AGGREGATE ARCHITECTURES: OBSERVING AND DESIGNING WITH CHANGEABLE MATERIAL SYSTEMS IN ARCHITECTURE

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INTRODUCTION

Architectural systems commonly seek to form clearly defined and seemingly permanent material assemblies. These are consequently structures where the both the location and the morphology of each element is assigned and controlled by the designing architect (Hensel and Menges 2008a, 2008b). However in recent years a specific class of material systems has come to be investigated, that challenges such notions of both permanence and control: loose granulates, which are known to the construction industry mainly in their bound form as an additive in concrete construction, are now being researched for their potential as a material system in their own right (Hensel and Menges 2008a, 2008b; Dierichs and Menges 2012).

Figure 1. Full-scale Aggregate Structures can be arranged by the designer rather than assembled.

Designing with such an aggregate system requires the architect to observe the system rather than to define its eventual form, to inter-

act with the evolving arrangement rather than to control its overall assembly (Hensel and Menges 2008a, 2008b). Aggregate Architectures thus not only require the development of a novel architectural material system on a purely constructional level, but also on the level of the design methodology itself (Figure 1).

The paper will give a brief introduction into aggregates in general and into aggregates in architecture in specific. The question highlighted will be that of observing and designing with loose granulates as a changeable architectural material system. It will be investigated using two case studies from different realms of aggregate architectures that require the architect to intervene in different manners respectively. This will allow for a wider discussion of the potentials and restrictions of designing with different degrees of permanence in an architectural material system.

AGGREGATES IN ARCHITECTURE

Aggregates are described as large amounts of elements being in loose, frictional contact (Cambou 1998). In natural systems they are known from sedimentary substances like sand or gravel, or from snow crystals (Bagnold 1954; Nicot 2004; Rognon, Chevoir and Coussot 2008). They display a range of sometimes counter-intuitive behaviors such as expansion under compression (Duran 2000) or the loads being highest at the periphery of a sand-pile rather than in its center (Ball 2004).

In architecture granulates are mainly known as an additive in concrete construction, yet are very rarely used as architectural material systems in their own right (Hensel and Menges 2008a, 2008b). There are five areas, where previous applications of loose granular matter are known. In Building Physics (i), aggregates are frequently used as an insulation material (Hausladen, de Saldanha and Liedl 2006). In Vernacular Architecture (ii), loose gravel is poured into wall structures both for stability and insulation (Houben and Guillot 1994). In Building Construction (iii), sand is used as a flexible and recyclable mould (Treib 1996; Dierichs 2010; Gramazio and Kohler

2011a, 2011b). Even though Geo-Engineering (iv) applies mainly to landscape interventions, attempts are being made at also using these sedimentary processes for architectural-urban applications (Trummer 2008). The most definite research into aggregates as architectural material systems however has been undertaken in the area of Form-Finding (v) both under Frei Otto (Gaß and Otto 1990) and more recently at the Architectural Association. Both natural and designed granulates have been investigated with regards to their behavior under self-load, airflow and different climatic conditions (Hensel and Menges 2006a, 2006b, 2006c, 2006d).

Despite these precedents, loose granular systems are a relatively unexplored field of architectural research and design. They do however display highly relevant characteristics both on the constructional and design methodological level, namely their capacity for continuous recycling as well as functional grading on the one hand and the need for the development of a novel attitude towards designing that allows the system to evolve, only varying the degrees of interaction (Figure 2).

Figure 2. A designed granulate re-configures through an outside trigger from one stable state to the other.

OBSERVING GRANULATES: MATERIAL AND MACHINE COMPUTATION

Prior to intervening with the aggregate system, the designing architect needs to develop suitable tools of observation, that render information about the granulate's performance both on the macro- and the micromechanical scale. This observation of a changeable material behavior is a fundamentally different design approach to the known architectural production mode of planning a definite and permanent form.

Computation being in principle information processing, the notion of Material and Machine Computation has been established (Dierichs and Menges 2010; Dierichs and Menges 2012). In this sense computation as an observational method renders the designer capable of relatively neutrally discovering the system under question, and is thus very suitable for the investigation of granular systems.

Material Computation denotes all computational procedures, where a material substance is doing the processing (Spuybroek 2004; Stepney 2008). Machine Computation requires the use of an abstract mathematical model that is doing the calculations. Both modes of computation can happen in an analogue and a digital fashion, where analogue simply means the continuous stream of

information whereas digital denotes the breaking down of information into discrete parts (Loleit 2004; Schröter 2004).

As aggregates are a widely researched field in disciplines other than architecture such as geology and industrial processing, the methods of observing granulates both through experiments and simulations are relatively well-developed.

