GLASS CAST:
A RECONFIGURABLE TOOLING SYSTEM FOR FREE-FORM GLASS MANUFACTURING

ABSTRACT

Despite glass's ubiquity in the modern built environment, it is rarely applied in applications requiring complex curvature. The high temperatures and complexity of techniques utilized in forming curved glass panels are typically very expensive to employ, requiring dedicated hard-tooling that ultimately limits the formal variation that can be achieved. This combination of economic and manufacturing barriers limits both the formal possibilities and potentially the overall envelope-performance characteristics of the glazing system.

This research investigates a methodology for utilizing reconfigurable tooling to form glass into doubly curved geometries, offering the potential for improved structural and environmental performance in a material that has remained largely unchanged since the advent of its industrial manufacturing. A custom-built forming kiln has been developed and tested, integrated through a parametric modeling workflow to provide manufacturing constraint feedback directly into the design process. The research also investigates the post-form trimming of glass utilizing robotic abrasive waterjet cutting, allowing for the output of machine control data directly from the digital model.

The potentials of the methodologies developed in this process are shown through the fabrication of a full-scale installation. By integrating material, fabrication, and design constraints into a streamlined computational methodology, the process also serves as a model for a more intuitive production workflow, expanding the understanding of glass as a material with wide-ranging possibilities for a more performative architecture.

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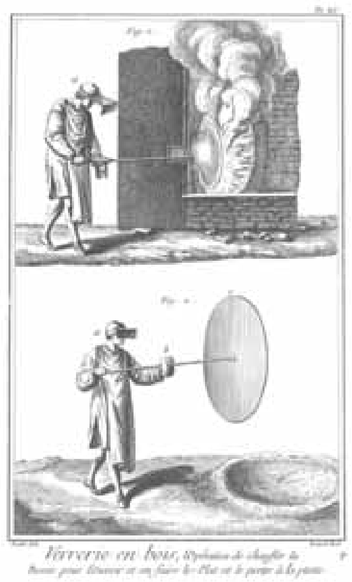

figure 1

INTRODUCTION/BACKGROUND

Specified as a component within nearly every complete building system, glass is an ever-present and easily overlooked aspect of our surroundings. Glass is overwhelmingly standardized in form and dimension, and recent advancements in glazing technologies have remained primarily targeted toward environmental and structural performance or manufacturing cost; rarely is the "flatness" of the work questioned. Even the historical development of flat-pane windows emerged from efforts to unroll or flatten the material from the forms in which it was blown (Figure 1), removing variation from the spatial characteristics and its volumetric implications (Staib 2007).

1.1 Theoretical Consideration

The introduction of industrially manufactured large-pane glass into the architectural lexicon could be considered a hallmark of the modern movement (Staib 2007), which leveraged its flatness alongside its thinness and transparency in the creation of the spatial experience. If the use of technology to accentuate the absence of mathematical curvature (i.e., flatness) is a characteristic of the modern movement (Tournikiotis 1999), then its application to achieve an abundant presence of curvature could likewise be a characteristic of the spatial and formal capabilities ushered in by the digital turn. Unfortunately glass's translation from one mode to the other has been hindered by the limitations placed upon it by its means of production, proving difficult to widely incorporate into emerging formal languages. Currently, the existing digital fabrication techniques for glass all deal with the material in its post-forming state. This makes it difficult for glass to be engaged by the processes that have enabled the production of more complex forms of architecture.

Despite these difficulties there have been a few notable efforts within the past 10 years to question both the flatness of glass and its typical application. While each contributes to the contemporary formal language of glass, none has been able to challenge the material's nature in a manner appropriate to the emerging performance goals of the built environment. One such example is the Prada Aoyama Epicentre in Tokyo by Herzog & de Meuron (Figure 2). In this project the facade glazing units are fabricated in three geometric configurations—flat, convex, and concave—and are placed according to programmatic proximities. The curvature in the convex and concave glazing units "was achieved by heating the flat planes … until the area began to sink beneath its own weight" (Prada Aoyama 2004). The limited palette of units was balanced through the patterning of their application, giving the visual appearance of more variety. The deformation of the glass was not intended to provide a performative characteristic, but was a formal gesture.

