Karola Dierichs

GRANULAR ARCHITECTURES

Granular Materials as "Designer Matter" in Architecture

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Edited by Professor Achim Menges, AADipl(Hons)

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Foreword

The dissertation of Karola Dierichs explores the architectural potential of granular materials, their form, structure and spatial formations as well as the associated formation processes. These investigations are characterized by a high degree of originality, as this field of research, which has only been considered to a limited extent in architecture thus far, is systematically studied and developed. The expectation to make a first, fundamental and comprehensive contribution to an architecture of granular materials is fulfilled by this pioneering research! It is in the nature of things that such a comprehensive development raises a multitude of new questions with every insight gained. All the more remarkable is the multifaceted nature of the observations and projects on which Karola's work is based, and the multidimensional reflection of her findings in regards to design methodology, production technology and architectural theory. In an impressive way, she succeeded in leading a risky research project to an excellent result, while also creating extremely fascinating architecture.

Professor Achim Menges, AADipl(Hons)

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A dissertation approved
by the Faculty of Architecture and Urban Planning of the
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Submitted by
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from Kassel

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Heinrich M. Jaeger, Ph.D.

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Universität Stuttgart
zur Erlangung der Würde
einer Doktor-Ingenieurin (Dr.-Ing.)
genehmigte Abhandlung

Vorgelegt von
Karola Dierichs
aus Kassel

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The research has been generously supported by the Holcim Awards for Sustainable Construction as well as the GETTYLAB. Thank you.

Karola Dierichs

Contents

List of Abbreviations

a_{dnc} Largest internal angle of double non-convex volume

a_{nc} Largest internal angle of non-convex volume

a_a Arm amount

a_l Axis length

a_t Arm taper

b_h Box height

b_l Box length

b_n Amount of boxes in box container system

b_w Box width

c_b Box container system

c_{ol} Length of container opening

c_{ow} Width of container opening

c_o Container opening

c_p Average particle count per cluster

c_s	Developable surface container system
d_m	Longest diameter of convex hull
e_c	Clustering "end effector"
e_s	Singling-out "end effector"
f_{oc}	Centre point of one-piece formwork
f_{oh}	Height of one-piece formwork
f_{ol}	Length of one-piece formwork
f_{or1}	Radius of principal curvature 1 of inflatable formwork
f_{or2}	Radius of principal curvature 2 of inflatable formwork
f_{ow}	Width of one-piece formwork
f_o	One-piece formwork
$f_p[t]$	Particle flow per time unit
h_c	Convex hull
m_{mp}	Mechanical property of overall granular material
m_{op}	Optical property of overall granular material
m_p	Particle mix
m_{tp}	Thermal property of overall granular material
p_{fg}	Geometry of formwork particles
p_f	Formwork particle type
p_g	Particle geometry

$p_g[t_1]$	Particle geometry at time instance 1
$p_g[t_2]$	Particle geometry at time instance 2
p_l	Lines connecting points describing particle geometry
p_{mp}	Mechanical property of material of particle
p_{op}	Optical property of particle material
p_o	Particle orientation
p_p	Set of points describing particle geometry
p_s	Structure particle type
p_{tp}	Thermal property of particle material
$p_t[n]$	Individual particle types
R	Revolution
R_a	Axis of revolution
R_c	Centre of revolution
$R_n[t]$	Number of revolutions per time unit
r_{sc}	Robot's "sensory control"
$r_{sc}[f]$	Robot's "sensory control" switched off
$r_{sc}[t]$	Robot's "sensory control" switched on
r_v	Release velocity of container opening lid
r_{xp1a}	"Pose accuracy" of industrial robot
r_{xp1r}	"Pose repeatability" of industrial robot

r_{xp2a}	"Path accuracy" of industrial robot
r_{xp2r}	"Path repeatability" of industrial robot
r_{xrl}	"Rated load" of industrial robot
r_{xw}	"Working space" of industrial robot
r_x	Model of industrial robot
RH	Relative humidity
s_h	Surface height
s_l	Surface length
s_r	Surface bending radius
s_w	Surface width
T	Temperature
v	Vibration
v_a	Amplitude of vibration
V_b	Built volume
V_c	Three-dimensional volume of convex particle
V_{dnc}	Three-dimensional volume of double non-convex particle
v_f	Frequency of vibration
V_{nc}	Three-dimensional volume of non-convex particle

List of Figures

Abstract

The thesis investigates designed granular materials in architecture. Granular materials are defined as high numbers of particles larger than a micrometre, between which mainly short-range repulsive contact forces are acting. In a designed granular material the geometry and material of the individual particle are determined by a designer. Consequently, the overall granular material can have characteristics which are novel in comparison to non-designed granular materials. In architecture, designed granular materials are understood to have new characteristics which fulfil specific architectural performance criteria.

The relevance of designed granular materials in architecture is threefold. All granular materials are both fully recyclable and reconfigurable due to the fact that the individual particles are in no way bound to each other. These first two aspects alone make any granular material, whether it is designed or not, a highly pertinent strand of architectural design research. However, designed granular materials, in addition to being recyclable and reconfigurable, bear the potential for the development of entirely novel material behaviours.

The scope of the work comprises on the one hand the development of a design system for both particle systems and construction systems. This design system is complemented by a catalogue of tests which investigate all aspects of the design system in isolation from each other. On the other hand, two case studies are conducted, which each integrate a different and selective set of system categories and are evaluated with respect to their contributions on a practical, methodological and conceptual level of design.

In the context of architecture, designed granular materials can be considered as a form of "material systems". More specifically, they belong to the group of "aggregate systems". In the wider transdisciplinary context, designed granular materials for architecture can be seen as a form of "designer matter (DM)". "Designer matter (DM)" is understood as matter which is designed in its structural characteristics at its mesoscale rather than its macro- or its microscale. The concept of "designer matter (DM)" is positioned and defined within the context of the related conceptual frameworks of "transformative materials", "mediated matter", "smart materials", "active matter", "metamaterials", "machine materials", "programmable matter" and "digital materials". The opportunities and challenges for "designer matter (DM)" in architecture are outlined.

The current state of research into designed granular materials is presented for both architecture and granular physics, on a conceptual as well as on a project-based level. In the field of architecture, a range of conceptual frameworks have been formed and related projects have been conducted. In granular physics several conceptual frameworks have been established and a wide range of designed particle shapes has been investigated. In this context the thesis aims to establish and validate a first version of a comprehensive design system for designed granular materials in architecture. This design system is also meant to serve as an interface with granular physics for forming and conducting collaborative research projects. The research development of this thesis is presented and evaluated with respect to the practical, methodological and conceptual foundations which have been laid during this phase.

The methods are introduced in terms of methodological frameworks, tools and techniques and the applied research methodology. With respect to methodological frameworks, the notions of "forward" and "inverse" design, of experiment and simulation and of the analogue versus the digital are introduced. The thesis is situated within the realm of "forward" design approaches, deploying experiments and simulations with analogue or digital means. Tools and techniques are mainly integrated from the realm of granular physics. The research methodology applied in the thesis first establishes a design system for both designed particle and construction systems. This is validated through feasibility tests, which tend to isolate one or a few system parameters. In a second step the system is tested through two case studies, which integrate a set of system categories. The case studies are complemented by statistical series investigating specific relevant sub-hypotheses. The results are evaluated on a practical, methodological and conceptual level of architectural design. The relevance of the results for a transdisciplinary collaboration with granular physics is discussed.

The core part of the thesis comprises the design system and the related design system catalogue as well as the two case studies.

The design system is established for particle systems and for related construction systems. It formulates the basic system categories and corresponding parameters. Particle systems are distinguished by particle material, particle geometry and particle mix; construction systems are differentiated by locally and globally effective construction systems as well as boundary construction systems. The design system catalogue is presented in the appendix. In this part of the thesis tests are summarized which investigate individual aspects of the overall design system for particle and construction systems.

The two case studies explore the integration of a different set of design system categories each. They were conducted both through full-scale prototypes and a related set of tests with statistical repetition. Both case studies are constructed in situ with a cable-driven parallel robot. Case study 1 investigates vertical structures made from a designed granular material consisting of highly non-convex particles. Case study 2 combines two designed granular materials, one consisting of convex particles and the other of highly non-convex particles, in order to form spatial enclosures. The case studies are evaluated with respect to their practical, methodological and conceptual contributions to architectural design research.

