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.

1 INTRODUCTION: AGGREGATES IN ARCHITECTURE

Aggregates are defined as large amounts of individual elements lying in loose contact to each other (Cambou 1998; Duran 2000). They are known from naturally occurring systems such as sand (Bagnold 2005) or snow (Nicot 2004; Rognon 2008). In architecture, however, loose granular systems are rarely deployed (Hensel and Menges 2008a, 2008b; Hensel, Menges, and Weinstock 2010; Dierichs and Menges 2010a). The few examples range from building physics (Hausladen 2006) to vernacular architecture (Houben 1989), geoengineering (Trummer 2008), and building construction (Treib 1996; Dierichs 2010; Gramazio and Kohler 2011a, 2011b). In terms of an actual architectural application, aggregates have been investigated most directly under Frei Otto (Gaß and Otto 1990) and more recently at the Architectural Association and Rice University (Hensel and Menges 2006a, 2006b, 2006c, 2006d).

However, both on a design methodological level and on a purely constructional level, loose aggregates are highly relevant as a field of architectural design research. Known architectural assembly systems allow the architect to precisely define the exact shape and location of the individual element within the overall architectural structure. Granular systems, however, challenge the designer to merely observe and interact with the evolving system and thus to guide rather than to plan these architectural arrangements. They thus open up the necessity to develop a novel design methodological approach (Hensel and Menges 2008a, 2008b). On a constructional level, the relevance of loose granulates as architectural material systems lies in their capacity to be entirely reconfigurable and to allow for functional grading using variant particle morphologies within one and the same material system (Dierichs and Menges 2012a). Aggregate structures hence present a relatively unexplored yet highly promising field of architectural research and design.

In this context, the focus of the research presented here is on the introduction of digitally poured aggregate structures using designed granular systems. As opposed to pick-and-place robotics, where the building parts are distributed in a controlled manner, the designed granular matter here is flowing out of a custom-made effector for the robot. This specific application can be seen as a form of digital additive manufacturing allowing eventually for the production of full-scale architectural structures (Figure 1).

In part 2 the paper will discuss the design of granulates with regard to their architectural performance using the notion of convex and concave hulls as a starting point. In part 3 a concise overview of the state of the art investigation of digital additive manufacturing will be given. This makes it possible to place the proposed method within the context of current research and to highlight its advantages and possible disadvantages. The fabrication method will consequently be described in greater detail using a six-axis industrial robot as a digitally controlled pouring device. In conclusion, an evaluation will be made as to how functionally graded designed granulates can be further used in combination with a digitally controlled additive manufacturing process.

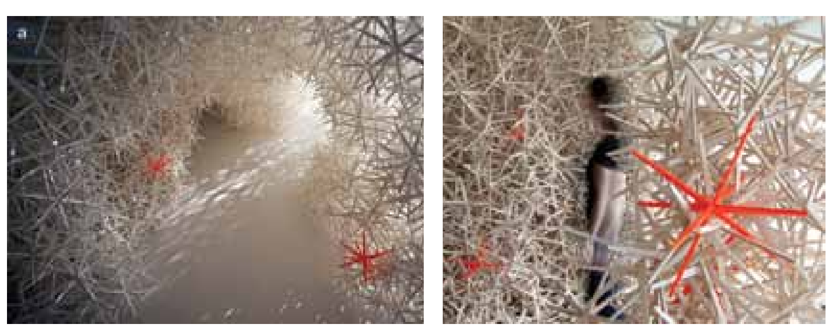

figure 1

figure 1

Prototype Aggregate Structure 2011 consisting of 50,000 particles (a) and full-scale Aggregate Structure 2011 (b).

figure 2

2 FUNCTIONAL GRADING OF DESIGNED GRANULATES

Functionally graded materials (FGM) are defined as material substrates that can change composition and structure. They thus display differentiated properties, which enables them to respond to varying design criteria within one and the same material structure (Miyamato et al. 1999). The concept applies to a very wide field of potential applications, ranging from machine engineering to medicine and automotive design. They are also increasingly introduced in the building sector. Their advantages lie in being materially efficient by responding in a very refined manner to the design parameters they encounter (Miyamato et al. 1999; Oxman 2010; Herrmann, Haase, and Sobek 2011; ILEK 2012).

In the context of the research into additive manufacturing with designed granular matter presented here, the following section will focus on functional grading of designed granular matter for architectural applications. Initially, the basic notions of convex and concave hull are introduced as an analysis and design tool for individually designed particles. Already developed particles are analyzed, and from there, a specific sheet-material fabrication geometry is developed that makes it possible to produce functionally graded granular matter from one sheet leaving only 7 percent waste.

