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Foreword

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Subtitle of the Dissertation

A dissertation approved
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University of Stuttgart
for the conferral of the title of
Unabbreviated Designation of the Title (Abbreviated Title)

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Further committee members:
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Date of the oral examination:
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Jahr der Publikation

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First Name Last Name

Contents

List of Abbreviations

c	Speed of light in a vacuum inertial frame
h	Planck constant
UTC	Coordinated Universal Time

List of Figures

List of Tables

Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Praesent porttitor arcu luctus, imperdiet urna iaculis, mattis eros. Pellentesque iaculis odio vel nisl ullamcorper, nec faucibus ipsum molestie. Sed dictum nisl non aliquet porttitor. Etiam vulputate arcu dignissim, finibus sem et, viverra nisl. Aenean luctus congue massa, ut laoreet metus ornare in. Nunc fermentum nisi imperdiet lectus tincidunt vestibulum at ac elit. Nulla mattis nisl eu malesuada suscipit.

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Zusammenfassung

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1

Chapter

1.1 Text examples

1.1.1 Fonts

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Helvetica Upright, **Bold**, *Italic*, ***Bold Italic***.

1.1.2 Section

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1.1.3 International characters

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αβγδεζηϑικλμνξοπρστυφχψω
ΑΒΓΔΕΖΗΘΙΚΛΜΝΞΟΠΡΣΤΥΦΧΨΩςϕϑθϵ
©®™

1.1.4 Referencing

This statement requires citation [8]. This statement requires multiple citations [13; 5; 4; 9; 12; 6; 2; 7; 11; 15; 14; 10; 1]. This statement contains an in-text citation, reminiscent of that in Dierichs *et al.* [3].
Referencing a labelled document element: Figure 2.2.

1.1.5 Abbreviations

Abbreviations are otherwise known as nomenclature. They are defined in-text like: c, h and UTC. Duplicate definitions are not output to the notation twice: UTC.

1.1.6 Indexing

This sentence defines a new term that we want to appear in the index.

1.1.7 Track changes

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[1] This is a comment about some text that was added.

[2] This comment is on some text that should be removed.

[3] This comment is on some text that should be replaced.

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See the `changes` LaTeX package documentation for further track changes options and examples.

1.2 This section title is very long and spans two lines

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Figure 2.1: Chapter introduction figure. It should always be the last thing before a new chapter on a new even page.

2

Chapter

The figure number of the chapter image: Figure 2.1 and current chapter: Chapter 2.

2.1 Figure examples

2.1.1 Small figure

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Figure 2.2: This is a small figure that spans the text width of the page and the caption is across two lines.

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2.1.2 Wide figure

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Figure 2.3: This is a large figure that spans the page width of the page but the caption does not.

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2.1.3 Minipage figure in-text

Figure 2.4: This figure is created using the minipage environment and is the width of the text.

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2.1.4 Makebox figure wide

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2.2 Table example

Column 1	**Column 2**	**Column 3**
Row 1	00	00
Row 2	00	00
Row 3	00	00
Row 4	00	00
Row 5	00	00
Row 6	00	00

Table 2.1: Example table.

3

PDF Chapter

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Granular Matter (2016) 18:25
DOI 10.1007/s10035-016-0631-3

ORIGINAL PAPER

Towards an aggregate architecture: designed granular systems as programmable matter in architecture

Karola Dierichs[1] · **Achim Menges**[1]

Received: 2 September 2015 / Published online: 6 April 2016

Abstract Aggregate architectures are full-scale spatial formations made from loose granular matter. Especially if the individual grain is custom-designed, the range of behaviours can be calibrated to match a wide range of architectural and structural performance criteria. The aggregate becomes programmable matter. The relevance of loose granular systems for architecture is on the one hand their rapid re-configurability, allowing for a system not to be destroyed but rather to be recycled. On the other hand aggregates per se can be functionally graded either within one and the same particle type or through mixing different particle geometries. This enables the variation of architectural properties throughout one and the same material system, which is one of the core postulates of current architectural design research. However, very few examples of designed granular matter in architecture exist. The results presented here are thus one of the first coherent bodies of comprehensive research in this field compiled over a period of five years. Methodologically aggregate systems challenge conventional architectural design principles: whereas an architect generally precisely defines local and global geometry of a structure, in a designed granular system he can only calibrate the particle geometry in order to tune the overall behaviour of the aggregate formation. Thus new design methods have been developed throughout the research projects, which are informed by the related fields of granular physics and behaviour-based robotics. In this context the article provides an introduction to both designed particle systems and suitable fabrication approaches in an architectural context. Case study projects serve to verify the applicability of the concepts introduced. The research findings are discussed with regards to their practical, methodological and design theoretical contributions. To conclude, further directions of research are highlighted.

This article is part of the Topical Collection on Jamming-Based Aleatory Architectures.

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Keywords Designed granular matter · Aggregate architecture · Behaviour-based robotics · Programmable matter · Material systems

1 Aim

Aggregate architectures are full-scale architectural structures made from designed granular materials. The research over-view presented in this article introduces the field of designed granular matter in architecture. The aim is to highlight relevant directions of investigation for this emerging area of architectural design research with exemplary case study projects (Fig. 1).