The thesis is summarized and its contributions are assessed in conclusion both with respect to the field of architecture and for the field of granular physics.

In the field of architecture, the contributions of the thesis are discussed on the practical, methodological and conceptual levels of design. On the practical level, the design system can be considered a first contribution to a systematic approach to designed granular materials and their related construction systems in architecture. However, the selective nature of this design system must be highlighted. On the methodological level, mainly "forward" design methods have been used for the development of the design system. This might be considered a limitation of the work, yet seems appropriate due to the fact that both parameters and problems must be formulated prior to the use of "inverse" methods of design. In this respect the results of the "forward" design processes can serve in a next step as an input for "inverse" models of design research. A set of tools and techniques has been integrated from granular physics into architecture. This consequently widens the range of architectural design tools. On the conceptual level, the integration of designed granular materials in architecture into the field of "designer matter (DM)" can be seen as a first step towards the establishment of a suitable conceptual framework for design. However, since both the notion of "designer matter (DM)" and the field of designed granular materials are novel in architecture, the two concepts need to be developed alongside and in relation to each other. In this context the thesis contributes to the conceptual notion of "designer matter (DM)" by demonstrating that a granular material can be designed for specific architecturally relevant behaviours.

For the field of granular physics, the design system can be considered as a contribution to interface with architecture. The challenge here is the seemingly trivial difference in research culture between architecture and granular physics: whereas in architecture results are frequently achieved through qualitative observation of full-scale prototypes, in granular physics research is conducted through quantitative laboratory tests. However, the proposed design system can be used and expanded to nest both of these research cultures. The applied research methodology proposed in the case studies of combining full-scale architectural structures with relevant statistical experiment and simulation series is one possible form of combining these two disciplines.

Further research in the field of designed granular materials in architecture can be conducted on the practical, methodological and conceptual levels of design. On the practical level, in the area of particle systems the investigation of graded granular materials, of different mechanical properties of the particles' material or of designed granular materials consisting of particles with variable geometry is highly promising. In the area of construction systems, the development of behavioural models of robotic construction is very relevant. Another key direction is for the construction systems to become increasingly simple, while the particles are progressively designed to perform parts of the construction process by themselves. On the methodological level, the integration of "inverse" design methods is the logical next step. This can be done on the basis of the proposed design system. On the conceptual level, the framework of "designer matter (DM)" needs to be further established both as a transdisciplinary model and within the field of architecture. Only then can designed granular materials be fully discussed as one form of "designer matter (DM)" in architecture.

Key to any further development of the overall research field is the integration of the two fields of architecture and granular physics.

Zusammenfassung

Die vorliegende Arbeit untersucht entworfene granulare Materialien in der Architektur. Granulare Materialien sind definiert als Systeme von Partikeln in hoher Anzahl, die größer als ein Mikrometer sind und zwischen denen hauptsächlich kurzreichweitige, repulsive Kräfte auftreten. In einem entworfenen granularen Material wird sowohl die Geometrie als auch das Material eines einzelnen Partikels von dem Entwerfenden bestimmt. Daher kann das entworfene granulare Material Charakteristika haben, die im Vergleich mit nicht entworfenen granularen Materialien neuartig sind. In Bezug auf eine Anwendung in der Architektur wird davon ausgegangen, dass entworfene granulare Materialien neue Charakteristika haben, die eine oder mehrere architektonische Leistungsanforderungen erfüllen.

Die Relevanz granularer Materialien für die Architektur hat drei Aspekte. Alle granularen Materialien sind sowohl vollständig rezyklierbar als auch rekonfigurierbar. Das liegt in der Tatsache begründet, dass die einzelnen Partikel nicht permanent miteinander verbunden sind. Schon diese ersten zwei Aspekte alleine machen jegliches granulare Material, ob es entworfen ist oder nicht, zu einem hochrelevanten Untersuchungsgegenstand in der architektonischen Entwurfsforschung. Darüber hinaus haben

entworfene granulare Materialien, zusätzlich zu ihrer Rezyklierbarkeit und Rekonfigurierbarkeit, das Potential, gezielt völlig neue architektonische Materialverhalten zu erzeugen.

Die Arbeit umfasst zum einen die Entwicklung eines Entwurfssystems sowohl für die Partikelsysteme als auch für die darauf bezogenen Konstruktionssysteme. Dieses Entwurfssystem wird ergänzt durch einen Katalog von Versuchen, die alle seine Aspekte isoliert voneinander untersuchen. Zum anderen werden zwei Fallstudien durchgeführt, die jeweils eine besondere und hochspezifische Reihe von Systemkategorien miteinander in Verbindung bringen. Diese zwei Fallstudien werden im Hinblick auf ihre praktischen, methodischen und konzeptionellen Beiträge zum architektonischen Entwurfsprozess diskutiert.

In einem architektonischen Kontext können entworfene granulare Materialien als "Materialsysteme" ("material systems") eingeordnet werden. Spezifischer gehören sie hier zu der Gruppe der "Aggregatsysteme" ("aggregate systems"). In einem weiter gefassten transdisziplinären Kontext können entworfene granulare Materialien als eine Form von "designer matter (DM)" angesehen werden. Dabei ist "Designer matter (DM)" definiert als ein Material, das in seinen strukturellen Eigenschaften auf der mittleren, Meso-Maßstabsebene des Materials entworfen worden ist, also nicht auf der Mikro- oder der Makro-Ebene. Der Begriff von "designer matter (DM)" wird innerhalb eines weiteren Begriffsfeldes positioniert und darin abgegrenzt. Dieses weitere Begriffsfeld umfasst die Konzepte von "transformative material", "mediated matter", "smart material", "active matter", "metamaterial", "machine material", "programmable matter" und "digital materials". Die Möglichkeiten und die Herausforderungen für eine Implementierung von "designer matter (DM)" in der Architektur werden formuliert.

Der Stand der Technik für entworfene granulare Materialien wird sowohl für die Architektur als auch für die relevanten Forschungen aus der Granularphysik dargestellt. Diese Übersicht umfasst sowohl die konzeptionelle als auch die projektbasierte Forschungsebene. In dem Bereich der Architektur sind erst einige wenige konzeptionelle Rahmenwerke und darauf bezogene Projekte erstellt worden. In dem Bereich der Granularphysik sind zwar ebenfalls erst einige wenige konzeptionelle Rahmenwerke für entworfene granulare Materialien formuliert worden; jedoch wurden hier bereits eine ganze Reihe von granularen Materialien aus entworfenen Partikeln untersucht. In diesem Kontext zielt die vorliegende Arbeit darauf ab, ein erstes umfassendes Entwurfssystem für granulare Materialien in der Architektur zu erstellen und zu validieren. Dieses Entwurfssystem wird darüber hinaus auch als Schnittstelle zum Bereich der Granularphysik verstanden, die es ermöglicht, kollaborative Projekte zu formulieren und durchzuführen. Die Forschungsentwicklung für diese Arbeit wird in ihrer grundlegenden praktischen, methodischen und konzeptionellen Wegbereitung vorgestellt.

Die Methoden werden auf drei Ebenen diskutiert: erstens auf der Ebene von methodischen Rahmenwerken, zweitens auf der Ebene der methodischen Werkzeuge und Techniken, drittens auf der Ebene der für die Forschungen angewandten Untersuchungsmethodik. Auf der Ebene der methodischen Rahmenwerke werden sowohl die Begriffe "vorwärts gerichtete" ("forward") und "inverse" ("inverse") Entwurfsmethoden eingeführt, als auch die Begriffe Experiment und Simulation, beziehungsweise analog und digital. Die Arbeit ist im Bereich der "vorwärts gerichteten" ("forward") Entwurfsmethoden angesiedelt und setzt sowohl Experimente als auch Simulationen mit analogen oder digitalen Mitteln ein. Die methodischen Werkzeuge und Techniken werden hauptsächlich dem Bereich der Granularphysik entnommen. Die in der vorliegenden Arbeit angewandte Forschungsmethodologie beruht zunächst auf der Erstellung eines Entwurfssystems für Partikel- und Konstruktionssysteme. Dieses wird durch Machbarkeitstests verifiziert, die einen oder wenige Systemparameter isolieren. In einem zweiten Schritt wird dieses System mittels zwei Fallstudien getestet, die mehrere Systemparameter integrieren. Die Fallstudien werden von statistischen Serien zu spezifischen relevanten Fragestellungen ergänzt. Die Ergebnisse werden auf einer praktischen, methodischen und konzeptionellen Ebene in dem Bereich der Architektur evaluiert. Die Relevanz der Ergebnisse für eine transdisziplinäre Kollaboration mit dem Bereich der Granularphysik wird diskutiert.

