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Material Computation in Architectural Aggregate Systems

abstract: Aggregates are defined as large amounts of elements being in loose contact. In architecture they are mainly known as an additive in concrete construction. Relatively few examples use aggregates in their unbound form as an architectural material system in their own right. The investigation of potential architectural applications however is both a very relevant and unexplored branch of design research.

Loose granular systems are inherently different from other architectural construction systems. One of the most decisive distinctions lies in the way information on those granular architectural systems is being generated, processed, and integrated into the design process. Several mathematical methods have been developed to numerically model granular behaviour. However, the need and also the potential of using so-called ‚material' computation is specifically relevant with aggregates, as much of their behaviour is still not being described in these mathematical models.

This paper will present the current outcome of a doctorate research on aggregate architectures with a focus on information processing in machine and material computation. In the first part, it will introduce definitions of material and machine computation. In the second part, the way machine computation is employed in modelling granulates will be introduced. The third part will review material computation in granular systems. In the last part, a concrete example of an architectural aggregate model will be explained with regard to the given definition of material computation. Conclusively a comparative overview between material and machine computation in aggregate architectures will be given and further areas of development will be outlined.

1 Introduction

Aggregates can be described as large amounts of elements being in loose contact *(Nedderman, 1992, 1; Duran, 2000, vii).* In architecture, they are widely known as an additive in concrete construction. Relatively few examples however use aggregates in their unbound form as an architectural material system per se (Figure 1). The rare precedents range from vernacular architectures *(Houben & Guillaud, 1994)* to recent experimentation in form-finding with designed aggregates *(Matsuda, 2006; Hawkins & Newell, 2006; Hensel et al., 2010, 228-241)*. As a working definition, aggregate architectures could be described as large arrangements of loose elements that are observed and modulated by the architect on the particle- or system-level to perform one or more typically architectural tasks *(Dierichs & Menges, 2010)*. The capacity of these loose arrangements lies in their ability to continuously adjust to changing system-external and system-internal influences. The investigation of their potential architectural applications is thus both a very relevant and unexplored branch of design research *(Matsuda, 2006, 262; Hensel & Menges, 2008a, 2008b)*.

Loose granular systems are inherently different from other architectural construction systems, which usually seek to form clearly defined assemblies, where each element is assigned a specific place that can be geometrically defined by the architect. In granular systems however, each element finds its own place, and it is the task of the designer to observe and interact with the evolving arrangement. One of the most decisive distinctions to known architectural principles lies in the way information on those granular architectural systems is being generated, processed and integrated into the design process *(Hawkins & Newell, 2006, 274; Hensel & Menges, 2008a, 2008b)*.

Several mathematical models, such as the Discrete Element Method, have been developed to digitally model granular behaviour *(Cundall & Strack, 1979; Allen & Tildesley, 1987; Pöschel & Schwager, 2005; Bicanic, 2004).* However, the need and also the potential of using so-called analogue or ‚material' computation is specifically relevant with aggregates, as much of their behaviour is still not being described in mathematical models. Furthermore, processor capacities limit the amount of information that can be calculated accurately to granular assemblies of about 20.000 particles on a regular personal computer *(Pöschel & Schwager, 2005, 14)*. Material computation can thus be a very resourceful complement to the use of digital models for processing information on granular system behaviour.

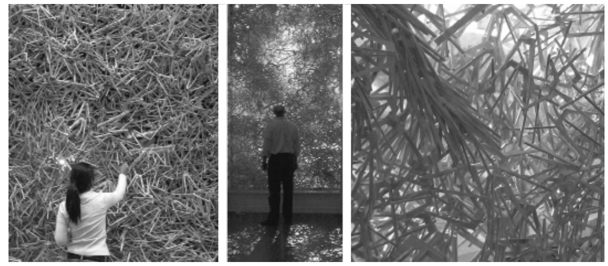

Figure 1. Aggregate Architectures, Anne Hawkins and Katie Newell (GPA Studio, Rice University, Michael Hensel and Achim Menges), Photo Credit: Achim Menges.

2 Definitions: Machine Computation versus Material Computation

Computation is in principle information processing and is by this definition not limited to digital processes, but also encompasses material models, where a substance is set to process information *(Terzidis, 2003, 65; Stepney, 2008)*. Material computation describes this branch of computing, yet a clear and commonly shared definition is currently being discussed in various schools of thought. A generic working definition of material computation and related terms is thus being introduced that on the one hand clearly delineates the boundary to machine computation and on the other hand describes how exactly information is being processed in a computational manner in those material models.