Another example of an aesthetic application of doubly curved glass panels can be found in the Hungerburg funicular railway stations in Innsbruck, Austria, designed by Zaha Hadid Architects (Figure 3). Each of the opaque glass panels is unique, described through the division of a complex doubly curved surface to minimize the amount of surface curvature across each panel (Schröpfer 2011). It is clear from the number of panels that an extensive library of custom molds was required for the forming process, making this solution prohibitively expensive.

An incremental improvement in this approach can be found in REX's Vakko Fashion Center in Istanbul, where an X-shaped deformation was introduced to the surface of the glass glazing units, produced with "a specially constructed oven in which the glass was heated locally on both sides and allowed to camber—under its own weight—3.5 to 4 cm away from the surface" (Figures 4 and 5) (Administrative Building 2011) in order to provide structural bracing across the assembly. Here the induced curvature of the glass was tied to specific performance criteria. While the project was able to question the function of sheet glass through the form given to it, it was only able to do so with a single glazing module, repeated throughout the facade.

These projects and others like them exhibit the interest within the profession to explore new ways to work with glass, challenging the modernist invocation of the material. Yet due to extensive manufacturing requirements, the means to directly experiment with the material is largely outside

figure 1

Crown glass-forming technique, circa 1770 (Glass Making 2010).

the reach of all but the highest of budgets. The methods presented in this research speculate on how the production of performative, doubly curved glazing can be democratized. Additionally, it explores the implications of integrating these methods into the design process through a singular process that expands upon preconceived spatial-tectonic notions of glass itself.

1.2 Material Considerations

Produced as a solid in the range of temperatures suitable for human exposure, glass is relatively difficult to modify in its firm state. Modifications to glass at these "cold" temperatures are primarily limited to operations of scoring, cutting, scratching, and etching—all techniques that run counter to glass's attributes of continuity, transparency, and smoothness. These cold techniques could further be associated with the operation of breaking glass, emphasizing the irreversibility of the material's formal qualities, as well as the limited subtractive nature of cold glass manipulation. As such, the default expectation and specification for glass presumes standard precut flat panels. While cold-bent, singly curved panels have seen limited use, the development of curvature in glass implies both complex panelization strategies, which further complicates the mullion system, as well as the introduction of costly thermal forming processes, which require highly specialized manufacturing facilities.

Created from a molten mixture of silicon oxide, alkaline oxides, and alkaline earth oxides, glass solidifies amorphously and without crystals. As such, none of its material properties have a directionality, and thus as a material it behaves more like a liquid. Because the structure of glass is amorphous, it has no distinct melting point; instead, as it moves through higher temperatures, the viscosity decreases as the temperature increases. Within a certain temperature range, glass is malleable and curvature can be induced more readily. If forced to curve at too low a temperature, stresses will cause brittle failure at areas of stress concentration. As glass moves above its glass transition temperature, it will begin to exhibit more ductile behaviors, allowing curvature to be induced. Upon cooling, glass will maintain the formal properties imposed upon it during its transition temperature. The structural capacity of the glass based on thickness, added stresses, weight distribution, and geometry must also be considered to prevent breakage.

As a consequence of its temperature-sensitive particularities, glass necessitates indirect methods of manipulation. Modifications within both temperature ranges require tooling as a mediator. Further, working with the formal composition of the material requires a controlled environment to move glass through the transition phase, hold it at the desired forming temperature, and move it back through the annealing phase for stress removal before its return to room temperature. As such, spatial and material experiments with glass are highly dependent on the surfaces and forces it encounters; in other words, its formwork or mold, and the controlled artificial environment dedicated to its alteration. Most often this is accomplished in a kiln, slumping or draping glass over a mold made of materials resistant to the temperatures required, manufactured to a specific shape, and resulting in a singular final geometry in the component. This process, while well proven, is inefficient, time intensive, and unforgiving of changes arising during the process.