Der Hauptteil der Arbeit umfasst also das Entwurfssystem, den dazugehörigen Katalog von Versuchen sowie die zwei Fallstudien.

Das Entwurfssystem etabliert die Partikelsysteme und die dazugehörigen Konstruktionssysteme. Es formuliert die grundlegenden Systemkategorien und entsprechenden Parameter. Partikelsysteme werden nach Partikelgeometrie, Partikelmaterial und Mischverhältnis differenziert. Konstruktionssysteme werden danach unterschieden, ob sie lokal oder global wirken, oder ob sie die Randbedingungen des Systems bestimmen. Der Katalog der Versuche zu dem Entwurfssystem wird im Appendix vorgestellt. In diesem Teil der Dissertation werden Tests zusammengefasst, welche die individuellen Aspekte des gesamten Entwurfssystems für Partikel- und Konstruktionssysteme exemplarisch untersuchen.

Die zwei Fallstudien befassen sich mit der Integration einer jeweils unterschiedlichen Kombination von Kategorien des gesamten Entwurfssystems. Sie werden durchgeführt als vollmaßstäbliche Prototypen, die begleitet werden von einem darauf bezogenen Satz von statistischen Reihen. Fallstudie 1 untersucht vertikale Strukturen aus einem entworfenen granularen Material bestehend aus hoch nicht-konvexen Partikeln. Fallstudie 2 kombiniert zwei entworfene granulare Materialien, eines aus konvexen und eines aus hoch nicht-konvexen Partikeln, um räumliche Umschließungen zu formen. Die zwei Fallstudien werden in situ mit einem Seilroboter konstruiert. Die Fallstudien werden im Hinblick auf ihre praktischen, methodischen und konzeptionellen Ergebnisse in dem Bereich der Architekturforschung ausgewertet.

Die Arbeit wird zusammenfassend dargestellt und ihre Beiträge werden abschließend evaluiert, sowohl im Hinblick auf den Bereich der Architektur als auch für den Bereich der Granularphysik.

Für den Bereich der Architektur werden die Beiträge der Arbeit auf der praktischen, der methodischen und der konzeptionellen Ebene evaluiert. Auf der praktischen Ebene kann das Entwurfssystem als ein erster Beitrag zur systematischen Erschließung von entworfenen granularen Materialien und deren Konstruktionssystemen in der Architektur angesehen werden. Jedoch muss hierbei auf die potentiell selektive Natur des Entwurfssystems hingewiesen werden. Auf der methodischen Ebene sind hauptsächlich "vorwärts gerichtete" ("forward") Entwurfsmethoden angewendet worden. Dies kann als Einschränkung der Arbeit aufgefasst werden, scheint jedoch angebracht im Hinblick auf die Tatsache, dass sowohl die Parameter als auch die Problemstellungen formuliert werden müssen, bevor "inverse" ("inverse") Entwurfsmethoden zum Einsatz kommen können. In dieser Hinsicht können die Ergebnisse aus den "vorwärts gerichteten" ("forward") Entwurfsprozessen im nächsten Schritt als Eingabe für die "inversen" ("inverse") Modelle der Entwurfsforschung dienen. Eine Reihe von methodischen Werkzeugen und Techniken sind aus dem Bereich der Granularphysik für die Architektur adaptiert worden. Die Konsequenz ist eine Erweiterung der Bandbreite der architektonischen Entwurfswerkzeuge. Auf der konzeptionellen Ebene kann die Integration von entworfenen granularen Materialien für die Architektur in den weiteren Forschungsbereich von "designer matter (DM)" als ein erster Schritt hin zu einem weiter gefassten konzeptionellen Rahmenwerk gesehen werden. Da jedoch sowohl der Begriff von "designer matter (DM)" als auch das Feld der entworfenen granularen Materialien neu in dem Bereich der Architektur sind, müssen beide Felder parallel und in Beziehung zueinander entwickelt werden. Insbesondere ist diese Untersuchung dahingehend ein Beitrag zu dem konzeptionellen Rahmenwerk von "designer matter (DM)", dass sie zeigt, wie granulare Materialien durch die Verwendung entworfener Partikel neue, definierte Eigenschaften erhalten können. Für den Bereich der Granularphysik kann das Entwurfssystem als Beitrag zu einer Schnittstelle zwischen Architektur und Granularphysik gesehen werden. Die Herausforderung liegt hier in dem scheinbar trivialen Unterschied zwischen den Forschungskulturen in der Architektur und der Granularphysik: während in der Architektur Ergebnisse häufig durch die qualitative Observation von vollmaßstäblichen Prototypen erzielt werden, wird in der Granularphysik in der Regel häufig mittels quantitativer Labortests geforscht. Das vorgestellte Entwurfssystem kann jedoch genutzt und auch ausgeweitet werden, um diese beiden Forschungskulturen zu umschließen. Das in den Fallstudien angewandte methodische Model, in dem vollmaßstäbliche architektonische Strukturen mit dafür relevanten Experiment- und Simulationsreihen kombiniert werden, ist eine mögliche Form, diese zwei Disziplinen zu kombinieren.

Weiterführende Forschungen in dem Bereich der entworfenen granularen Materialien können auf der praktischen, methodischen und konzeptionellen Entwurfsebene durchgeführt werden. Auf der praktischen Ebene ist in dem Bereich der Partikelsysteme die Untersuchung von gradierten granularen Materialien, von verschiedenen mechanischen Materialeigenschaften der Partikel und von granularen Materialien aus geometrisch variablen Partikeln vielversprechend. In dem Bereich der Konstruktionssysteme ist die Entwicklung von verhaltensbasierten Modellen für robotische Fertigung sehr relevant. Eine weitere wichtige Entwicklungstendenz ist die Vereinfachung der Konstruktionssysteme, während die Partikelsysteme so entworfen werden, dass sie einen großen Teil der konstruktiven Prozesse von selber leisten. Auf der methodischen Ebene ist die Integration von "inversen" ("inverse") Entwurfsmethoden der logische nächste Schritt. Dies kann auf Basis des vorgeschlagenen Entwurfssystems geschehen. Auf der konzeptionellen Ebene muss das Rahmenwerk von "designer matter (DM)" etabliert werden, sowohl im allgemeinen transdisziplinären als auch im architektonischen Kontext. Erst dann können entworfene granulare Materialien in vollem Umfang als eine Form von "designer matter (DM)" in der Architektur betrachtet werden.

Entscheidend für die weitere Entwicklung des gesamten Forschungsfeldes ist dabei die Integration der beiden Bereiche Architektur und Granularphysik.

Figure 1.1: Tetrapods in a cylinder. Particles with a non-convex geometry are contained inside a cylinder. The particles have been designed based on a parametric particle model, which allows variation of the particle dimension, arm amount, axis length and arm taper. The particles in this test have the values 50/4/20/0.2 (see section 9.1.1.1.1.1). Karola Dierichs | ICD, University of Stuttgart | 2018

1
Aim

The aim of the thesis is to establish granular materials, consisting of designed particles, as "material systems" in architecture [176] (see figure 1.1).

1.1 Definitions

Since the two notions of granular materials and designed granular materials are core aspects to the understanding of this thesis, they will be briefly defined in the following sections. For other technical terms the glossary in appendix B offers a first point of reference. The overarching notion of "material systems" is introduced in section 4.2.

1.1.1 Granular materials

Granular materials are defined as extremely large numbers of distinct particles, which are in size above a micrometre and have predominantly short-range contact forces acting between them [222; 11, p. 1; 115, pp. 1–3; 83, S374; 82, p. 267; 196, p. 1259; 197, p. 32]. Examples of granular materials in nature are sand, gravel or snow [222; 11, p. 3; 83, S374; 82, pp. 267–268; 196, p. 1259; 197, p. 32]. After water, granular materials are the substance which is second most processed by humans, for example in the construction industry they are widely used in their bound form as an aggregate with cement to form concrete [145; 11, pp. 1–2; 182, p. 229; 181, p. 77; 178, p. 81; 115, p. 3; 83, S374; 82, p. 268]. However, in their unbound form they are rarely deployed as an architectural "material system" [182, p. 229; 181, p. 77; 178, p. 81].