2.1 Convex and Concave Hulls

Defining the convex and concave hulls of a set of points is one of the basic problem sets in computational geometry. A convex hull is defined as the polygon enveloping a given set of points, where all interior angles are lower than 180 degrees; a concave hull is defined as the polygon enveloping a given set of points, where interior angles are higher than 180 degrees (de Berg et al. 1997). Especially in the numerical simulation of granular matter, the concept is frequently applied, as concave hulls of a particle shape need to be simplified into convex hulls in order to render the overall simulation computationally lighter through the simplification of collision detection between particles.

2.2 Analysis of Designed Particle Morphologies

The notion of convex and concave hulls is integrated initially into an analysis system for particle designs already developed in an architectural context. This analysis comprises altogether six categories: the bounding box (01), the convex hull (02), overall concave hull (03), detailed concave hull (04), plate number (05), and joining steps (06) (Figure 2).

The bounding box (01) serves to analyze the aspect ratio of a particle, which is the relation of the longest to the shortest axis. The convex hull (02) maps the outer convex face of all points defining the particle. The overall concave hull (03) maps the first level of concavity without detailed features. The detailed concave hull (04) maps and identifies all features of the particle. The plate number (05) counts the number of plates needed to compose the particle if sheet material is used. In combination with this, the joining steps (06) describe the number of steps needed to join the final particle.

Altogether five particle designs which have been developed over the past nine years at the Architectural Association, Rice University and Stuttgart University, have been analyzed in order to establish a first morphological catalog of designed architectural aggregates (Figure 3).

figure 2

Detail of particle-analysis categories sampling the particle design developed by Anne Hawkins and Catie Newell (tutors: Michael Hensel and Achim Menges) at the GDA Studio/Rice University, showing bounding box, convex hull, overall concave hull, and detailed concave hull.

figure 3

Overview of the analysis by bounding box, convex hull, overall concave hull, and detailed concave hull of five particle types developed specifically for architectural applications.