Material computational methods for granular systems use different experimental setups depending on the forces affecting the aggregate (Bagnold 1954; Hicher 1998; Duran 2000; Dauchot, et al. 2002; Lanier and Radjaï 2009). Also, boundary conditions are varied to test for example 2.5 D and 3D set-ups (Duran 2000; Dauchot, et al. 2002). Particle coloration is frequently applied to trace so-called witness particles (Ball 1999; Duran 2000). The data thus gained are collected using photographic techniques and image evaluation procedures (de Josselin de Jong and Verruijt 1969; Duran 2000; Dauchot et al. 2002; Ball 2009).

Machine computational methods for aggregates use different mathematical models to compute the behavior of the granulate. The Discrete Element Method (DEM) is the most widely-spread model. It allows for the computation of soft spherical particles (Cundall and Strack 1979; Pöschel and Schwager 2005). Event-Driven Molecular Dynamics (ED) is mainly used for sparse particles systems with hard collisions using an event-based time-stepping model (Luding 1994; Pöschel and Schwager 2005). Rigid-Body Dynamics Algorithms apply to hard polygonal particles and use an inverse manner of computing forces from a list of contact points (Pöschel and Schwager 2005; Featherstone 2008). Discrete Simulations Monte Carlo (DSMC) calculate overall behavioral probabilities for an aggregate rather than the motion of individual particles (Pöschel and Schwager 2005). The suitable method thus needs to be chosen depending both on the system and the behavior itself that is to be evaluated. Common aim to all methods is the reduction of time required to do the computation, the so-called computational cost.

Both Material and Machine Computation need to be applied in conjunction in order to investigate a specific granular system. Whereas material procedures allow for the observation of large granular masses, they do not offer the possibility yet of establishing an accurate 3D digital Model and the collection of numerical data is very cumbersome. Machine computational procedures find their limits in the amount of particles that can be processed – currently 10000 on a regular personal computer (Pöschel and Schwager 2005), yet in those limits they offer the possibility of 3D digital Models as well as inherently rendering exact numerical data about each individual particle, such as forces, torques and speeds. They are especially relevant with regards to collecting information on the micro-mechanical behavior of a granular substance.

Observing aggregates thus requires the combination and evaluation of information gathered both from material and from machine computational processes.

DESIGNING WITH GRANULATES: MODES OF INTERACTING WITH THE AGGREGATE SYSTEM

One can discern two fields of influence affecting an aggregate system. First, there can be natural forces affecting the system, such as gravity, wind or environmental vibration. These need to be strong enough in magnitude to let the aggregate re-organize from one stable state to the other. Such natural processes can be observed especially in sedimentary environments, such as coastal dune-fields or deserts (Bagnold 1954; Siever 1988; Hensel, Menges and Weinstock 2010).

Second, artificial influences can affect the system, such as deliberate pouring of the aggregate, re-organizing it, adding grading to the material, using formwork, or even artificial vibration and -airflow. CAM tools such as industrial robots can be equipped to produce such influences, thus maximizing the control over the influencing parameters (Dierichs and Menges 2012).

In both cases, the system frequently displays self-organized criticality that is the spontaneous re-organization of the system from one stable state to the other without the need to accurately tune its parameters (Bak, Tang and Wiesenfeld 1987). Change thus does not only happen through the controlled process of adding or removing parts but also through momentous re-organization (Dierichs and Menges 2012).

Consequently there are two modes of designing: Either the architect can strategically intervene through artificially influencing the system or he or she can observe the natural influences affecting it, letting formations happen and only being able to predict probable outcomes. These two modes are occurring in combination in almost any Aggregate Architecture, as merely observing natural processes would not qualify as a design process and purely artificial control of the granular system is virtually impossible.

The architect then becomes a choreographer of events. These events can be seen as actualizations of virtual states rather than realizations of possible configurations. In this regard they are novel phenomena (Kwinter 2003).

CASE STUDY 01: GEOMORPHODYNAMIC MICROCLIMATES

Case study 01 introduces an Aggregate Architecture project that emphasizes the use of natural influences over that of artificial ones, yet still requires the designing architect to interact in a very minimal manner with the evolving system.

The project is located on an island in Northern Germany. The island is under threat of erosion due to wind and tidal impact. The proposal is to re-arrange the already present natural aggregate sand in such a way that new dunes are forming. The effects on the natural reserve are expected to be manifold: The new dunes will allow for further solidification of the sand through vegetation, yet they also reduce wind-speeds through an increase in surface roughness. Visitors to the site seeking wind-shelter will be directed to these artificial dunes, leaving the natural reserve intact as a protection layer for the land situated behind (Hensel, Menges and Weinstock 2010).