1.3 Position

There exists an opportunity to instrumentalize the malleable state of glass when it is explicitly controlled through reconfigurable molding techniques, harnessing the spatial potentials embedded in the ability to manipulate and then solidify glass. If the tool set and artificial environment are engineered together as a system, the fabrication process becomes interlaced between the formal ambitions of curvature and the intrinsic qualities of glass. Reconfigurable molds result in a singular tool by which to achieve variability in output. Constructed with an intelligent range by which to modify output, the variability within the tool setup reduces waste by the elimination of multiple permanent molds. Such an ambition collapses variability in components and material operations into one output.

figure 2

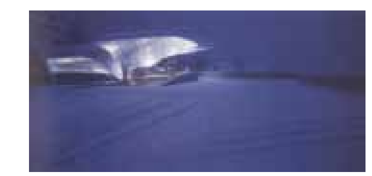

figure 3

figure 2

Prada Aoyama Epicentre by Herzon & de Meuron (Prada Aoyama 2004).

figure 3

Hungerburg funicular station, Innsbruck, Austria (Schröpfer 2011).

figures 4 and 5

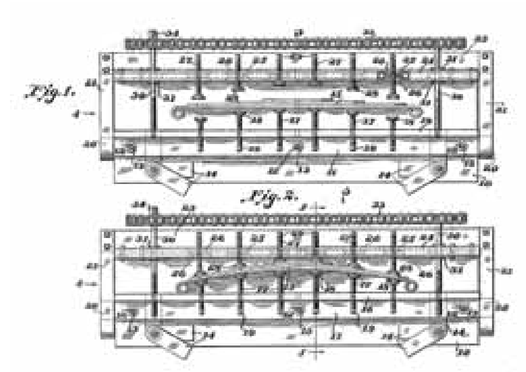

figure 6

The equipment and software developed for Glass Cast are tied very specifically to particular material attributes and modifications, providing potential for the highly controlled production of variably shaped glass panels.

2 APPROACH

The methodology tested here seeks to develop a suitable forming and finishing process for the production of doubly curved glass panels. Designing the system to produce double curvature allows maximum flexibility in the design of components, with the intent that such variability will be driven by external factors to enhance the overall performance of the glazing system. Implicitly, the system could also be used to produce simpler geometries that still benefit from the use of a reconfigurable molding system. The methodology incorporates the development of the forming process, the post-form trimming of panels, as well as the development of software-based tools to enable the feedback of process and material constraints directly into the digital modeling environment.

2.1 Reconfigurable Molding

Variable or reconfigurable tooling in molding and forming processes is not a new concept. It has attracted the interest of manufacturing engineers and designers alike for well over 150 years, as it promises to significantly reduce the unit cost to produce a unique component (Munro and Walczyk 2007). While many variations have been proposed over that time, one that appears repeatedly is a variable pin mold. The first recorded US patent of a variable pin mold was granted in 1863 to John Cochrane for the bending of metal plates in naval construction, with many derivative patents issued for the forming of carriage and automobile leaf springs (Figure 6) (Cochrane 1863).

A variable or reconfigurable pin mold can approximate a 3D surface in a way analogous to a multivariable integral in mathematics. By extracting the height of points on the surface according to a regular projected grid, the "pins" can be raised to support and geometrically approximate the surface. For some materials such as sheet metal, this would require the sheet to be fully constrained on its edges, and significant force applied to the array of pins as they are pressed into the sheet. For a material such as glass, temperature can be used to soften the glass to a point where gravity alone will induce plastic deformation.

The drawback of such a design is the inherent complexity, but one advantage is the flexibility of the system to make multiple parts from a single reusable system. The process of slump-forming glass takes advantage of the material's gradual transition from rigid to plastic. By forming at temperatures that are on the lower end of the forming range, the deformation can be minimized, allowing a sheet of glass to span short distances on the mold without continuous support. This is an important parameter, as producing a variable forming surface with continuous support increases the number of controlled points per unit distance; however, reducing this number also reduces the ability to approximate complex curvatures.

figures 4 and 5

Custom glass-forming equipment (left) and finished units (right), Vakko Fashion Center by REX (Administrative Building 2011).

figure 6

Patent drawing of reconfigurable pin tooling for the forming of leaf springs (Williams and Skinner 1923).

figure 7

The custom reconfigurable kiln in use.

figure 8

Similar kiln in use at Nikolas Weinstein Studios (Weinstein 2011).

figure 9

The primary components of the custom kiln: bell frame (A), insulated bell (B), reconfigurable pin array (C), platten cart (D).

2.2 Custom Reconfigurable Kiln

Due to the major modifications required to the forming kiln for the inclusion of a reconfigurable mold, a custom kiln was designed and fabricated in-house (Figure 7), closely based on a similar kiln in operation at the artisanal glass workshop of Nikolas Weinstein Studios (Figure 8). A variety of changes were made in an effort to improve the overall process efficiency as well as to adapt the process to the forming of sheet material.