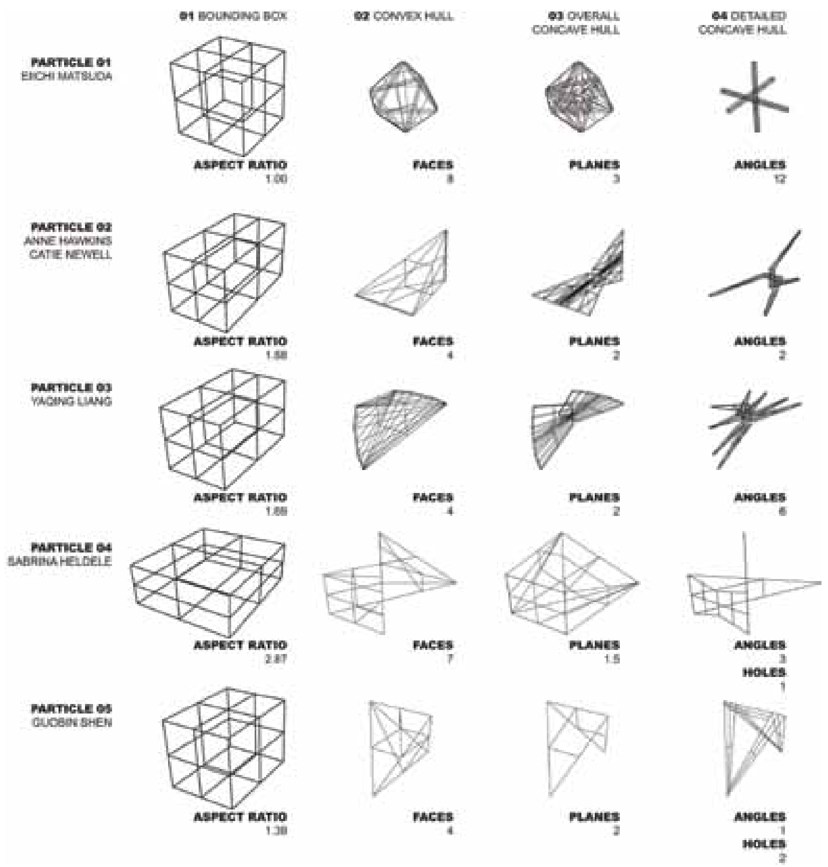

figure 3

Comparing the results in the category of the bounding box (01), Particle 01 by Eiichi Matsuda shows the lowest and Particle 04 by Sabrina Heldele the highest aspect ratio. In the category of the convex hull (02), Particle 01 shows the highest amount of faces. Again in the analysis of the overall concave hull (03), Particle 01 shows a maximum of eight planes and thus of concavity. The analysis of the detailed concave hull (04) leads to a more qualitative assessment of the particle designs, identifying the two main different morphological features developed so far—the angle and the hole—and their respective frequency in a given design. In terms of amount, Particle 01 shows the highest count of angles with 12 altogether but no additional morphological features. The plate number (05) and joining steps (06) are lowest in Particles 02 by Anne Hawkins and Catie Newell and 03 by Yaqing Liang, with only two pieces and one move needed to assemble the entire particle from sheet material.

The performance of the overall granular system is of course governed by the individual particle's morphology. The following, however, is only to be understood as an indication of possible effects, as more detailed experiments both on the scale of a few hundred and on the scale of tens of thousands of particles need to be conducted to verify the exact relationship between the categories established and the overall system's performance. The bounding box and through that the aspect ratio can calibrate the angle of repose of an aggregate, with higher aspect ratios leading to steeper angles (Ball 2004). An increase of the number of faces in a convex hull may lead to a higher degree of friction within the system, leading to greater load-bearing capacity. Equally, the number of planes

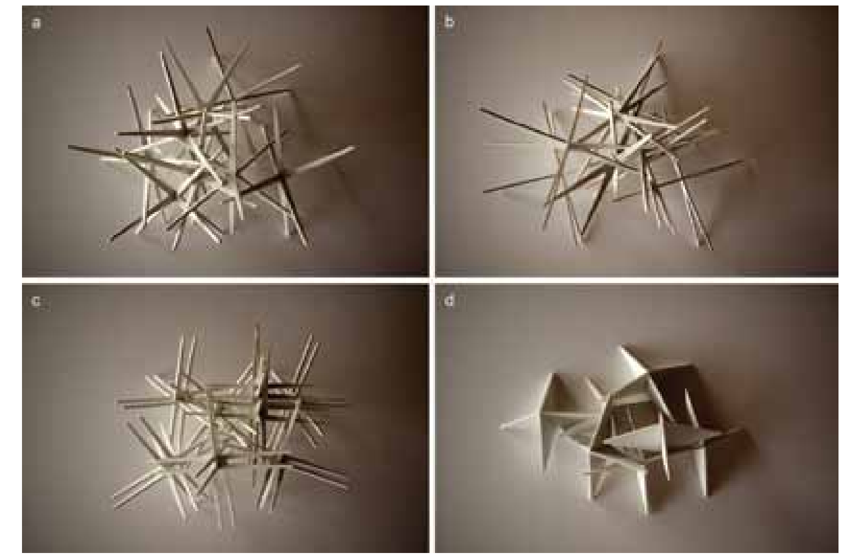

figure 4

figure 4

Particle types achieved through geometric variation and nesting showing 60 degree x-type (a), 30 degree x-type (b), slotted t-type (c), and rhomboid (d).

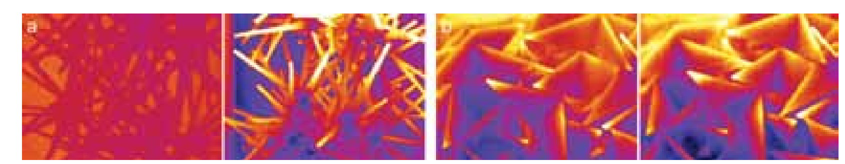

figure 5

figure 5

Performance under rapid cooling is tested for the 60 degree x-type (a) and the rhomboid particle type (b).

in the overall concave hull and angles in the detailed hull control interlocking between particles and will proportionally increase frictional contact points. The plate number and joining steps needed to manufacture the particle obviously govern the production time and cost, which are very relevant parameters considering that numbers of parts quickly move into categories of tens of thousands.