The aggregate behavior lying at the core of these investigations is the effect of a simple sand-pile forming a Barchan- or crescent-dune under an airstream or wind (Dauchot et al. 2002). These dunes have a sloping windward side and a sheltered wind-shadow. They are as it were self-feeding as what is removed on the windward slope is deposited on the lee-side (Bagnold 2005).

This basic behavior was tested in a laboratory setting investigating various pile numbers, pile distances and arrangements as well as mono- and multi-directional directions of airflow (Figure 3).

Figure 3. A sand-pile arrangement is exposed to varying directions of airstream in laboratory.

Layering two colors of sand was used to clearly display the windward erosion, only removing the upper, lighter colored sand. Subsequently, the set-up was tested onsite, simply piling up the sand on the beach and leaving it to form under local wind-impact.

The tools of observation used in this project were entirely in the realm of Material Computation, i.e. the laboratory and on-site set-up as well as the deliberate use of colored aggregate and of time-lapse photography to observe the evolution of the dune morphology in subsequent steps. The modes of intervention through the designer merely involved deliberately re-organizing the abundantly present granular material sand, then allowing for the reformation under the present environmental force of the wind. The mode of designing through deliberately letting certain previously studied behaviors of the aggregate system happen is thus very strongly represented in this project.

CASE STUDY 02: ROBOTICALLY POURED AGGREGATE STRUCTURES CONSISTING OF DESIGNED GRANULATES

Case study 02 presents an Aggregate Architecture project that requires quite a high degree of deliberate intervention by the designing architect both on the level of the design and the pouring process itself. It is thus a valuable counterpoint for case study 01 and the subsequent discussion on working with changeable material systems such as granular substances. The granular system in this case consists of specifically designed particles. The main morphological feature of these is a non-convex hull that allows for the formation of interlocking frictional bonds between the particles. This leads to an increase in load-bearing capacities of the aggregate, for example the formation of arches and vaults supporting under self-weight (Hensel and Menges 2006b, 2006c; Tsubaki 2011; Dierichs and Menges 2012). Other morphological features of the aggregate particle can be calibrated for different degrees in heat conduction or transparency. Based on an analysis of already existing particles, a novel particle design was developed, that includes the most successful morphological features as well as uses sheet-production processes in a material-efficient manner leaving only 7% waste material (Figure 4).
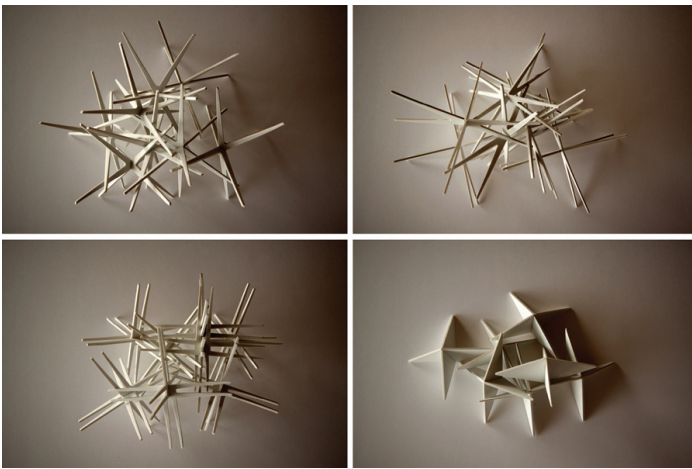

Figure 4. Designed particles manufactured from sheet material.

Pouring of these designed granulates can of course happen manually, however in this case study, a six-axis industrial robot was being used to arrange the granulates in a primarily linear wall-structure. For that purpose a magazine emitter-head was designed as a pouring tool fitted to the spindle of the robot. Using KRL input points, the linear tool-path was defined, tilting the tool in the y-axis and moving it in the z-direction. At 75% speed, the particles slide out of the previously filled magazine, interlocking with each other layer by layer. First and last particles are colored for tracing their eventual position after each pouring repetition (Figure 5).
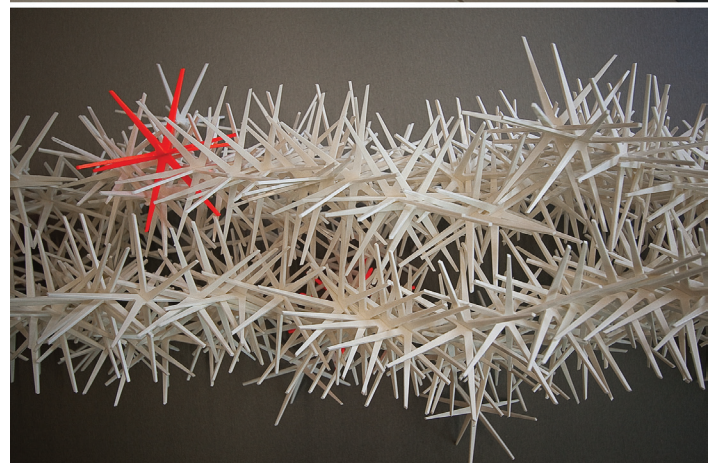

Figure 5. Robotic Pouring of designed granular matter using a linear pouring-path.