The general schematic for the kiln is based around a "bell" kiln, with elements in the top of a moveable lid (Figure 9). The floor is composed of 99 articulated hexagonal tiles. The tiles can be raised by a servo-driven moving platen below, which constitutes a single axis CNC motion-control system. In order to create variation in the height of the floor surface, the tiles are driven by rods, using preset locking collars to engage the platen. The tiles can be removed or replaced with other forms based on desired formal outcome of the glass and the process by which it is to be manipulated.

Initially the research involved determining the correct heating cycles and testing the forming limits for the specific glass panels used. Each batch of glass from a manufacturer can have varying material composition and attributes, which in turn alter its forming characteristics. Similarly, the overall volumetric conditions of the kiln, as well as the layout of heating coils and thermocouples will alter the process model. Empirical testing is required to tune the kiln to develop a repeatable process for forming the specific type and thickness of glass.

As glass slumping is a dynamic process, parameters such as heating rate, soak time, strain rate for forming, and cooling rate all have to be tested in order to get reliable values. Material effects due to these parameters include stretch marks (Figure 10) that indicate excessive deformation rates, devitrification (a hazing effect), which is a result of glass being held at high temperatures for too long, and imprint marks from materials that come into contact with the glass at elevated temperatures.

Currently the kiln-forming process involves the following steps:

1. The servo positions the platen at the correct height for each lock collar, in sequence, allowing the manual setting of the collar height. After setting the 99 (or required number) of collars, the platen returns to the starting point.
2. The waterjet cut glass blank is placed in the kiln, and the heating cycle is started.
3. When the kiln has reached minimum forming temperature, the platen begins to rise. The platen engages each collar in order, slowly raising the respective tiles.
4. When the platen has reached the end of the stroke and the heating cycles are complete, the cooling cycle begins.
5. Cooling rates in glass forming go through several critical stages, most notably the annealing cycle. The glass is held at this point to remove residual stresses and prevent cracking of the piece. For this reason the glass cools considerably more slowly than it heats.
6. Once the panel has cooled, it is removed from the pins/tiles.

2.3 Process-Integrated Computation

In order to expedite the production timeline for the kiln-forming process, a custom computation workflow was developed in the Grasshopper plug-in for McNeel's Rhinoceros 3D modeling software. Leveraging open-source frameworks in tandem with the accessibility of the component-based visual programming language of Grasshopper, the final software component was able to accommodate both the design and production aspects of the glass-slumping process in one cohesive workflow. Providing design feedback based upon the physical capabilities of the glass/kiln pairing allows for the final geometry to be informed by material and fabrication constraints. By embedding these factors into the software, feedback loops develop on an intrinsic level (within the computational process) as well as an extrinsic level (within the fabrication process and workflow, which also includes the designer).

figure 7

figure 8

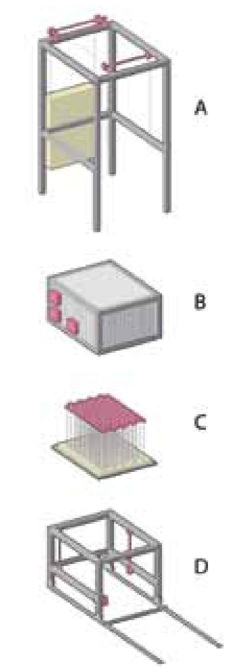

figure 9

figure 10

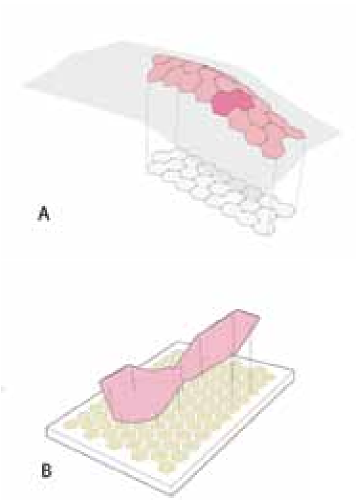

figure 11

The primary function of the Grasshopper definition is to provide the designer with feedback based on the capability of producing the designed geometry with the kiln. This was done through a careful analysis of the geometric properties of the desired final panel shape in comparison with empirically derived values such as the maximum surface curvature allowed by the reconfigurable pin tooling. If it is determined that the desired panel geometry exceeds the constraints of the process (i.e., moving a portion of the pin tooling beyond the acceptable vertical travel limit), the trouble area is visually identified through a color-coding system, showing the designers specifically where they need to focus their efforts. If desired, the definition can also make rudimentary design changes by automatically correcting the input geometry, providing a simulated surface of the new panel geometry that can then be integrated back into the assembly model.