2.1 Experiment – Simulation

In the research field of science philosophy, a discourse about the exact definition and delineation of the two terms, experiment and simulation, has developed especially over the past years *(Morgan & Morrison, 1999; Guala, 2002; Morgan, 2002; Morgan, 2003; Winsberg, 2003; Winsberg, 2009; Parker, 2009)*. Winsberg gives the most precise definition, stating that a simulation needs to be based on valid principles that are adequate to reliably model a target system. An experiment however is not based on such externally valid principles, but is rather aiming at establishing and controlling internally valid testing conditions. It is often used to establish the very principles, a simulation is later based on *(Winsberg, 2009, 23-25)*.

2.2 Analogue – Digital

The two terms ‚analogue' and ‚digital' are frequently used to denote the difference between a physical and a numerical-digital model. In architecture especially the distinction between so-called analogue and digital models has become quite common, yet this notion is based on the relatively simple distinction between architectural models that are built physically and those that are modelled on a personal computer (*Gaß & Otto 1990, 1.4–1.5; Spuybroek, 2004, 352; de Landa, 2004a, 21, 2004b, 374–375)*. Digital however means in principle only the discrete and discontinuous representation of information. Analogue on the contrary denotes the continuous representation of information, that is based on similarities between model and target *(Loleit, 2004, 204; Schröter, 2004)*.

2.3 Material Computation – Machine Computation

Another distinction is that between material and machine computation. In material computation, a physical substance is set to process information. The computation is based on the innate capacities of the material itself, which can be described as ‚found computation'. In machine computation, a specifically developed algorithm is established to conduct a computational procedure. This can also be described as ‚designed computation'. Both material and machine computation are based on a common model, of information input, information processing and information output *(Yan, 1998; Harding, Miller & Rietman, 2006; Stepney, 2008*).

2.4 Overview

The three groups of terms, experiment and simulation, analogue and digital, as well as material computation and machine computation, have been defined in the previous section. They can be combined in various manners to establish different forms of computational models (Figure 2). One can start to distinguish analogue material computation and digital material computation, as well as analogue machine computation and digital machine computation. Relating the definitions given by Loleit and Winsberg however, we suggest that analogue models can be described as experiments and digital models as simulations *(Loleit, 2004, 204; Winsberg, 23–25)*. All of these forms of computation have at their core the capacity to manage large amounts of information following the basic principle of variable information input, information processing and variable information output. If they are used in an architectural design context, as is now increasingly the case, they allow for making information the founding aspect of the design itself.

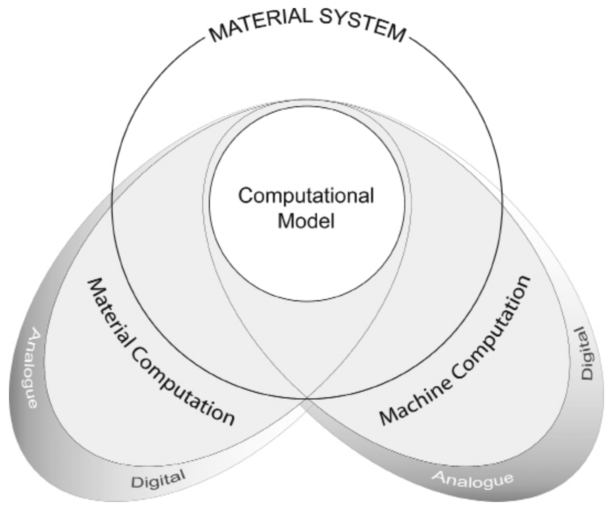

Figure 2. Diagrammatic Overview of Different Forms of Computation, Image Credit: Karola Dierichs.

3 Information Processing in Digital Machine Computation of Aggregates

The following introduces several mathematical models and the ways that information processing in digital machine computation is employed in modelling the behaviour of granular substances.

3.1 Force-based Molecular Dynamics

The best known method of digital machine computation in aggregates is called force-based Molecular Dynamics, in short Molecular Dynamics (MD). It originates from a mathematical model developed by Cundall and Strack in 1979 *(de Josselin de Jong & Verruijt, 1969; Cundall & Strack, 1979)*. It uses Newtons's equations of motion, that allow for the calculation of pairwise particle collisions based on known forces and torques. The models use periodic time-stepping and allow for soft particle collisions *(Allen & Tildesley, 1987, 71–109; Luding, 1994, 7–10; Duran, 2000, 184–199; Pöschel & Schwager, 2005, 13–30; Jean, 2009, 206–216)*.

