cutting, waterjet cutting), it is more difficult to achieve through casting or forming technologies (concrete casting, injection molding, vacuum forming). This is because formwork is not adaptable. Once you produce a mold, typically at a high cost, that mold makes one component only. If you want variation, a new mold must be produced for each new component. With the projects Hexwall and VarVac Wall we put forward a simple question: can an intelligent, adaptable vacuum-forming mold be developed that allows for difference from one component to another without the necessity for multiple molds? The research positions our design efforts strategically at the front end of the fabrication process. Our goal is to develop a malleable tool that allows for endless variation in a fabrication process where variation is typically impractical.
INTRODUCTION

The digital generative processes are opening up new territories for conceptual, formal, and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the “making of form” to the “finding of form,” which various digitally based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the variable, singularity by multiplicity (Kolarevic and Malkawi 2005).

Architects are taught that construction works best when it is premised on a strategy of economy and repetition. Construction units (bricks, sticks, sheets, and rolls) are produced and distributed as repetitive components that reduce in cost based on volume and standardization. Variation, whether in the form of cutting, specific placement, finishing, or any number of other modifications, will likely add to the bottom line of a project. Our industry is predicated on the idea that the more specific the modification, the more expensive the work. The paradigm “cost-reduction through standardization” dramatically limits the architect’s ability to creatively respond to sophisticated sets of forces acting upon a building.

Fortunately, as new technologies come to bear on construction processes the limitations of late twentieth century construction techniques are challenged. While the aggregation of repeatable units with variation from one unit to the next is already achievable at lower costs through subtractive fabrication technologies (CNC milling, laser cutting, water-jet cutting), variation can be more difficult and costly to achieve through casting or forming fabrication technologies (concrete casting, injection molding, vacuum forming). This is because the formwork required for casting or forming a material into its final shape is not adaptable. Once a mold is produced, typically at a high cost, that mold produces one repeatable unit. Value depends on limiting the number of dissimilar units and maximizing the number of standard repeatable units. If variation is desired, a new mold must be produced for each unique component. This negatively impacts the aggregate cost of the job.

In our past research, we have explored vacuum forming as a method for producing low-cost, complex architectural surfaces. While individual panels have achieved complexity and nuance, the cost of the mold and its inflexibility has prohibited aggregation with difference. After numerous vacuum-formed projects were faced with this limitation, we asked the question: could we develop a more sophisticated and cost effective mold that allowed for endless variation in a fabrication process where variation is typically impractical?

NATURE OF THE PROBLEM

Our design research explores the growth of surface complexity through careful attention to program and technical performance criteria (Figures 1 and 2). We contend that purposeful difference along the length of an architectural surface can offer locally tuned solutions to the fluctuating situational needs of occupants. Therefore, our materials research challenges traditional, repetitive construction methods, replacing them with techniques that offer inexpensive, differentiated surfaces. While this type of research is not new, our recent approach to building difference through dynamic mold making is. We believe it offers a novel and substantive contribution to the discourse surrounding custom fabrication processes, and the potential for new, coincident relationships between activity and material arrangement.

To begin, a brief description of vacuum forming is necessary. Vacuum forming is a process by which a sheet of thermoplastic is heated until it becomes pliable, at which point it is stretched over a mold. A vacuum is introduced to the void between the plastic and the mold, resulting in a precise duplicate of the mold’s geometry. Depending on how many copies a fabricator wishes to produce, molds can be made out of a host of materials, ranging from MDF (medium-density fiberboard) to cast aluminum, to composite materials, like fiberglass. What is important to highlight here is that molds are generally quite costly while the parts they produce (which range from utility sinks to car dashboards) are relatively inexpensive due to the economics of mass production.