1.1.2 Designed granular materials

In a designed granular material the geometry and material of a particle are defined by a designer and consequently achieve specific effects with respect to the overall granular material [102, p. 25.1; 194, p. 14; 176, p. 64; 175, pp. 262–263]. In one school of thought, design can be defined as the exploration and use of the interrelation of a "material system" and its behaviour – of form and performance, of cause and effect – in order to create objects, such as buildings or industrial products [180, pp. 31–35]. In granular physics it is generally accepted that particle shape affects granular behaviour, and this relationship can be considered one instance of such a form–performance interrelation [16, p. 48]. A granular material consisting of such designed particles can have characteristics which are novel and different from those found in non-designed granular materials [102, p. 25.1; 194, p. 14]. In architecture granular materials made from designed particles can display new characteristics which fulfil relevant architectural performance criteria, such as structural stability, light transmission or thermal and sound insulation [209, p. 29.2; 102, p. 25.3; 99, pp. 87–88, 91].

1.2 Aims in architecture

Within the context of architecture the aim of the thesis is to establish a comprehensive framework for designed granular materials as architectural "material systems" on a practical, methodological and conceptual level.

The practical level comprises all processes that are dealing with the actual conduction of a test or a prototype [336; 337]. The methodological level comprises the systematization of these processes into a procedure which renders specific desired results and is repeatable [335; 334]. The conceptual level encompasses the overarching ideas which the results achieved through the practical and the methodological level bring into the field of architectural design [330; 329].

On the practical level, the aim is to establish and validate a design system for designed granular materials in architecture. This system should serve as a starting point and reference for architectural designers working with designed granular materials and related construction systems. The individual aspects of the design system can be selected, composed and developed into a multitude of architectural applications.

On the methodological level, the goal is on the one hand to establish a methodological framework for the development, observation, analysis and application of designed granular materials in architecture. On the other hand, the aim is to review and propose actual tools and techniques which are suitable for both the design of and architectural design with granular materials. These tools and techniques are mainly sourced from the field of granular physics.

On the conceptual level, the thesis aims to offer a suitable framework for designed granular materials in architecture. Due to the fact that the research intersects with granular physics, this conceptual framework needs to be transdisciplinary in nature yet discussed specifically with respect to architecture.

1.3 Aims for granular physics

Within the context of granular physics the thesis aims to establish the aforementioned design system as an interface between granular physics and architecture which facilitates collaborative research projects. The individual aspects of the system can be used both for quantitative analysis in the realm of granular physics and for qualitative analysis in the realm of architecture.

1.4 Structure of the work

The thesis is structured into eleven chapters and two appendices. Initially the relevance within architecture and the scope of the work are established. Next, the wider research context is introduced, which also offers the basis for the discussion of design conceptual frameworks. The current state is presented in detail both within architecture and granular physics on a conceptual and practical level. The research development of this thesis is introduced as laying the foundations of the work on a practical, methodological and conceptual level. Methods are presented both as methodological frameworks and tools and techniques. The main body of the work consists of the proposed design system and its validation through two case studies and a catalogue of 22 tests, which is shown in appendix A. The results are summarized and evaluated on the practical, methodological and conceptual levels of design as well as with respect to their role for granular physics. Further lines of research for architectural design alone and for the collaboration with granular physics are outlined.

Figure 2.1: Spheres in a cylinder. A granular material consisting of spheres, which by definition have a convex geometry, is contained inside a cylinder. The spheres have been sourced from industry and are thus a readily available bulk material. They have a diameter of circa 40 millimetres and a weight of circa 2.24 grams per particle. Karola Dierichs | ICD, University of Stuttgart | 2018

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Relevance

Granular materials, consisting of designed particles, are relevant to architectural research in three main aspects. They can be recycled, they can be reconfigured and their behaviour can be designed (see figure 2.1).

2.1 Granular materials can be recycled

First, a granular material, whether it is designed or not, can be fully recycled. This is due to the fact that the particles are in no way bound to each other. Recycling denotes that the exact same granular material can be re-used time and again for very different applications and locations.

This is an invaluable feature for contemporary architectural design since material recycling is one of the key requirements [209, p. 29.3; 2, p. 28.1; 102, p. 25.3; 181, p. 77].

2.2 Granular materials can be reconfigured

Second, a granular material can be reconfigured. This is also a feature that applies both to designed and non-designed granular materials. Reconfiguring is defined as the re-forming of a granular structure from one stable formation to another while the overall structure remains in place as a whole. Reconfiguring is different from recycling, which denotes the dismantling and reconstructing of the entire structure in a different location.

While architecture is in most cases considered immutable and permanent, adapting a structure through reconfiguration can open up a new approach to architectural design [209, p. 29.3; 95, pp. 76–77; 182, p. 235; 181, p. 77; 178, p. 82]. Reconfiguration can be relevant on different scales of architecture: it can pertain to adjusting the structure on an intermediary scale, for example to modulate light, or it can denote the rearrangement of entire spatial configurations [95, p. 80; 181, p. 77; 178, p. 82].

2.3 Granular materials can be designed

Third, a granular material can be designed. If the geometry as well as the material of the individual particle is determined by a designer, the behaviour of the overall granular material can be defined [209, pp. 29.2–29.3; 102, p. 25.1; 194, p. 14; 182, pp. 236–241; 176, pp. 64–65; 175, pp. 262–263; 174, pp. 274–275]. This is what is understood as a granular material by design [209, pp. 29.2–29.3; 102, p. 25.1; 194, p. 14; 176, pp. 64–65; 182, pp. 236–241; 175, pp. 262–263; 174, pp. 274–275].

Designing the behaviour of a granular material is highly relevant in the context of architecture, since in addition to being recyclable and reconfigurable, the granular material can now also be calibrated to have characteristics that apply to a wide range of specific architectural applications [209, p. 29.2; 102, p. 25.3; 99, pp. 87–88, 91; 182, pp. 236–241; 176, pp. 64–65; 175, pp. 262–263; 174, pp. 274–275].

Figure 3.1: Tetrapods. Particles with a non-convex tetrapod geometry remain stable to form a column after a containing cylinder has been removed. The particles have been designed for this stability, which renders them a designed granular material that is suitable for architectural structures, such as columns or domes. Karola Dierichs | ICD, University of Stuttgart | 2018

3
Scope

The scope of the work comprises contributions on a practical, methodological and conceptual level of architectural design as well as contributions to the collaboration between the fields of architecture and granular physics (see figure 3.1).

3.1 Architecture

3.1.1 Practical

The core of the work is formed by two main chapters, which are situated in the practical realm of architectural design.

Chapter 8 establishes a generic design system, which is developed using mainly qualitative feasibility tests conducted both through research and teaching. In chapter 9 two interrelated case studies are conducted, which use both full-scale architectural prototypes and pavilions as well as statistical experiments and simulations. Thus, the validation of the design system is conducted through the realization and evaluation of the two case studies.

3.1.2 Methodological

With respect to methodological frameworks, the notions of "forward" and "inverse" design, of experiment and simulation and of analogue and digital media are introduced (see section 7.1). "Forward" design approaches denote working from cause to effect, "inverse" ones from effect to cause. Only "forward" design approaches are used in this thesis. "Inverse" ones are highly promising, yet precise system set-ups and problem statements need to be established for them in advance, which is exactly what is done through initial tests using "forward" strategies. With respect to the other two methodological frameworks, both experiments and simulations as well as analogue and digital media are deployed.

The tools and techniques for observation, analysis and design with granular materials are adapted mainly from the field of granular physics into the field of architecture (see section 7.2). Established tools and techniques from granular physics are transferred to the realm of architecture. Since their mere adaptation from granular physics is already an innovation in architecture, this step needs to be integrated first before advancing to newly developed tools and techniques.

The applied methodology of research consists of the two core elements outlined in section 3.1.1: the design system and the case studies (see section 7.3). The case studies each integrate a different selection of system categories of the design system and are analysed not only with respect to their contributions on a practical level, but also on a methodological and conceptual level of design.