Designed granular matter is defined as an aggregate system, in which the individual particles are artificially made and calibrated to fulfil certain performance criteria [20]. Just like in a naturally occurring aggregate such as sand, gravel or snow the individual grains are not bound by a matrix but only lying in loose frictional contact [11,25]. However through the design of both geometry and material make-up a range of system behaviours can be achieved which cannot be found in natural systems per se, the designed granular system becomes programmable matter [8]. Within an architectural context loose granular systems have rarely been deployed, but more commonly are known in their bound form as a component in concrete construction [21].

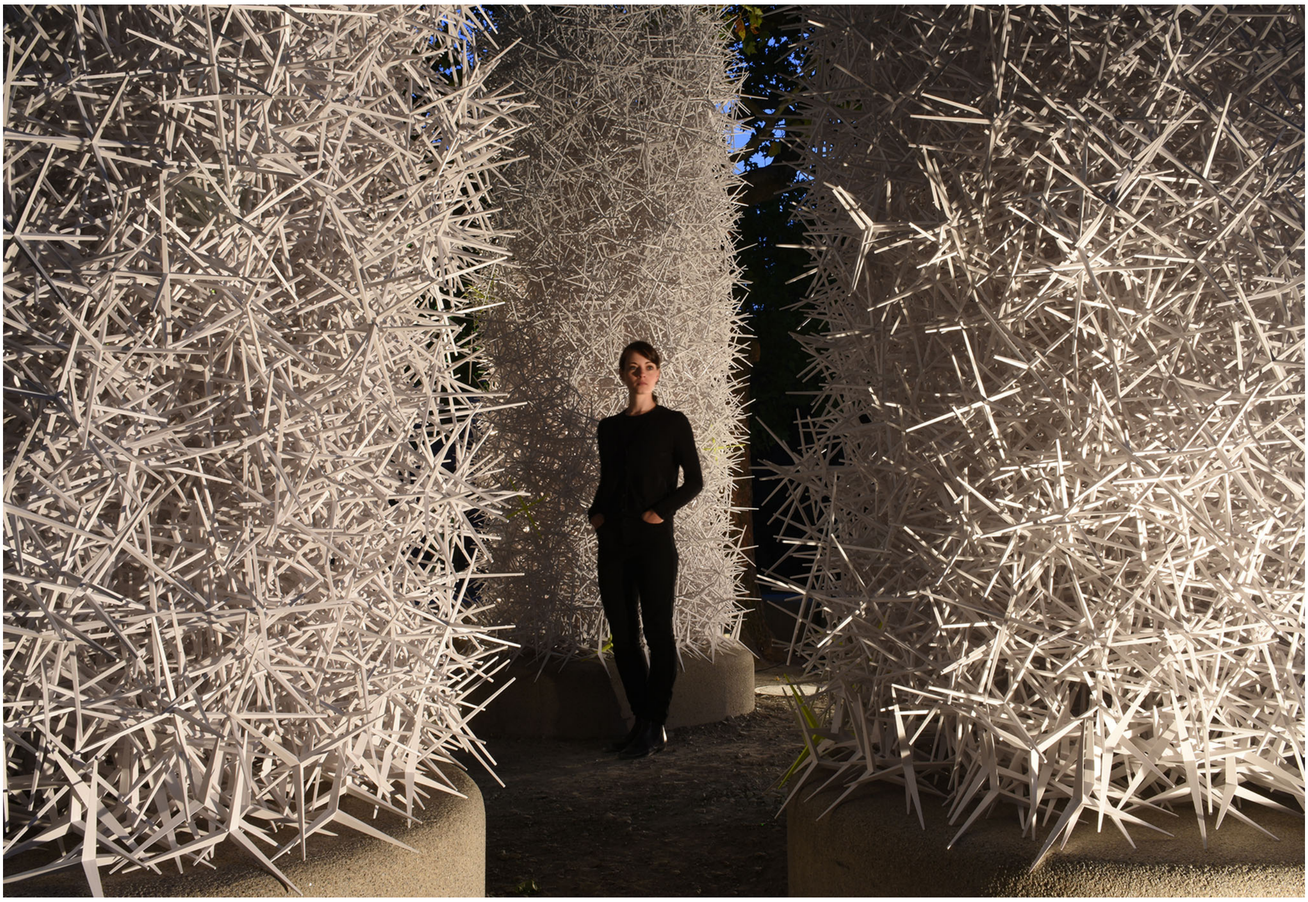

Fig. 1 The ICD Aggregate Pavilion 2015 explores vertical structures as space forming elements. Programmed verticality is one of the core features which a specific set of non-convex designed granular systems can achieve

Aggregates, especially designed aggregates, are a material system that challenges current paradigms of architectural design practice: architects conventionally control both geometry of the local element and the exact overall global geometry of a structure through precise drawing techniques when working with a designed aggregate system however, the geometry of the individual part, the granule, is defined not to achieve precise geometry but rather to calibrate a certain material behaviour with a scope of possible formations. This paradigm shift requires and promotes an entire new set of concepts, methods and practical tools: the conceptional design thinking needs to move from designing a finite structure towards an evolving formation, which moves from one stable state to the other; methods need to be based in the realm of information processing rather than artistic design intentions, thus gathering data from the granular system itself rather than imposing a preconceived form onto the system; and finally adequate tools and technologies both in terms of physical experiments and numerical simulations need to be integrated into the design discipline, frequently drawing from and building on techniques developed in granular physics [7].