It is also important to outline why vacuum forming specifically interests us. First, as mentioned above, thermoplastic is generally inexpensive. Whether forming in PETG (Poly-Ethylene Terephthalate Glycol), polystyrene or most other thermoplastics, identical final components are inexpensive. The material is light, requiring little structural support. It is tough, impervious to water, and non-corrosive. Most thermoplastics can be recycled and there are new bioplastics on the market that are produced from renewable resources. Finally, and potentially of most interest to architects, vacuum-formed components can themselves serve as
This chart identifies and compares exceptional precedent work that we used to situate our current research.
The first precedent is the Philips Pavilion, completed by Le Corbusier and Edgard Varèse for the World’s Fair Expo ’58 in Brussels. The scale and formal complexity of the pavilion made its construction a challenge and would have been prohibitive in material cost and time to create using traditional formwork. To rectify this problem, an ingenious solution was devised to generate the molds necessary to make the pavilion’s nine unique hyperbolic paraboloid concrete walls. Instead of erecting formwork and casting the project vertically, a relief of each paraboloid was fashioned on the ground in large casting beds of sand (Figures 4 and 5). When cured, each of the unique shapes was hoisted into place; erected much like a modern tilt-wall building (Zephir 2005). The lessons for our research were many. The leap made by Corbusier and his team to use a flexible, cheap and low-tech material to create formally specific parts was most crucial.

A variation on this last idea—creating complexity through flexible, cheap, and low-tech means—can be seen in the experimental concrete projects of Spanish architect Miguel Fisac and is continued in the work of American designer Andrew Kudless with his project P-Wall. Much of Fisac’s architectural production utilized concrete. Innovative hollow post-stressed precast concrete beams were used to build the bone-like structures of buildings like The Church of Santa Ana in Madrid. Wood board-formwork was constructed to create the rotated paraboloid floors of the Laboratorios Jorba or Pagoda Building. But it was Fisac’s experimentation with flexible fabric formwork and concrete on projects like Casa La Moraleja that specifically inform our research (Figure 6). Fisac constrained large fabric membranes with wire, string and other materials, and cast concrete directly into them to create repetitive billowing forms (Millan and Lumber n.d.). Andrew Kudless expanded on this approach with P-Wall (2006), a unitized wall that explored the use of fabric as a “…self-organizing material under force. Using nylon fabric and wooden dowels as form-work, the weight of the liquid plaster slurry causes the fabric to sag, expand, and wrinkle” (Kudless 2009) (Figure 7). Both architects explored the use of a flexible material, the application of limited and intermittent formwork, and the interplay of force and variability to create form. Both also challenged the paradigm of predictability in form making for mass production. Mark West is another important reference source for this type of exploration (West 2008).

Forming Casting Tiling, a project by Adam Marcus at the University of Minnesota, offers another strategy for creating variability through mold production. Individual flat panels are digitally milled with specific void spaces (Figure 8). The completed panels are stacked in varying sequences to create a larger negative volume appropriate for casting. The strategy can generate a variety of formally constrained but unique blocks. The approach builds on the idea of predictable variability and the use of modularity to achieve a variety of results (Marcus 2013).
PREVIOUS WORK

Several of our fabrication projects preceding the current research have informed our thinking on the topics of variability and adaptability in the forming process. These “seed” innovations include, first, the development of a mold that flips its orientation to achieve variability; second, a technique of combining vacuum forming with other fabrication technologies to alter the final components through post-processing strategies; and third, the idea of varying material in the forming process to achieve difference.

The first innovation was discovered in “Toy Shelf,” a furniture project that explored variability through the use of a malleable material and an adaptable mold (Figure 9). The shelf was the result of a simple strategy; bend thermoplastic sheets over a mold made with a series of unique profiles. Rotating and flipping the mold generated formal complexity. The shelf spawned the idea of manipulating a single mold to create multiple intricate shapes.

Next came “Drape Wall,” which first introduced us to vacuum forming. While panels were formed through a traditional process of stretching a heated sheet of plastic over a CNC-milled MDF form, variability was achieved through a technique of milling the panels after they were formed (Figure 10). Even though the panels were identical in shape, our post-vacuum-forming manipulations allowed them to still differ from one to another. We could change the geometry, size, and number of apertures from panel to panel quickly and easily.