A direct link between the KRL control-points and a Rigid-Body Simulation software from the animation industry was established allowing for the computation of the robotic pouring process.

The modes of observation in case study 02 combine both Material and Machine Computation, using as well the physical experiment as the simulation to gather data about the system in question. The Rigid-Body Dynamics method was chosen in this case as it specifically al-

lows for the relatively fast computation of hard polygonal particles like the ones designed. In terms of material computation, a very controlled laboratory set-up is used in the form of a robotically controlled emitter-head. This set-up can be further refined if the particle emission is not driven by gravity but by a constant pump, thus rendering the accurately timed deposition of granular material possible. Coloration of witness particles is used as a sub-tool to trace the behavior of certain particle instances such as the first and the last of each pouring set.

The modes of intervention through the designing architect are lying both on the level of the particle and on the level of the entire aggregate system. The individual granulate is an industrially produced and geometrically controlled element, not a naturally found one like sand. The pouring process is numerically controlled through the input of point-coordinates using the Kuka Robotic Language (KRL). The system is most likely to remain in its once-poured condition unless unexpected processes of self-organization are occurring. The only unexpected or changeable aspect of this process is the manner in which the poured matter arranges itself. The overall morphology might remain self-similar in the sense of pattern-recognition, but can display local variances. The overall system changes mainly through a deliberate input by the designer - such as further pouring, solidification or re-arranging. The mode of designing through strategically intervening with the aggregate structures is thus prevalent in this project.

COMPARISON CASE STUDY 01 AND CASE STUDY 02

Both case study 01 and case study 02 are understood and developed as Aggregate Architectures that is architectural material systems consisting of loose granular masses. Case study 01 would fall into the category of geo-engineering projects, that also have an architectural implication, case study 02 would classify initially as a form-finding project.

Both projects use observational tools and design approaches in a very different combination and consequently effect. Whereas the first one relies solely on Material Computation both in the lab and outside, the second one aims to combine Material and Machine Computation in such a manner that the information sets thus gathered complement each other to form a larger model of understanding the aggregate system and its behavior. This choice is mainly due to the fact that in the second case study the aggregates are designed, which makes the detailed observation of their micromechanical behavior highly relevant.

The modes of influence the designer has on the design output represent somewhat the opposite poles in terms of designing with aggregates. What joins both projects is the fact that working with a changeable material involves allowing the aggregate to find its state rather than designing a form. The degrees of interaction however can vary: case study 01 exemplifies a minimum degree of interaction, using both an already existing granulate as well as simply resorting to piling it in a specific manner, letting the naturally present environmental effects do the rest; case study 02 presents a relative

maximum degree of influence, using designed particles, as well as a digitally controlled pouring process, that primarily is not meant to self-change unless further impact by the designer is given.

One can thus distinguish degrees of interaction and consequently of control in designing with an aggregate system, ranging from very minimal input and a high degree of self-formation of the system and its affecting forces to a maximum input with a relatively controlled self-forming process of the aggregate and systemic-change being mainly orchestrated by the designing architect.

CONCLUSION AND OUTLOOK

The notion of an Aggregate Architecture has been introduced as architectural material systems consisting of loose granular matter. Material and Machine computational processes have been suggested as observational tools and two modes of designing with the system, namely either consciously triggering the aggregate or letting self-organizational processes happen, have been described. The two case studies presented show different ways of using the observational tools and design strategies. They show how only different degrees of interaction are possible and even desired with regards to an aggregate system as opposed to conventional approaches to design, where a relatively high level of control over both system and parts is achieved.

Inherently linked with this notion of degrees of interaction is the theoretical understanding of aggregates as architectural systems and their difference from conventional ones: Whereas conventionally structures are thought of as permanent, aggregates imply working only with degrees of changeability. Some granular structures might only change over long periods of time and only through the outside trigger of a designing architect, some might change more rapidly due to influences outside the reach of design. These varying types of systems can even be combined into one, displaying varying degrees of permanence and change. Further research will be directed towards these combined granular systems, both with regards to their design methodology and design theoretical implications.

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