The instructions required to control the servo that raises and lowers the kiln platen to the proper vertical locations for the setting of the lock collars are also generated by the Grasshopper definition. As the process-feedback portion of the definition requires the design geometry to be situated over a virtual kiln bed, computing the servo positions and exporting the information in the necessary file format for the kiln controller was a logical function to add to the workflow. A subroutine was introduced to locate the design geometry above the virtual kiln bed based upon a minimal bounding box condition to ensure an efficient usage of the servo movement (Figure 11). The inclusion of these steps further automates the closed-loop manufacturing system, generating the necessary machine control data in real time.

2.3 Robotic Abrasive Waterjet Trimming

In order to accurately produce doubly curved glass panels, a methodology was required for both sizing the panels prior to forming as well as trimming the parts after removal from the kiln. In order to limit deformations around holes for fasteners, this also required the ability to cut holes in the 3D formed surface accurately. Regardless of the manufacturing process used to cut the glass, trimming the parts after forming applied several strict requirements to the overall process.

Both milling and abrasive waterjet cutting are suitable for cutting glass. Milling provides the most accurate tolerances and leaves the highest-quality surface finish. This comes at a high cost for equipment and tooling, requiring machines similar in scale to the stone industry and diamond tooling. An alternative technique is the use of multi-axis or robotic abrasive waterjet cutting. Abrasive waterjet has the advantage of high cutting speeds with reasonably good edge finishes. Due to the cutting action, abrasive waterjet produces relatively small reaction forces in the material being cut. This is important as it reduces the forces on the fixture used to support the part, thereby making the fixture cheaper to produce.

Fixturing is an important aspect of any process where complex three-dimensional surfaces are machined. In the case where components are uniquely shaped, it is desirable to employ a reconfigurable jig. Modular vacuum grippers are an effective method for restraining glass during waterjet cutting, provided the geometry is not excessively curved (Figure 12).

In order to trim the panels, it is critical that the resultant panels closely match the original 3D models. Deviations of the actual surface from the 3D model beyond +/- 3 mm can result in poor-quality edges and tolerance issues with abrasive waterjet cutting, which typically uses an ideal standoff between the nozzle and the material of 2-4 mm. While it would be possible to digitize the toolpath to correct for discrepancies, in general, the requirements of surface continuity and the tectonics of assembly will have equally high tolerance requirements on the shape of the panel (depending on detailing). As mentioned before, the cutting process also uses a reconfigurable fixture set manually to "match" the panel. This manual step therefore requires that after the panel is locked into place by the vacuum gripper, three known points must be measured on the surface of the part, in order to compensate for the variable placement of the fixture. These three points are used to transform the toolpath to match the real-world position of the glass.

figure 10

Glass "stretch" as a result of movement at high temperatures.

figure 11

Two parts of the computational process in Glass Cast: the generation of the glass panel geometry (A) and the extraction of the pin heights for slumping (B).

figure 14

figure 12

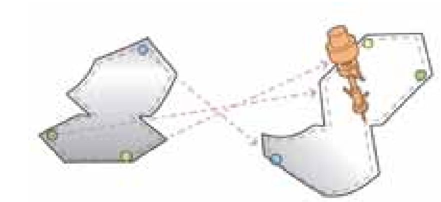

figure 13

figure 15

3 FINDINGS

In order to test the general methodology described, an installation was designed and built as a proof of concept. Currently two alternative methods for forming panels have been tested. For the installation, a technique referred to as catenary or drape forming was used (Figure 14). In this method the panels are supported from predetermined attachment points, at corners of a flat panel, as opposed to fully supporting the entire surface. The placement of these corners corresponded with the diagonal grid that makes up the floor of the kiln. By supporting the glass at the corners, the height of each corner was individually set in order to control the tangency of the edges of the panel. The shape of the panel was also controlled by varying the maximum temperature and duration of the forming cycle; longer, hotter cycles result in deeper catenary shapes. One advantage of this technique is that by minimizing any contact with surfaces in the kiln, surface clarity is preserved. In addition, the process maintains a more explicit control over the points, which later became the points of attachment for the installed glass panels. One disadvantage is that the technique limits the control of tangency at the attachment points, due to limits on the angular flexibility of the pivoting rod ends.