Finally, “OSWall” (Open Source Wall) introduced us to the idea of variability through the use of multiple materials in the vacuum forming process (Figure 11). The wall was constructed by forming materials with different properties: soft, hard, thick, thin, insulated, non-insulated, transparent, translucent, opaque, etc. OSWall resisted the rigid predictability of vacuum forming by varying the actual material being shaped.

These modest discoveries—flip-flopping a mold, post-form manipulating a component and varying the molded material—opened us to new ways of thinking about the vacuum forming process in its entirety and how we might begin to strategically and productively disrupt that process. This brings us to a discussion on the current work.

CURRENT WORK

Our current work focuses primarily on manipulation of the mold itself to achieve difference. Through the creation of a dynamic mold, we are, for the first time, able to produce final vacuum formed components with nearly infinite variability from a single mold. Two current projects, “Hexwall” and “VarVac Wall” take two very different approaches to achieving this variability in the vacuum form process.
HEXWALL

With “Hexwall,” we put forward a simple question: can an intelligent, adaptable vacuum forming mold allow for difference from one component to another without the necessity for multiple molds? Hexwall is a small part of a larger renovation project. In an existing bathroom, adjacent to a window, the client called for a feature wall that would reflect light into the room during the day and illuminate the room at night. To address these parameters, we developed a white, backlit, topographically active wall surface that grew or shrank in sectional thickness, dipping into the space or receding from it, according to local changes in program (Figure 12). In one area, the wall bends into the space to scoop reflected daylight. In another, it plunges out of the space to make room for an adjacent door that swings into the wall. These local deviations in profile necessitated a highly adaptable fabrication system.

We decided to use modular panels of vacuum formed polystyrene. Because each twelve inch by twelve inch panel was different from the next, we developed a dynamic mold made from an array of one inch hexagonal rods that could be adjusted in height. Inspiration for this came from a simple children’s toy: a pin art impression mold. With this toy, children can replicate the shape of their hand or face by impressing it into the mold, which incrementally changes the height of each pin. This same idea appears in our variable mold. A CNC-controlled armature adjusts the height of each hexagonal pin before the plastic is shaped over the mold (Figure 13). After one panel is formed, the robotic armature adjusts pin heights again, driven by a spreadsheet extracted from a Rhino model. Then, a second panel is molded, and so on. With Hexwall, we used just one mold to ultimately produce a matrix of sixty-three dissimilar panels, which in turn, combined to form one large contextually-sensitive, topographic surface (Figure 14).

VARVAC

“VarVac” is an extension of the “Hexwall” research. In concept, it is similar: variation in final panel shape is produced through strategic manipulations to the original mold. In practice, however, VarVac is different from Hexwall in several important ways. First, and most significantly, VarVac is much more difficult to predict. Hexwall panels were one-to-one replicas of the mold on which they were produced, so their resultant shapes were highly predictable. VarVac suspends the heated plastic in the air, so the resulting shapes of its panels are quite unpredictable. Second, VarVac revisits the idea of post-processing the plastic on the CNC router after it is molded (originally explored in Drape Wall, described earlier). When Hexwall’s panels came off of the mold, they were finished and ready to be installed. With VarVac, strategic cuts in the panels, tied to their shape, determine their acoustic properties. This system is explained in detail below.
Like Hexwall, VarVac is one small component of a larger renovation project, in this case, the front office of a School of Architecture. The entire space is to receive a new liner that incorporates storage, display, reception, and seating. VarVac forms one wall of this liner, located behind a main reception desk (Figure 15). We are conceiving of this wall as acoustically heterogeneous. In other words, parts of the wall will absorb sound—in particular the zone behind the receptionist, where most conversations occur—while other parts will reflect sound (Figures 16 and 17). To achieve this difference, segments of the wall will be comprised of vacuum-formed panels with milled perforations and an acoustic backing, while others will remain solid and reflective.