3.1.3 Conceptual

A basic introduction of a conceptual design framework for designed granular materials is given in chapter 4. This presents an initial integration of the work into a wider transdisciplinary context through contextualizing it. However, the thesis is not a theoretical investigation, mainly owing to the fact that the practical basis of working with designed granular materials needs to be established. More profound research needs to be conducted into the suggested or even a new range of design conceptual frameworks.

3.2 Granular physics

For the realm of granular physics, the scope of the work comprises the design system as a suggested interface for collaboration between architecture and granular physics (see chapter 8). This interfacing has been investigated in small collaborative tests. However, a more comprehensive and long-term integration of the two fields still needs to be established in the framework of a project application.

Figure 4.1: Spheres. Once a containing cylinder has been removed, spheres which by definition have a convex geometry flow out. They are thus a less stable material than non-convex particles. This low stability allows for the spheres to serve as a removable formwork in a more stable designed granular material in order to form spatial enclosures. Karola Dierichs | ICD, University of Stuttgart | 2018

4 Context

The thesis is situated within the two main research fields of architectural "material systems" and "designer matter (DM)" [300; 179; 176]. Following a basic distinction between the related terms "material" and "matter", section 4.2 gives a brief definition of granular materials as an architectural "material system". Section 4.3 then introduces the concept of "designer matter (DM)", positions it within related conceptual frameworks and draws an outline of "designer matter (DM)" in architecture. Consequently designed granular materials in architecture are discussed both as a form of architectural "material systems" and "designer matter (DM)" (see figure 4.1).

4.1 Material versus matter

"Material" and "matter" are closely related terms, yet they have slightly different connotations. Whereas the term "material" denotes a substance that something else can be made from, the term "matter" refers to the very substance itself [332; 333; 150; 149].

The following section introduces several fixed terms, of which either "material" or "matter" form an integral part. In these fixed terms "material" and "matter" are used regardless of their connotations. In the overall context of the thesis the dictionary definitions and connotations of material and matter are adhered to.

4.2 "Material systems" in architecture

The concept of an architectural "material system", as it is used in the context of this thesis, was originally introduced by Michael Hensel and Achim Menges [248; 173; 179; 180; 176]. In this definition, an architectural "material system" is the interrelation between material, structure and form on the one hand, and their performance on the other [248, pp. 44, 48, 55–56; 173, pp. 63–83; 179, p. 18; 180, p. 31; 176, p. 63]. Processes of self-formation are an integral part of a "material system", rendering morphology and morphogenesis inextricably interconnected [248, pp. 48–49; 179, p. 20].

Computation plays a crucial role in defining "material systems", as it allows for the integration and development of different aspects of the "material system" with respect to its characteristics and processes of formation as well as its performance [248, pp. 44, 48, 51–55; 173, pp. 63–83; 179, pp. 18–19; 180, pp. 31–32; 176, p. 66].

Hensel and Menges have defined three groups of "material systems": (i) "proliferated component systems", (ii) "globally modulated systems" and (iii) "aggregate systems" [176, pp. 63–64].

(i) A "proliferated component system" can be conceived of either from a product which is semi-finished or from components which can be modified to be different from each other [176, p. 64]. Semi-finished materials, for example rods, are usually broken down into smaller units; the process of modification then lies in the definition of the cut sizes and the patterns of assembly [176, p. 64]. A component is a fully finished product [176, p. 64]. It is modified based on intrinsic and extrinsic factors and then assembled into a system with other components [176, p. 64].

(ii) In a "globally modulated system" the overall "material system" is modified through local control points [176, p. 64]. These "material systems" thus gain their formation through finding a stable state based on their material composition and external factors, which encompass critical control nodes for the entire system and extrinsic forces acting on the system [176, p. 64].

(iii) "Aggregate systems" consist of a multitude of units in loose contact [176, p. 64]. They are controlled through defining the individual unit, the process of aggregating the units and the external boundary conditions [176, p. 64]. They can be perceived as the contrary of assembly systems since the individual parts are not physically connected to each other [176, p. 64]. However, they are still considered a system since the interactions of the constituent parts can be observed and deployed for design [176, p. 64].

Other categories which are applied to the analysis of "material systems" are the distinctions between plastic and elastic deformation as well as isotropic and anisotropic materials [176, pp. 64–65].

A "material system" is usually developed in two stages: the definition of system elements and the development or evolution of the system [179, pp. 20–22]. The system elements are defined as parametric models, which merely define critical non-dimensional geometric relations and material characteristics but not a dimensionally defined form [179, pp. 20–22]. Once the system elements are defined it is developed or evolved into more and more defined formations [248, p. 48; 179, p. 22; 176, p. 63]. Evolution is here not understood in the sense of an optimization, through for example a genetic algorithm, but as a continuous feedback process between analogue and digital models with multiple input parameters from both formative and performative aspects of the system [179, pp. 22–23]. In order to perform as an architectural structure a "material system" needs to be further developed with a consideration of building context, spatial organization, environmental conditions and a programme for their use [176, p. 63]. The material system becomes more and more adapted and defined during this process [248, pp. 55–56; 179, pp. 22–23].

4.3 "Designer matter" in architecture

"Designer matter (DM)" is a term introduced by Pedro M. Reis, Heinrich M. Jaeger and Martin van Hecke [300]. It embraces several tendencies in both the design and natural sciences which aim to tailor materials at a structural mesoscale [300, pp. 25–26]. A range of other terms have been used to describe the movement. The following sections will outline the overarching notion of "designer matter (DM)" in more detail, give a brief overview of the related terms and situate the concept of "designer matter (DM)" in the field of architectural design.

4.3.1 "Designer matter"

Pedro M. Reis, Heinrich M. Jaeger and Martin van Hecke describe "designer matter (DM)" as a transdisciplinary phenomenon, appearing in different fields, such as physics, materials science and architecture among others [300, p. 26]. The main characteristic of "designer matter (DM)" in Reis, Jaeger and van Hecke's definition is the fact that it addresses the design of structural characteristics of a material at its mesoscale, which makes it different both from micro- and macroscale approaches [300, pp. 25–26]. Microscale approaches, for example in materials science or chemistry, focus on the smallest units of a material [300, pp. 25–26]. In macroscale approaches the material is considered a continuum [300, p. 25]. The mesoscale of a material is then considered to lie in between the micro- and the macroscale [300, p. 25]. The definition, which Reis, Jaeger and van Hecke offer, is therefore a non-dimensional one, and instead refers to the inherent scales of the material itself.

This development according to Reis, Jaeger and van Hecke is enabled by new conceptual frameworks, theoretical progress in soft matter physics as well as advanced computational and novel experimental methods [300, p. 25]. Conceptual frameworks in the wider community start to see forms of chaotic behaviour in a material as opportunities rather than problems [300, p. 25]. Theoretical progress in soft matter physics opens up new opportunities for the determined tailoring of matter towards a specific behaviour [300, p. 25]. Computational methods have become available to wider user groups enabling a larger community to reliably model complex material behaviours [300, p. 25]. Experimental methods have expanded due to the spreading of digital fabrication such as 3D printing, allowing for fast testing of systems with a wide range of geometries and materials [300, p. 25]. "Designer matter (DM)" is intended to encompass a wider range of concepts currently used describing the phenomenon in the research community [300, p. 25].

The following sections give a brief overview of some of these concepts, which are included in the notion of "designer matter (DM)". Reis, Jaeger and van Hecke name the fields of "transformative matter, mediated matter©, smart matter, active matter, metamatter or machine matter" as being comprised in the notion of "designer matter (DM)" [300, p. 25]. In this overview the terms "transformative material", "smart material", "metamaterial" and "machine material" are used rather than "transformative matter", "smart matter", "metamatter" and "machine matter", since the former seem to be more widely deployed judging by the available literature. Furthermore the notions of "programmable matter" and "digital materials" are added in this overview as they bear a close relation to the field of "designer matter (DM)". Their differences among each other are highlighted and their respective relevance to the overall field is pointed out.

4.3.2 Overview of terms related to "designer matter"

4.3.2.1 "Transformative material"

The concept of "transformative materials" refers to the notion that a substance can change its characteristics and consequently its overall performance [375]. Reis, Jaeger and van Hecke refer to the term "transformative matter", however the term "transformative material" is used in the sources referenced here [300, p. 25]. This approach does not appear to be very widely used or elaborated upon, but nevertheless might serve as a useful approach for framing some of the present and future research in the field of "designer matter (DM)".