In addition, due to the fact that the "draping" technique offers very little control over the curvature at points away from the fixed corners, this technique is not well suited to post-forming trimming of the panels. In cases where precise trimming is required, development of the fully supported slumping technique is better suited. This technique was tested through the development of a series of forms designed with G1 continuity, panelized appropriately for the constraints of the kiln. All of the pins within the projected area of each panel were set and utilized. The advantages of this technique include strict control over the geometry of the surface and the ability to post-cut with the robotic waterjet process. This resulted in an improvement to the tolerance of the surface curvatures, as well as the edge profile. This method presented difficulties as well, driven by the need to limit the plasticity of the glass to prevent marking by the hexagonal tiles (Figure 16). Several solutions are proposed for this—including the generation of a smoother forming surface for the tiles—and will be tested in future research.

The proof of concept installation (Figures 17–19) demonstrated the full cycle of the design process, from formal ambitions to equipment and tooling construction, as well as process modifications based on material attributes and computational feedback leading to the final physical output.

figure 12

Multi-axis robotic abrasive waterjet trimming of a glass panel on a custom reconfigurable vacuum gripper jig.

figure 13

Three-point transformation of toolpath from digital model to digitized panel orientation.

figure 14

Glass panel in kiln after drape forming.

figure 15

Hexagonal tiles used in full-support slumping.

figures 16–19

Ongoing research seeks to refine the process model with respect to the time and temperature relationship to curvature, as well as the capability to resolve the boundary conditions for panels to a reasonable level of tolerance, as required by contemporary facade systems.

4 CONCLUSIONS

This research investigates the capabilities for developing continuous, doubly curved, panelized glazing systems through reconfigurable tooling. Rarely are the formal and performative possibilities of glass challenged within the built environment, due to the difficulties associated with forming panels accurately, as well as the high cost of associated tooling.

The typical expectation is that glass will be a flat pane, thus reinforcing the ubiquity of the formal qualities of sheet stock prevalent among contemporary building systems. By embedding the understanding of material behaviors, process constraints, and production efficiencies into computational design tools, the overall methodology can evolve beyond the influence that any single factor can produce. Through in-depth material and process experimentation, architectural production can move beyond a simple subtractive manipulation of industrially manufactured sheet materials using CNC production techniques, toward a more performative, material- and process-centric approach, which preserves design intent throughout the design and fabrication process. This research can therefore be seen as an example of a method of working that necessitates the development of feedback loops between material, process, and the role of the designer toward a more performative materialization of architecture.

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figures 16–19
Finished proof of concept installation.

FUNCTIONALLY GRADED AGGREGATE STRUCTURES:
DIGITAL ADDITIVE MANUFACTURING WITH DESIGNED GRANULATES

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ABSTRACT

In recent years, loose granulates have come to be investigated as architectural systems in their own right. They are defined as large numbers of elements in loose contact, which continuously reconfigure into variant stable states. In nature they are observed in systems like sand or snow. In architecture, however, they were previously known only from rare vernacular examples and geo-engineering projects, and are only now being researched for their innate material potentials. Their relevance for architecture lies in being entirely reconfigurable and in allowing for structures that are functionally graded on a macro level. Hence they are a very relevant yet unexplored field within architectural design.

The research presented here is focused on the potential of working with designed granulates, which are aggregates where the individual particles are designed to accomplish a specific architectural effect. Combining these with the use of a computer-controlled emitter-head, the process of pouring these aggregate structures can function as an alternative form of 3D printing or digital additive manufacturing, which allows both for instant solidification, consequent reconfiguration, and graded material properties.

In its first part, the paper introduces the field of research into aggregate architectures. In its second part, the focus is laid on designed aggregates, and an analytical design tool for the individual grains is discussed. The third part presents research conducted into the process of additive manufacturing with designed granulates. To conclude, further areas of investigation are outlined especially with regard to the development of the additive manufacturing of functionally graded architectural structures.

The potentials of the methodologies developed in this process are shown through the fabrication of a full-scale installation. By integrating material, fabrication, and design constraints into a streamlined computational methodology, the process also serves as a model for a more intuitive production workflow, expanding the understanding of glass as a material with wide-ranging possibilities for a more performative architecture.