3.2 Further Models

Quite a range of alternative mathematical models to the MD algorithm has been developed. The main driver behind those is to arrive at less computationally intensive procedures than the relatively intensive MD calculations. The methods will be briefly listed in the following.

(01) Event–driven Molecular Dynamics (ED) are based on systems of hard spheres, where at one point in time only two particle are in contact. The time-stepping is thus deteremined by the events, i.e. the collisions themselves *(Luding, 1994, 8; Duran, 2000, 184–190; Pöschel & Schwager, 2005, 135–137; Jean, 2009, 216–220)*.

(02) Monte Carlo Simulations are probability calculations. In the modelling of granular media, they are mainly used to simulate the relaxed state of a granular arrngement, such as a sand-pile at relative rest *(Duran, 2000, 202–206; Pöschel & Schwager, 2005, 191–192)*.

(03) Quite a few less relevant methods, such as the Rigid Body Dynamics *(Duran, 2000, 199–202; Pöschel & Schwager, 2005, 211–214)*, Cellular Automata *(Pöschel & Schwager, 2005, 243)* and the Method of Stepest Descent *(Duran, 2000, 206–207; Pöschel & Schwager, 2005, 271–273)*, have been developed to simulate granular behaviour. They can be interesting with regards to specific problems *(Duran, 2000, 207)*.

3.3 Summary

The models introduced in the preceding section are all falling into the category of digital machine computation. They are simulations, as they are all based on abstract principles, i.e. mathematical models, that reliably render specific system behaviours. They are digital, as information is processed in a discontinuous, discrete manner. And they are machines, as the algorithm behind them is a designed or rather humanly devised one. Like any computational procedure, they follow the basic principle of varying information input, information processing by an algorithm and resulting information output.

4 Information Processing in Analogue Material Computation of Aggregates

The following section will review the way information processing in analogue material computation is employed in modelling the behaviour of granular substances. The five different aspects typically describe the experimental conditions and the way data are captured, but other than in models of digital machine computation, the actual algorithm is thought to be innate in the granular substance itself.

4.1 Experimental Setup

The basic experimental setup depends on the forces that affect the granular system in question. These can be gravitational forces as well as airflows and vibrations *(Bagnold ,1954, 25–31; Duran, 2000, 119–127; Dauchot et al., 2002, 1; Hicher, 1998; Lanier & Radjaï, 2009, 9–10*). Depending on these effective forces, the entire experiment is conducted in such a way that they are modelled as accurately as possible.

4.2 Boundary Conditions

The boundary conditions of an experiment can equally vary. On the one hand the roughness of walls and ground planes can be used to callibrate their friction *(Dauchot et al., 2002, 1; Duran, 2000, 95–96, 120 & 176).* On the other hand, two-dimensional experiments are conducted using two planes with a very thin layer of granules between them, but also, three-dimensional cells are frequently used. Two-dimensional cells allow for studying a specific section of a granulate, while three-dimensional cells give information on the overall behaviour of the system *(Duran, 2000, 75)*.

4.3 Particle Marking

Markings are used to observe the behaviour of the individual particles themselves. So-called witness or tracer particles are particles, that are coloured, so that the movements of an individual granular element can be observed *(Ball 1999, 200–202; Duran, 2000, 165 & 171–173)*. Axial markings are used in two-dimensional cells to determine rotations within the granulate *(de Josselin de Jong & Verruijt, 1969; Lanier & Radjaï, 2009, 10)*.

4.4 Photographic Data Capture

Photographic methods are especially relevant for the observation of granular media. Photo-elastic processes are used, to investigate load transfer in an aggregate *(de Josselin de Jong & Verruijt, 1969).* Parallel lighting and a modulating light-intensity grid are being used to define the topography of granular arrangements *(Dauchot et al., 2002, 1–2).* CCD (Charge Coupled Device) Cameras are very often deployed. They translate optical information into electrical signals which are turned into digital image information *(Duran ,2000, 104–105).* Stroboscopic light can be used on its own or in combination with a CCD camera and is coupled with specific properties of the granular system, such as the vibration period. This way, the system is observed at the exact same point in each cycle *(Duran, 2000, 85–86; Ball, 2009, 116)*. Time-lapse photography allows for capturing the sequential development of a granulate *(Duran, 2000, 104–105)*.

4.5 Image Processing

Image processing techniques are deployed to evaluate the photographically documented results according to specific criteria. The relative velocity of particles or the relative movement of particles can, for example, be drawn from image data *(Duran, 2000, 91–93; Lanier & Radjaï 2009, 10)*. This way one can also observe, how often a specific region in a granulate is visited by the respective same particles. These methods are also called Computer Posed Photograph (CPP) *(Duran, 2000, 173–174)*.