2.3 Sheet-Material Fabrication of Functionally Graded Designed Granulates

Based on the above analysis of existing particle types, a new design has been developed, combining mainly the features of Particles 01, 02, and 03. The new type uses the same joining principle of a simple slot-joint seen in Particles 02 and 03, thus allowing for only one joining step and making the design suitable for sheet-material production processes such as waterjet- or lasercutting. The geometry, however, in its simplest form of a nested t-shape would display the exact morphology of Particle 01, which in terms of faces, planes, and angles showed the maximum potential of frictional interlocking between particles. Varying the element's geometry from a t-shape to a nested x-shape widens the morphological and subsequently the aggregate's performance in three directions. First, it adds two interlocking angles, increasing the count to 14. Second, varying the angle between the sides of the basic x-shape adjusts the bounding box, regulating the angle of repose as well as the packing density, with lower angles packing more tightly than wider ones. Third, the negative form of the sheet-material can be designed to form another type of granulate, starting from a basic rhomboid.

Through this, the sheet-material is used to a maximum of 93 percent, i.e., leaving almost no waste and at the same time producing morphologically differentiated granulates. Additional features can be added such as holes within the rhomboid or slots within the arms of the basic t-shape (Figure 4).

Several small-scale tests have been conducted in order to investigate the behavioral effects of these morphological variations. For example, varying the angle between the branches of the x-shape from 60 degrees to 30 degrees leads to a 30 percent higher packing density of the granulate at the same material mass. Load-testing was conducted on both the basic t-shape with added slots and the 60 degree x-shape particle. The slotted t-shape resulted in a slightly higher force-tension curve than the 60 degree x-shape. Equally, the insulation capacity of the 60 degree x-shape particle was compared to the basic rhomboid shape, with the x-shape showing rapid cooling and the rhomboid retaining heat due to its higher mass (Figure 5).

The possible morphological variations and their effects on the overall behavior of a granulate have been shown on a very simple level. Research needs to be directed toward further morphological refinement and also toward testing the effect of those variations on the behavior of the entire granular system. One possible layer of information can be the investigation of snow crystals, which display similar concave geometries (Dierichs and Menges 2012a).

3 ADDITIVE MANUFACTURING WITH DESIGNED GRANULATES

Additive manufacturing is defined as a process where material is disposed of and joined in layers according to a frequently digitally defined tool-path. It is the opposite process of subtractive manufacturing, where material is removed sequentially. In recent years, there has been an increased focus on additive manufacturing on an architectural building scale (Soar and Andreen 2012). In this part of the paper, the most prominent examples of this tendency will be introduced briefly. Subsequently the proposed fabrication method of using designed granulates in combination with a digitally controlled emitter-head will be explained in greater detail, highlighting its specific advantages in the context established.

3.1 Additive Manufacturing in Architecture State of the Art

Architectural practice has started to engage with additive manufacturing since roughly 10 years ago (Soar and Andreen 2012). The aim here is to take the manufacturing process from relatively small prototyping applications into the printing of buildings or parts of buildings. Initially Joseph Pegna developed an additive fabrication method solidifying cement with steam in 1997, and in 2001 Behrokh Khoshnevis of the Viterbi School of Engineering at the University of Southern California developed the "Contour Crafting" system (Contour Crafting 2012; Soar and Andreen 2012). These first approaches were followed by developments at Loughborough University in 2003, where a large-scale free-form construction facility was created (Menges 2008; Soar and Andreen 2012). Almost in parallel, Enrico Dini researched, patented, and tested the possibility of an "epoxy resin and binder printing machine" in 2004 and in 2007 patented D-Shape, an inorganic full-scale additive manufacturing process (Dinitech 2012; Soar and Andreen 2012). In 2008 the 3D Concrete Printing Group at Loughborough University under Richard Buswell transformed the large-scale facility; the group is investigating concrete printing on a building scale. It makes it possible to build one-to-one scale architectural structures according to numerical input using a technique that deposits concrete very accurately (Loughborough University 2012a; Soar and Andreen 2012). In the same year, Rupert Soar formed Freeform Construction Ltd in order to further develop the MineralJet manufacturing process (Loughborough University 2012b; Soar and Andreen 2012).

In 2011 Fabio Gramazio and Matthias Kohler at the ETH in Zurich investigated sand as a freeform concrete mold, which might be seen as a form of additive manufacturing if one is considering the production process as a whole. Whereas nonstandard concrete molds tend to use materially expensive and frequently subtractive production processes, this research project investigates the use of sand as a reusable mold. The sand-mold is poured using a robotically controlled emitter-head, allowing for a wide scope of free-form molds based on the granulate's innate behavior as well as the pouring patterns and specific tool designs (Gramazio & Kohler 2011). Similar processes have been researched at the AA Emergent Technologies and Design Programme in 2008, where the sand-mold is formed by environmental parameters such as airflow and is subsequently covered with a granular phase-change material to produce the actual building part (Dierichs 2008).