4.3.2.2 "Mediated matter"

"Mediated matter" is a concept developed by Neri Oxman at the Media Lab at the Massachusetts Institute of Technology [246; 255]. The group is committed to designing materials that mediate between "objects", "humans" and the "environment" [246; 255]. It uses nature as an inspiration, integrating synthetic biology with computer-based design approaches, digitally controlled fabrication processes and materials science [246; 255]. The projects span across several scales, for example between wearables and architectural interventions [246; 255]. The notion of "mediated matter" is very closely related to the concept of a material ecology, which is understood to be the interrelation between material "objects" and their surrounding "environment" by the means of computational design and fabrication [277, pp. 1–2; 276, pp. 321–322, 325; 275, p. 20].

The "mediated matter" approach does bear the main trait of "designer matter (DM)" since it works with materials which are tailored at the mesoscale to achieve macro-level effects. The field is distinguished from other approaches in the research area by emphasizing the exchange that the material has with its user and surroundings, rather than highlighting the act of designing matter itself. It can be considered a sub-group of "designer matter (DM)", but as an overarching term for the wider research field it does not seem suited as it is both relatively focused and apparently used by one research group only.

4.3.2.3 "Smart material"

The term "smart material" is broadly used; however, its exact connotation is not always clearly delineated [1, p. 8]. Reis, Jaeger and van Hecke refer to the concept as "smart matter", yet the term "smart material" appears to be more widely used [300, p. 25].

In a dictionary definition "smart materials" are described as being able to alter their characteristics in a directed manner as a response to external triggers [17]. Shape-memory alloys are one example of "smart materials" among others [17].

A similar definition is given by Axel Ritter in his overview monograph on "smart materials" [302]. He describes "smart materials" as substances and products thereof which have properties which can be reversibly changed through an external physical or chemical stimulus [302, pp. 8, 26]. Examples of such stimuli include light, temperature or electrical currents [302, pp. 8, 26]. Ritter emphasizes the aspect of reversibility of the transformation as key to categorizing a material as smart [302, pp. 8, 26]. In that respect he distinguishes between "non smart materials", "semi smart materials" and "smart materials" [302, pp. 8, 26]. "Non smart materials" cannot react reversibly, "semi smart materials" can react reversibly once or several times, "smart materials" respond to a trigger entirely reversibly [302, p. 8].

Mariella Ferrara and Murat Bengisu give an account of colour-changing "smart materials", but also offer a wider definition of the overall field in the initial chapters [120]. In their definition, too, "smart materials" change property based on external triggers and do so reversibly [120, pp. 1, 7]. A "smart material" is consequently distinct from a common one by having two states which alter according to an input [120, p. 5].

One of the most encompassing accounts of the emerging area of "smart materials" is given by Michelle Addington and Daniel Schodek of Harvard University [1]. Stating that in current usage "smart materials" can both refer to a material as being a substance and as being a series of actions, Addington and Schodek arrive at a working definition and characterization of "smart materials" with the traits of "immediacy", "transiency", "self-actuation", "selectivity" and "directness" being key to classifying a given material as smart [1, pp. 9–10]. "Immediacy" denotes the ability to react in real-time [1, p. 10]. "Transiency" describes a material's capacity to react to more environmental influences than just one [1, p. 10]. "Self-actuation" means that the responsive principle is intrinsic and not extrinsic to the substance [1, p. 10]. "Selectivity" implies that the reaction of the material can be predicted [1, p. 10]. "Directness" indicates that the reaction is clearly related to the triggering factor [1, p. 10]. Starting from these five criteria, Addington and Schodek proceed to define "property change" and "energy exchange" materials, which both go "reversibly" through these transformations and further have a "discrete size and location" [1, pp. 79–81].

"Smart materials" are most commonly designed in the dimensions of micrometres or even nanometres [120, pp. 3, 6–7; 1, p. 80]. However, there are tendencies to apply the same criteria to bigger length scales within a material [300, p. 28; 340, p. 6608].

Under the premise that the principles of "smart materials" can be applied also to a mesoscale, "smart materials" can be considered a form of "designer matter (DM)". "Smart materials" emphasize the reversible reaction of a material to a given stimulus. They are designed in the sense that this reaction is deployed in a predetermined and desired manner. The notion of "smart materials" is not suited as an overarching concept for the emerging field, since only some but not all materials which can be considered "designer matter (DM)" fall under the definition for "smart materials". Furthermore it still needs to be investigated whether the principles of "smart materials" can be taken from the nano- or micrometre dimensions to larger dimensions of design. Under these circumstances it seems appropriate to consider "smart materials" as one sub-group of "designer matter (DM)".

4.3.2.4 "Active matter"

"Active matter" is defined as a substance consisting of large numbers of individual elements which use energy coming from the surrounding environment for activation, mostly forming ordered movement [266, pp. 025002.15–025002.16; 289, p. 16; 142, p. 1; 296, p. 324]. Early work was conducted by Bruce A. Finlayson and Laurence E. Scriven [296, p. 326; 121]. They presented evidence that biological systems can show hydrodynamic instabilities based on activity within a fluid [296, p. 326]. According to a review by Gabriel Popkin two pieces of seminal work leading to the field of "active matter" were conducted in the 1990s [289, p. 17]. In 1997 Stanislas Leibler, a biophysicist, demonstrated that systems close to biological ones can be modelled using micro-tubes and proteins [289, p. 17; 268]. In 1995 Tamás Vicsek, also a biophysicist, used small moving arrows and showed that they form systematic patterns if sufficient arrows are used to fill a confined space [289, p. 17; 356]. John Toner, a physicist, took on Vicsek's experiments and applied the laws of hydrodynamics to them [289, p. 17; 346]. These two models – Vicsek's particle model and Toner's continuous one – initiated a wide range of "active matter" studies [289, p. 17]. Only in recent years, however, have theoretical approaches and experimental methods been integrated [289, p. 17]. Examples include research conducted under Andreas Bausch [289, p. 17; 314] as well as Zvonimir Dogic [289, pp. 16–17; 309]. Bausch and Dogic also did collaborative work with Maria Cristina Marchetti [289, p. 17; 208].

The field of "active matter" encompasses biological systems, such as flocks or cytoskeletons, as well as designed systems consisting of active particles [289, p. 16; 142, p. 1; 296, pp. 324–325].

The investigation of designed systems is especially relevant to the field of "designer matter (DM)". Some examples in this subgroup include so-called "surfers" [278], "motile colloids" [46], "filaments" in fluids [204] and also experiments with granular materials [374; 87; 216]. Designed "active matter" is also sometimes considered as a role model for biology [289, pp. 17–18]; examples referenced in the review by Popkin include: [49], [309], [310], [297], [5] and [33]. Skylar Tibbits from the Massachusetts

Institute of Technology (MIT) has deployed the term "active matter" in a more comprehensive manner, as describing a material which is designed to "sense, actuate, assemble, or compute" [342, p. 15]. Yet he delineates the term against "programmable matter" and "smart materials" only, and does not yet offer an in-depth argument as to why "active matter" in particular – and not any other conceptual framework – can be used as a comprehensive term for the emergent field [342, pp. 14–15].

In summary the field of "active matter" does not solely address questions of "designer matter (DM)", as it encompasses both designed and biological systems. But only designed "active matter" can be considered "designer matter (DM)". This is due to the fact that designed "active matter" operates on the mesoscale of a material, which in this case consists of multi-body systems of artificially designed units using energy from the environment. Designed "active matter" emphasizes the motility of its designed components, making it a very distinct form of "designer matter (DM)". Due to this high level of specificity, the notion of "active matter" does not lend itself as an overarching conceptual framework for the wider field of research into "designer matter (DM)" but can rather be regarded as a specific sub-group.

4.3.2.5 "Metamaterial"

A "metamaterial" is a designed material made of operative elements that are embedded in a functional matrix or combined into a larger assembly [266, p. 025002.14; 205, p. 126501.2]. Reis, Jaeger and van Hecke refer to the term as "metamatter"; however, the term "metamaterial" seems to be more widely established [300, p. 25]. An array of constituents is thus included in a base medium [117, p. 5]. The term was coined by the British physicist John Pendry [160, p. 3; 323; 280]. It refers to a material which has properties that exceed those of naturally occurring ones, the root of the term being derived from the Greek word "meta", meaning "beyond" [205, p. 126501.2; 223].