4.6 Summary

The methods described in the above section serve to set up analogue material computational models. They are experiments, as they do not work on an abstract principle, but rather rely on a likeness between model and target system. They are analogue, as information is continuous, non-discrete, and relies on similarities. They are material computational models, as it is a found algorithm, that of the granulate itself, that is doing the processing of information. Like any computational procedure, they are based on the input of information into the system, the information processing via an algorithm, namely that inherent in the granular substance, and the output of information.

5 Example: Analogue Material Computation in Architectural Aggregate Models

5.1 Wind-Shelter Design Based on Aeolian Aggregate Formations

The design serving as an example for analogue material computation in aggregate architectures is for semi-enclosed spaces, that are using the natural behavior of sand to form wind-sheltered areas (Figure 3 and Figure 4). The laboratory setup used to develop the project is that of a group of sand piles being exposed to an airstream and thus forming wind-exposed and wind-sheltered spaces. Going back to the classification in section 4 of this paper, the model was set-up using the following experimental techniques.

1) The experimental setup is that of a wind-table, that allows formodeling the behaviour of wind in large open areas.

2) The boundary condition was, in this case, only a flat surface. Roughness has not been deployed deliberately, but can be used to more reliably model frictional behaviour of the aggregate with the ground plane.

3) Different coloured aggregate has been used in some models to make the removal of sand on the windward side visible.

4) Time-lapse photography with steps of one second with a regular camera is being used to show the development of an aggregate arrangement under airflow over a set period.

5) Image processing is not applied to the digital images, but can be used to further analyze the obtained image data, especially the two-coloured data sets.

5.2 Analogue Material Computation in Architectural Aggregate Models

This specific analogue material, computational model used for the Wind-Shelter Design is one typical example of this branch of information processing. The setup is clearly an experiment, not a simulation, as it does not use an abstract principle to model a target system. The information is thus processed in an analogue manner, i.e. continuously and through similarity between model (laboratory experiment) and target (eventual design). Here the material itself computes, as the innate capacity of the sand is used and not a designed machine algorithm. The models are however clearly computational, as varying input information such as pile arrangement or wind direction, is processed by an algorithm, i.e. the material sand, to produce specific information sets, namely the eventual configuration and its degree of wind-exposure captured by a set of digital time-lapse images.

6 Conclusion

Aggregate architectures have been introduced as a very relevant yet unexplored branch of design research. Information processing through material computation is important in this branch of research, as much of the granular behaviour remains as of yet un-described in mathematical models.

Figure 3. Laboratory Experiment for Wind-Shelter Design, Karola Dierichs (EmTech Dissertation, Architectural Association, Michael Hensel, Achim Menges and Michael Weinstock), Photo Credit: Karola Dierichs.

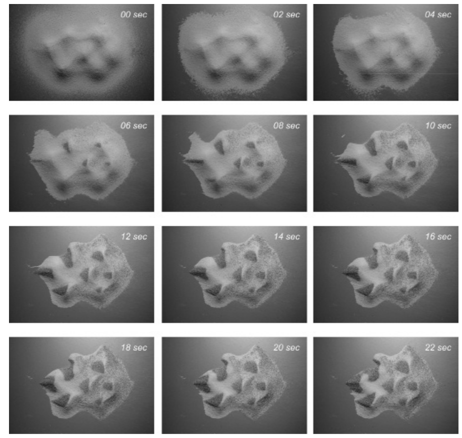

Figure 4. Time-Lapse Photography of Two-Coloured Sand-Piles under an Airstream, Karola Dierichs (EmTech Dissertation, Architectural Association, Michael Hensel, Achim Menges and Michael Weinstock), Photo Credit: Karola Dierichs.

The definitions of experiment and simulation, analogue and digital as well as material and machine computation and their respective capacity to manage large amounts of information in the design process have been introduced to form a basis for the discussion on material computation in architectural aggregate models. This has served as a starting point for a more detailed description of information processing in machine and material computation in the research field of architectural aggregate models. Material computation allows for producing analogue information on the behaviour of large amount of aggregates. Machine computation allows for gaining exact numerical information on specific questions regarding granular systems, for example on micro-mechanical behaviour. In combination, these two informational streams of material and machine computation allow for a more profound view of a specific aggregate than either in separation.

Further research can be conducted into the relevance of material computational models not only on a practical but also on a design methodological and design theoretical level. The information process lying at the core of these computational models will then not only be perceived as being relevant on an applied level, but also give rise to new design procedures and theoretical approaches.

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