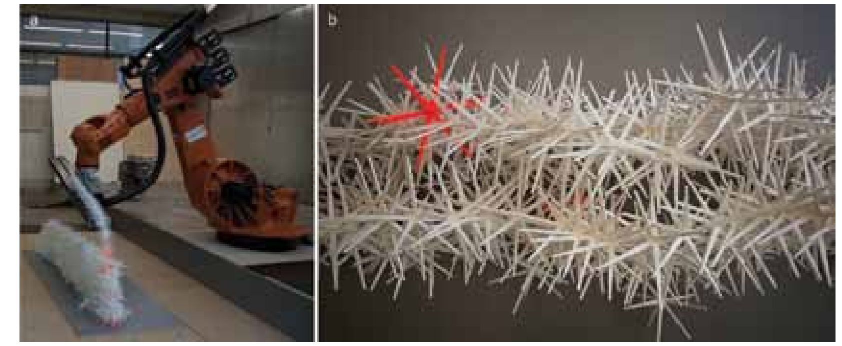

figure 6

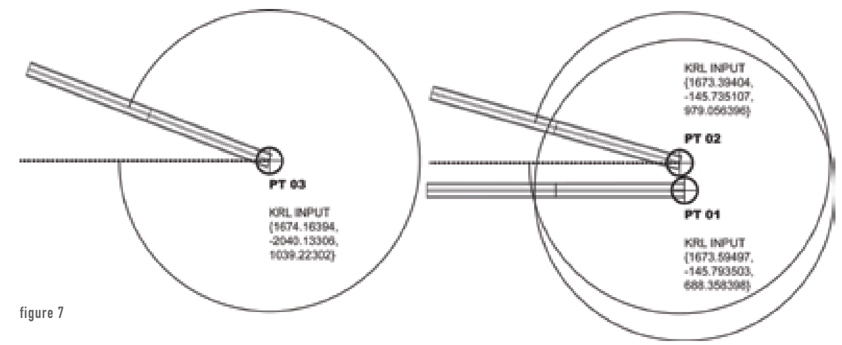

figure 7

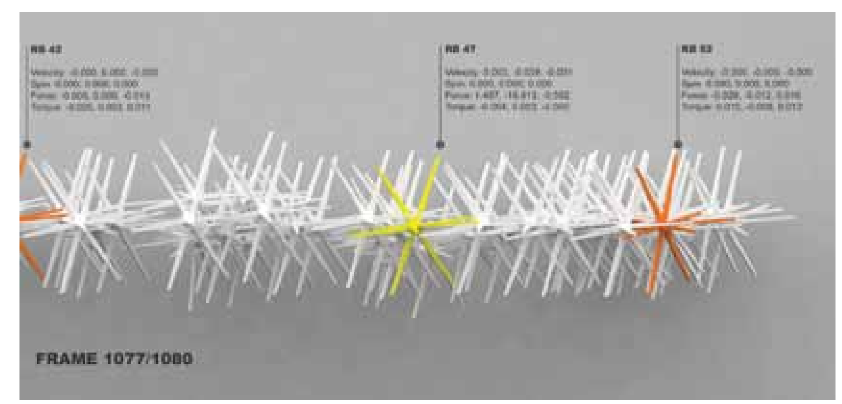

figure 8

figure 6

Full view of robotic pouring using a magazine emitter-head (a) and detail of the poured Aggregate Structure (b).

figure 7

Computationally derived rotations of the magazine emitter-head, which are linked to a Rigid-Body Dynamics simulation software (K. Dierichs, T. Schwinn).

figure 8

Detail of Rigid-Body Dynamics simulation of linear robotic pouring with a magazine emitter-head. Five sets of 25 particles each have been simulated. Selected particles are color-coded for comparison with physical experiments.

3.2 Architectural Additive Manufacturing with Designed Granulates

The proposed construction process of additive manufacturing with designed granulates at an architectural scale can be seen as a viable alternative to current state-of-the-art methods. This part of the paper will give a brief assessment of digital additive manufacturing with designed granulates in the state-of-the-art context established. Subsequently, a specific application of the manufacturing process using a six-axis industrial robot will be described in greater detail. Given the construction materials applied in the currently known additive manufacturing processes introduced in section 3.1, the actual production process tends to be very time-consuming, as in general terms one layer needs to be cured before the next one is applied. Additionally, the structures might be recyclable, but they are not reusable as phase-change mostly cannot be reversed. Using designed granular substances, however, allows for fast-binding and fully reversible material arrangements. Designed aggregates are, as it were, reversible phase-change materials, where the duality of aggregate and binder is transposed into a single material—the aggregate—in which the function of the binder is replaced by friction joints. The detailed design of the individual granulate has been discussed in detail in section 2. Another critical point is that all additive manufacturing processes currently researched focus on solid, heavyweight construction. In contrast the manufacturing process proposed here offers the possibility of lightweight construction, an increasingly important characteristic in many applications.