The concept of "metamaterials" is very often used in the context of optics and electromagnetics, but can also describe phenomena in other fields such as thermodynamics or even quantum mechanics [205, pp. 126501.2, 126501.30]. "Mechanical metamaterials" are also playing an increasing role in this research area [266, pp. 025002.14–025002.15]. Early work in this field was conducted in the 19th century by Jagadis Chunder Bose and Karl Lindman in 1920 [205, p. 126501.2; 117, p. 5; 224; 45].

"Metamaterials" can in some cases be considered to be "programmable" [122, p. 175503.1; 76, pp. 1, 8; 37, p. 1346]. The term "digital metamaterials" is also used [286, pp. 1–8; 76, pp. 1, 8; 86, p. 1115]. However, different from the concept of "digital materials" as described in section 4.3.2.7, a "digital metamaterial" uses a quasi-binary information of two substances to code a "metamaterial" [86, p. 1115].

"Metamaterials" are one relatively established and clearly defined field of "designer matter (DM)". They too address material design at an intermediate scale. This approach to "designer matter (DM)" especially highlights the fact that a designed material can be developed which can go beyond naturally occurring phenomena. This is a trait which a lot of other approaches to "designer matter (DM)" pursue and it is one of the core arguments for the overall field. The term "metamaterial" thus might be as suitable as "designer matter (DM)" for the overarching field. However, since it has already been very specifically applied in some fields such as electromagnetics or optics, the use of the term for a wider range of research endeavours might be misleading.

4.3.2.6 "Machine material"

The notion of a "machine material" does not appear to be very widely broached. Reis, Jaeger and van Hecke use the term "machine matter", but the key authors refer to the concept mainly as "machine material" [300, p. 25; 72]. In a "machine material" the elements are designed in such a way that the substrate performs more like a machine, which operates in a desired manner in and of itself, rather than as a material which is operated upon [73, pp. 994, 995; 75, p. 532; 72; 74; 71; 38, pp. 53–54].

"Machine materials" are a form of "designer matter (DM)" as in their case, too, the material is tailored at a mesoscale. The distinct aspect of this concept is the emphasis on the fact that the process of designing the material can be deployed not only to develop its behaviour but also to make it operate as a machine. As this concept is very specific and does not apply to a wide range of projects within the field, the term is not suitable as an overarching concept; however, it aptly describes a sub-group of "designer matter (DM)".

4.3.2.7 "Digital material"

One of the first researchers to use the term "digital material" was Neil Gershenfeld at the Massachusetts Institute of Technology's Media Lab [137; 287; 288; 133]. Gershenfeld and his co-workers highlight that despite advances in digital manufacturing, these processes still use "analogue materials" rather than "digital materials" [136, p. 123; 135, p. 50].

The group defines "digital materials" as consisting of discrete elements [136, p. 123; 288, p. 1]. These elements can have any geometry or size and a range of mechanisms for fitting together [288, p. 1]. However, the elements need to fulfil the following constraints: they can be broken down into smaller and simpler units; any two elements have a limited number of ways of linking together, with defined positions and orientations; and lastly the process of assembling should be fully reversible [136, p. 123; 288, p. 1; 60, p. 1221]. These premises allow for structures to be assembled through local logics rather than global placements [60, p. 1221]. The elements themselves are intended to be mass-produced and low-cost [136, p. 125]. Furthermore the mechanical characteristics of "digital materials" can be designed [288, p. 4].

Under the general premise that "digital materials" need to be developed alongside digital machines, Gershenfeld and his collaborators have identified a range of advantages for working with "digital materials". First, they can be fully taken apart and re-used rather than disposed of like many of their "analogue" counterparts [136, p. 123; 60, p. 1221; 135, pp. 51–52; 288, p. 1]. Second, in a "digital material" the sizing of a structure happens through accumulating the units with their local positions and orientations, and structures are not limited in size by the working space of a machine [136, p. 123; 135, p. 51; 60, p. 1221]. Third, they allow for finding and adjusting of faults in the system [136, p. 123; 60, p. 1221; 135, p. 51; 288, pp. 2–4]. This again sets "digital materials" apart from "analogue" ones, which tend to incrementally increase faults [135, p. 51]. Another important, fourth aspect is the fact that "digital materials" can be made from a wide range of different substances, whereas "analogue materials" are often limited in their choice depending on the machine they are being processed with [136, p. 123; 60, p. 1221; 135, p. 51; 288, p. 4]. Lastly, the often relatively simple operations obviate the need for highly specialized tools for assembly and allow it to be a fast process [136, p. 125; 60, p. 1221; 288, p. 1]. In terms of an analytical method, the similarity of "digital materials" to analytical models such as the finite element method (FEM) makes them suitable for computational analysis [136, p. 125]. Related research into the design of physical 3D printing voxels as a "digital material" has been conducted by Jonathan Hiller and Hod Lipson at Cornell University [188; 189; 187; 186]. Hod Lipson and co-workers have also developed electromechanical discrete elements which integrate concepts of both "digital materials" and "programmable matter" as described in section 4.3.2.8 [237].

"Digital materiality" is a term coined by Fabio Gramazio and Matthias Kohler [154]. It denotes the interrelation of material and information mainly through digitally controlled fabrication processes such as robotics [155, p. 7]. "Digital materiality" is not the same as a "digital material": in many ways the two concepts approach the topic from opposing sides. Whereas "digital materiality" aims to use digitally controlled fabrication processes for a given material, a "digital material" aims to develop a digital logic in the substance itself.

"Digital materials" can be considered a form of "designer matter (DM)" as they address the mesoscale and by definition also allow for the tuning of material characteristics through the design of a unit. What makes this approach to "designer matter (DM)" distinct from others is the emphasis on the establishment of the dichotomy between "analogue" and "digital materials", and thereby an emphasis on the assembly process of the material. The term "digital materials" thus refers to a very specific type of a geometrically defined designed material and is not suited as an overarching term for the field of "designer matter (DM)".

4.3.2.8 "Programmable matter"

The term "programmable matter" was originally introduced by Tommaso Toffoli and Norman Margolus in 1991 [345]. Their CAM-8 machine is an implementation of their concept of "programmable matter" [192; 345]. In Toffoli and Margolus's original definition "programmable matter" is a "fine-grained computing network" with "polynominal interconnections" [344, p. 187; 345, pp. 264, 266]. "Programmable matter" has the following characteristics: it can be arranged into clusters of any size; it can be dynamically rearranged; it can be controlled interactively; and it allows for processing in real-time [344, p. 187; 345, p. 266]. The programming model is based on "signals", "events" and "initial conditions" [345, p. 267].

In 2007 the Defence Advanced Research Projects Agency (DARPA) launched a research programme for the investigation of "programmable matter", which initiated major development in the field [57, p. 62; 81].

The use and understanding of the term "programmable matter" has considerably widened since its introduction by Toffoli and Margolus. In this broader sense "programmable matter" is merely understood as a material that can change its form and other physical characteristics through controlled user input [341, pp. 8–9; 57, p. 62; 37, p. 1346; 271, p. 8; 227, pp. 16–17; 274, pp. 92, 95; 343, pp. 216, 217, 224; 212, p. 1447; 367, pp. 103, 117; 211, p. 17; 169, p. 12441; 139, p. 2485; 9, p. 1; 141, p. 99; 134, p. 238]. The idea of "programmable matter" is currently used in a very flexible manner throughout a range of disciplines. However, in its core concept of a material which can produce specific outputs through input by a user, "programmable matter" addresses one important aspect of "designer matter (DM)": the behaviour of a material can be controlled through designing the properties of its component elements. Again, as in the previous cases, this process occurs on the material mesoscale. The term "programmable matter" is already used in a very wide spectrum of applications and might be a suitable conceptual framework in place of "designer matter (DM)".

However, in its original sense, "programmable matter" relates to a material whose network of constituent elements can perform digital computing operations. The suggestion within the context of this thesis is therefore to preserve the term "programmable matter" for these types of materials only and use the term "designer matter (DM)" for the wider research area, relating for example also to materials which have custom-tailored material elements but which cannot perform numerical computations.