This migration from maximum absorption to maximum reflection is developed through an internal logic that ties morphology to acoustic properties. The wall is made up of panels that billow out into the space like a giant, exaggerated quilt. We established a rule that if the volumetric pillows on a particular panel reach out to a cross-sectional depth of six inches or more, those pillows are cut off by an imaginary cutting plane (visually, think of the difference between a rounded hill and a flat-topped butte). As a pillow grows in size more of it is removed, resulting in a more absorptive panel. As a pillow shrinks, it receives either a smaller slice or no slice at all, resulting in a more reflective panel. So, in areas where the wall is most absorptive, it is made of panels with a few, large, billowing pillows. In areas where the wall is most reflective, it is made of panels with many, small, repetitive bumps. Its physical appearance is in essence a map of its acoustic properties.

To make panels that billow out to different degrees with varying sized bumps, we developed a mold comprised of a large frame across which we stretched insulated wires (Figure 18). These wires form an open grid, like a super-sized window screen. Polystyrene sheets are heated and slumped onto this open grid where gravity takes over to form the geometry of the pillows. The further apart we space the wires the deeper the draw of the plastic, which results in a bigger pillow. It is a simple system, which gives us a nearly infinite variety of panel permutations through a basic mold reconfiguration.

Complexity in VarVac lies in the system we developed to digitally predict the geometry of its pillows and iteratively test different panel configurations. To accomplish this we built the wires and frames in Grasshopper. The location of wires on each panel is randomly generated, but wire density is based on an imported gradient image. Where the image is more saturated in magenta, the wires are spaced further apart, where it is less saturated, the wires are spaced more closely. The image correlates directly to how we want the wall to perform acoustically. Then, using the Grasshopper plugin, Kangaroo, we slumped a surface over the wires. Interestingly, there was no way to truly predict the shape of the panels in Kangaroo. We intuitively knew what looked right, but in order to precisely tune the digital model, we needed to physically prototype...
the panels. Then, we could measure their depth under various wire spacing conditions and adjust the settings of the digital model to more accurately predict how the panels would really look.

This back-and-forth working method, between the physical and the digital, as a necessary part of the project’s development, is uniquely pivotal to its success. In addition to helping us accurately predict its appearance, it has allowed us to accurately map tool paths for cutting the pillows on the CNC-mill. To turn the wall’s “hills” into “buttes,” we produced a custom rotary blade for the mill that cuts the panels from the side (X and Y direction) rather than from above (the Z direction). This frees the tool path from having to be overly precise. The combination of precision in the digital model and allowance for imprecision in the actual cutting process allows us to generate tool paths directly from the Kangaroo/Grasshopper model without physically measuring each panel as it emerges from the vacuum-former (Figure 19). While a subtle streamlining of our production methodology, this has proven to be an invaluable time-saver.

Hexwall and VarVac Wall have proven to us that there is tremendous potential in the field of dynamic mold making. The following section briefly speculates on future research.

FUTURE RESEARCH

Two categories define the future of our variable molding research: plastic and non-plastic. Under the category of plastic, we have developed a matrix of experiments, further sub-divided into two categories: variation in the mold and variation in the molded. Up to now, most of our efforts have focused on variation in the mold.

PLASTIC: VARIATION IN THE MOLD

Hexwall and VarVac explore making changes to the mold that yield components with subtle variation from one to the next. Further experiments in this spirit are illustrated in the matrix included here (Figure 20). This diagram identifies strategies that vary the mold in one dimension, like Hexwall, strategies that vary the mold in two dimensions, like VarVac, and strategies that vary the mold in three dimensions through the use of inflatable bladders.

Under this three-dimensional molding strategy, we see limitless possibilities. If sheets of plastic can be drawn over a mold using negative vacuum pressure, then they might also be forced into shape through positive pressure or inflation. Traditional vacuum forming assumes a baseline “flat” condition. A sheet of material is drawn over a mold and a figure is pushed into that sheet. Volumes are limited in height by the elasticity of the material being formed and the size of the forming table. Because the vacuum formed material must be pulled directly off of the mold, volumes cannot include undercuts. Complex relief is not possible. This basic limitation results in applications that behave like more traditional planar elements (walls, ceilings, and floors). However, an inflatable mold...
could produce something truly volumetric, resulting in higher degrees of relief or in objects that are self-supporting and formally independent. The scale of fabrication could increase dramatically as the vacuum former itself would no longer restrict production.