3.3 Robotically Poured Aggregate Structures

As a case study, a specific manufacturing process with designed granulates using a six-axis industrial robot as a digitally controlled emitter-head is investigated (Figure 6). In this experiment, the robot is equipped with a linear magazine-emitter head, which allows for the interlocking of granulates only after pouring. Other pouring devices such as pumps can be developed to achieve different and possibly even more controlled aggregate configurations.

In its most basic application, the magazine is filled with the designed granulate, tilted in the z-axis, and moved in the y-axis at 75 percent speed. The granules interlock to form self-supporting linear structures (Figure 6b). Further research is currently being conducted in varying the tool-path to form differentiated spatial configurations.

Using an industrial robot offers the opportunity to control the robotic pouring paths with numerically defined points through accessing the Kuka Robotic Language (KRL). This makes the experiments reproducible, on the one hand, which is especially interesting with regard to a material that has a high degree of self-forming behavior. On the other hand, this numerical control makes the connection to a simulation program possible, which in turn allows for the pre-simulation of pouring paths. For that purpose a link between KRL, a parametric design environment, and a Rigid-Body simulation tool has been established (Figures 7 and 8). This makes it possible to either translate the KRL input points into the 3D model space of the simulator, which would be called a forward conversion, or (vice versa) to translate the digital pouring pattern into machine control code, which would be called a backward conversion. Physics-based modeling in advance of the actual experiment can be applied in order to pre-test a wider variety of pouring configurations as well as to investigate micromechanical behaviors within the granulate (Pöschel and Schwager 2005; Dierichs and Menges 2010b, 2012b).

Integrating robotic sensing can further refine the manufacturing process with designed aggregates, so that the emerging configuration can be scanned and pouring patterns respond in a feedback process.

Further research needs to be directed toward more differentiated spatial arrangements as well as toward refining the digital pouring device itself. The production method seems, however, to short-circuit specific issues encountered in known additive manufacturing processes, namely the relative duration of the production process as well as the reusability of the material.

4 CONCLUSION AND OUTLOOK: DIGITAL ADDITIVE MANUFACTURING WITH FUNCTIONALLY GRADED DESIGNED GRANULATES

Initially, the functional grading of architectural granular systems has been discussed starting from an analysis of already existing particle designs. The newly developed particle type for sheet-material manufacturing has been explained in its morphological features and first performative tests. Consequently, the general process of digital additive manufacturing with designed granulates has been introduced using a robotic pouring method as a case study. Its advantages—the fast frictional interlocking as well as the capacity to fully decompose the aggregate—have been highlighted and positioned within the current state of the art of additive manufacturing.

Using functionally graded granular macro-matter within the process of digital additive manufacturing on an architectural scale can eventually allow for achieving graded performative effects within one and the same material system. The goal for future research is, on the one hand, the development of viable robotic-pouring patterns eventually leading to full-scale architectural structures with differentiated spatial organizations. On the other hand, various individual granular morphologies need to be developed that allow for calibrating the functionality of the granular structures especially with regard to the structure's solidity and insulation. These granular morphologies need to be tested both on the scale of a few hundred and on the scale of several tens of thousands of particles.

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THE DIGITAL-PHYSICAL FEEDBACK LOOP:
A CASE STUDY

ABSTRACT

Kukje Art Center, Seoul's new gallery designed by architects SO-IL, features a totally bespoke chain mail mesh system. A single sheet of double-curved, tensioned mesh, made of interlocking rings, wraps the building. This paper discusses the stages of a feedback loop process employed by the authors to refine a digital model of the mesh that captures chain mail's behavioral tendencies as it negotiates the building's geometry. At each stage of the feedback loop process, the working digital model was used as the basis for a physical mockup, which was used to evaluate and refine the digital model. Ultimately, the model output of a relaxation algorithm was used as the basis for engineering simulations and the sizing of the mesh that wraps the building.

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