In this context, the research presented here is a first step to both systematize the field of designed aggregates in architecture and to test its applications and implications through proof-of-concept experiments and simulation series. It is the result of a 5 years research project conducted at the Institute for Computational Design at the University of Stuttgart, Germany on both Master and Doctoral level. In the present paper scope, relevance and context of the field will be introduced. A state of the art overview of designed granular matter in architecture will be given and the applied methods, tools and technologies introduced. The results are structured into particle system and fabrication system definitions and overview followed by topical case study projects. The results are evaluated and discussed in terms of their relevance for the overall field and areas of further research are outlined.

2 Scope

The research into designed aggregates in architecture can be distinguished very generally into two main areas: the grain morphology and behaviour of the aggregate system on the one hand and full-scale fabrication methods on the other. Grain morphology encompasses both the geometry and the material composition of the individual grain and its effect on the behaviour of the aggregate system as a whole, when grains are accumulated to large masses. Fabrication methods entail the use of formwork or no formwork, methods of affecting the overall granular system such as vibration or compression, as well as robotic processes of aggregation, disaggregation and observation.

The focus of the research has mainly been on designed aggregate systems with only one grain type in order to understand the effect of a specific geometric feature such as hooks or arm lengths on the aggregates behaviour. The mixing of different grain types widens the scope of possible and highly relevant granular behaviours, but has so far only been marginally explored. Equally the mixing of designed and naturally found grains has not been considered in this context. With regards to fabrication methods the main goal has been the exploration of suitable construction techniques that use as little formwork as possible as well as the development of online-controlled and large-scale robotic processes. The integration of different robotic fabrication systems has not been considered in this context so far.

3 Relevance

The relevance of designed granular systems in architectural applications is three-fold: first, the synthetic design of the individual grain leads to unprecedented behaviours in the amassed aggregate. Through that, granular systems become highly interesting in an architectural context as relevant behaviours can be pre-programmed into the material. Second, designed aggregates allow for functional grading either through varying densities in a single-particle aggregate system or through combining grain sizes or even aggregate types. These graded systems are separable into their unmixed state and thus fully recyclable. Lastly, since granular systems can go through both solid and liquid phases, in architectural terms they allow for constant formation and reformation of a structure thus abandoning the pervasive architectural notion of endurance and eventual destruction of a building. These two aspects are the core drivers in the layout of the design experiments introduced here.

4 Context

Aggregate architectures are situated within the larger fields of material systems and programmable matter in architecture.

The past 15 years have seen a turn towards the material system as one of the main, if not the most important design driver in architecture. A material system in this context is seen as a construction principle that is based on a materials innate behaviour and which integrates both structural and environmental performance criteria. Frequently these material systems are digitally fabricated [15,19]. The term material system goes back to the 19th century physicist and theoretician James Clerk Maxwell, who defined it in his work Matter and Motion [23,33]. In the present-day context, three main groups have been distinguished: globally modulated systems such as membranes, proliferated component systems such as brick walls, and aggregate systems [19]. Aggregates are thus considered an individual group on a system-level since they are distinct from the other two groups: they are not made from a global matrix or even consisting of joint components but instead are loosely poured from individual elements. However they do display characteristic behaviours based on the particle morphology and boundary conditions and can thus be considered to have systemic properties [19].

The second strand of research this project is based in, is that of programmable matter in architecture. Programmable matter can be defined as a material that is specifically designed to behave in a distinct manner. Within architecture it is a fairly novel branch of research [14,28,42]. Conventionally architects work with a given material with pre-determined properties that the global design needs to be based on. However, the ability to program the material itself denotes a new design paradigm in which the design is shifted from the global macro-scale of a building to the local micro-scale of the material. Aggregates only can be considered a form of programmable matter if the individual particle is synthetically designed with specific characteristics that in turn influence the combined behaviour of the multi-particle structure. Thus the level of control moves from the overall geometry of a structure to that of the individual particle. The observation of the global effects produced by the specifically designed individual particle geometry is observed through empirical studies working back and forth between particle and system. In addition existing simulation models based on evolutionary algorithms can be used to optimize particle geometries for predefined global system characteristics [37].

5 State of the art

Precedents of architectural projects that deploy designed granular materials as architectural construction systems are extremely rare [21]. Initial research has been conducted under the supervision of Michael Hensel and Achim Menges at the Architectural Association, London through Eiichi Matsuda's diploma thesis in Diploma Unit 4 as well as Rice University, Houston, Texas through Anne Hawkins' and Cathlyn Newell's GPA Studio research [18,20]. Both projects focused on highly non-convex macro particles made from wood sticks or cut sheet material respectively. Exper-

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Appendix Name

A.1 Section in appendix

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