Other experiments will consider the role failure can play in the molding process. In one test, we will investigate rigid foam as a molding material that is milled on its underside to create crevasses of open space. Under forces applied to the mold in the vacuum-forming process, these crevasses will collapse and the plastic will deform unpredictably into the resulting voids. In another test, we will produce a mold from columns of foam with varying density. The rigid, dense columns will deform minimally under the pressure of the vacuum, where the porous, flexible columns will deform more. This will result in a topographically varied panel dependent upon the distribution of porous and dense foam in the mold.

**PLASTIC: VARIATION IN THE MOLDED**

In this line of research, we will alter the plastic before it is molded and jettison the mold together to achieve variation. In one set of experiments, we plan to alter the cross-section of plastic before it is heated and slumped to achieve variability in the final component. By starting with thick plastic and then selectively milling away regions of material, we can control the topographic shape of the final molded component without a mold.

Related to this is the idea of varying a molded material’s actual properties prior to forming. Here, we would mold a hybridized material designed to deform in different locations at different temperatures and/or incorporating varying levels of elasticity or rigidity in the same sheet of material. If the material being shaped were able to contain zones that behaved in variable yet predictable manners, it would be reasonable to assume that the application of consistent force and heat would result in a variably shaped final component. Similar to the milling experiments described above, this would free the vacuum forming process from the clear limitations of formwork. Each fabricated component would possess an inherent intelligence that would inform its final shape.

**NON-PLASTIC: INFORMING NEW REALMS OF PRODUCTION**

We anticipate that variable molding strategies developed in this research might start to inform non-vacuum forming and non-plastic modes of material production. We’ve already seen examples of this in Wes McGee’s variable glass-forming work at the University of Michigan (McGee and Newell n.d.) or in the variable molding processes developed in the sailboat industry for high performance sails. Our future research will also experiment with the use of variable molding to impact the production of traditional and previously unconsidered realms of material production.

As one preliminary example of this, we are experimenting with the use of variably-formed vacuum panels as molds themselves for the production of inexpensive pre-cast concrete units. In another, we are using them as molds to generate panels of pressed industrial felt. These are just initial sketches of where this work might go. We anticipate some of the most far-reaching, widely applicable, and impactful outcomes of our research to be situated in this field of investigation.

**CONCLUSIONS**

Real-time variability in forming fabrication processes sponsors a more careful examination of the relationship between program and material (function and form). This is not to suggest that a one-to-one relationship is best or desired. However, the ability to carefully tune that relationship might allow for the exploration of new and novel dialogues, whether comfortable or uncomfortable, efficient or inefficient, compliant or resistant. In addition, our research suggests that variability in the production of architectural
components can be achieved as easily and efficiently as repetition and consistency. By decoupling monetary economy from formal repetition, many of architecture’s long-standing limitations can be undermined and vigorously challenged.

The bottom line is that our research is not just about the development of new material production technologies. Rather, the systems we have developed set the groundwork for interrogation of more conceptual architectural themes. Moving forward, we hope to foreground an argument that inextricably joins a technically oriented line of research such as ours (flexibility where there previously was none) with larger, weightier issues of timeless and broad importance (like the relationship between program and material). Only with such lofty goals in mind can this type of research resonate with a wider audience and maintain relevance within a larger architectural discourse.

WORKS CITED


BLAIR SATTERFIELD is an assistant professor of architecture at the University of British Columbia, co-founding principal of HouMinn Practice (with Marc Swackhammer), and a co-founding member of the web-based modern plan company Hometta. Satterfield has extensive practice experience and has garnered multiple AIA and national SARA awards for architecture, landscape, and urbanism. Satterfield’s academic research focuses on issues of performance and production in building components. HouMinn has been published and exhibited extensively and the firm’s research has collected such honors as the 2008 R&D Award from Architect Magazine and the Best in Environments award from ID Magazine. Satterfield holds degrees from the University of Illinois at Urbana-Champaign and Rice.

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