4.3.3 Summary: "Designer matter" in architecture

In section 4.3.1 "designer matter (DM)" has been introduced as an overarching conceptual framework for different transdisciplinary trends to design matter in its structural characteristics at the mesoscale [300, pp. 25–26]. The term is intended to embrace the related notions of "transformative matter, mediated matter©, smart matter, active matter, metamatter or machine matter" [300, p. 25]. Consequently these six related approaches have been introduced in greater detail in section 4.3.2. The terms "transformative material", "smart material", "metamaterial" and "machine material" are used instead of "transformative matter", "smart matter", "metamatter" and "machine matter", since the former appear to be more widely employed in the available literature. The concepts of "programmable matter" and "digital materials" have been added as they seem immediately relevant to the discussion. The different concepts have been evaluated with respect to their relevance to the notion of "designer matter (DM)" and with respect to their serving as an alternative overarching conceptual framework for the emerging field.

"Transformative material" refers to a substance that can change its characteristics and consequently its behaviour. The term does not appear to be widely used but touches on a relevant aspect of "designer matter (DM)". As an overarching conceptual framework it does not appear to be suitable as it describes a very specific aspect of the overall research area (see section 4.3.2.1).

"Mediated matter" interrelates material "objects", "humans" and the surrounding "environment". Given that design happens at the mesoscale of the material, it can be considered a form of "designer matter (DM)"; however, the concept seems to be quite specific and is thus not suited as an overarching term for the field (see section 4.3.2.2).

"Smart materials" are responsive to external stimuli in a controlled and reversible fashion. They are frequently designed in the dimensions of micrometres or nanometres; however, the approach appears to be transferable to mesoscale operations and consequently "smart material" can be considered a form of "designer matter (DM)". Like "transformative materials", the concept frames a precise aspect of some materials which have been designed; consequently the term "smart material" is not appropriate as an overarching concept for the field (see section 4.3.2.3).

The term "active matter" refers to multi-body systems with pattern formation through environmental energy. As system design occurs at the mesoscale, "active matter" is a form of "designer matter (DM)". However, also in this case, the described systems are quite specific and the term does not apply to the wider field (see section 4.3.2.4).

The term "metamaterial" refers to elements which are embedded in a host material, generating a substance with characteristics that go beyond naturally found ones. This field, too, operates on a mesoscale of material design and is consequently a form of "designer matter (DM)". The meaning of the term "metamaterial" – rooted to the Greek word "meta", meaning "beyond" – renders the term itself quite suited to describing the wider field, as it encapsulates one of the binding core ideas. However, the field of "metamaterials" is already strongly rooted in specific disciplines such as electromagnetics and optics. Widening its use to other fields might render the terminology confusing (see section 4.3.2.5).

"Machine material" is, like "mediated matter" and "transformative material", a term seemingly used within one research group only. It refers to a material that is tailored to have machine-like properties. Again, this occurs at a mesoscale which positions "machine materials" within the definition of "designer matter (DM)". As an overarching term "machine material" is not suitable as it describes only a specific sub-set of systems (see section 4.3.2.6).

"Digital materials" consist of distinct elements of any size or geometry whose geometry can be broken down into simpler units, these units having only a limited number of ways of linking together with defined orientations and positions allowing for reversible assembly. "Digital materials" also address material design at the mesoscale, and are therefore "designer matter (DM)". The notion of "digital materials" refers to quite a specified type of system in which the component units are designed and is thus not suited as an overarching term (see section 4.3.2.7).

"Programmable matter" describes substances where a controlled input achieves a controlled output. It mainly operates on a mesoscale and describes an important aspect of the overall field and consequently might be suitable as an overarching term; in fact the concept of "programmable matter" is already being used to describe a very wide range of research projects. However, in its original sense "programmable matter" refers to a network of units which perform digital computing operations, so the suggestion within the framework of this thesis is to reduce the term back to these types of systems and use the novel and generic term "designer matter (DM)" instead (see section 4.3.2.8). In summary most of the related terms describe a specific sub-aspect of the overall field of "designer matter (DM)". Only the concepts of "metamaterials" and "programmable matter" would allow for a more generic use. However, either their current use for specific fields, in the case of "metamaterials", or their history, in the case of "programmable matter", does not seem to render them as suited to describing the emerging field of research as "designer matter (DM)" is.

The definition of "designer matter (DM)" as being a material which has been tailored or designed at the mesoscale, is both novel and broad enough to allow for a wide range of present and future developments to take place under its umbrella [300, pp. 25–26]. "Designer matter (DM)" will consequently serve as an overarching conceptual framework for the research presented here.

As a general observation the featured sub-groups appear to have different degrees of establishment within the research community, ranging from widely used research concepts like "smart materials" to concepts apparently established through one group only such as "mediated matter". This might call for a revision and coherent establishment of sub-themes within the field of "designer matter (DM)" [300, p. 28].

"Designer matter (DM)" applies to a very wide range of research fields, among others chemistry, mechanics, materials science and also architecture [300, p. 26]. It is a concept that spans across several disciplines. In architecture its exact meaning and significance still need to be defined, tested and verified. The following paragraphs will give a first attempt at this integration of "designer matter (DM)" within architecture. The significance of introducing design at a mesoscale of architecture is two-fold. On a very simple level, material behaviours can be created that did not exist previously, much in the sense of a "metamaterial". In doing so materials can be optimized for architectural performance or even entirely novel material behaviours can be tailored. Secondly, "designer matter (DM)" in architecture can introduce new design paradigms on the macroscale in a bottom-up process: if materials behave by design rather than obeying the designer, the act of designing itself changes. The challenges in introducing "designer matter (DM)" in the architectural process involve first and foremost the identification of relevant topical areas for material design and suited performance criteria. On the other hand, working at building-scale dimensions is core to architectural design. These relatively large dimensions need to be practically, methodologically and conceptually integrated in the notion of "designer matter (DM)" in architecture in order to render it a relevant architectural design approach rather than merely a contributing field.

4.4 Summary and evaluation of the context

In the context of architectural "material systems" designed granular materials belong to the group of "aggregate systems". Here they form the sub-group of granular materials consisting of designed particles in contrast to granular materials composed of particles which are non-designed (see section 4.2). The designed production of the particles allows for the precise definition and parametrization of their geometry and consequently for the calibration of the behaviour of the overall granular material.

In the context of "designer matter (DM)", designed granular materials can be classified as a form of "designer matter (DM)", since the design occurs on the mesoscale of the granular material, namely the particle (see section 4.3). However, they do not seem to fall into any of the named sub-groups.

"Transformative materials" emphasize the transition from one state to another (see section 4.3.2.1), which is not a key question with respect to designed granular materials. "Mediated matter" as a concept might apply also to designed granular materials; however, the emphasis on negotiating between "human", "environment" and material "object" (see section 4.3.2.2) also does not seem central for the development of designed granular materials. "Smart materials" refer to the ability of a material to respond reversibly to external triggers (see section 4.3.2.3); this might apply to some designed granular materials, but is not a core research paradigm for this specific field. Some systems of "active matter" use granular materials (see section 4.3.2.4). However, granular "active matter" systems are quite a specific application of granular materials. They lay the emphasis on the behaviour of the granular material as a whole under an external energy source rather than on the interrelation of particle geometry and granular behaviour, as is the case for designed granular materials. "Metamaterials" relate primarily to periodically organized units in or on a substrate, which designed granular materials are not (see section 4.3.2.5). "Machine materials" are understood to operate more like machines rather than mere materials, which is not the goal of a designed granular material (see section 4.3.2.6). At first sight granular materials bear a close similarity to "digital materials", simply due to the amount and limitless growth potential of the structures; however, "digital materials" require the units to have a limited number of ways of linking together as well as definite positions and orientations (see section 4.3.2.7), which criteria granular materials do not fulfil. The notion of "programmable matter" refers in its original meaning to a network of digital computing units (see section 4.3.2.8), a confined notion which in the context of this thesis is suggested to be reintroduced. Thus, granular materials cannot be seen as a form of "programmable matter" even though this has been previously stated in related publications [102; 381; 89; 99; 95].

It therefore seems appropriate to consider designed granular materials in general, and in architecture in particular, as a distinct sub-group in the overall field of "designer matter (DM)" at this moment in time. As indicated in the preceding section, a new classification of the area of "designer matter (DM)", which also embraces designed granular materials in a larger sub-theme, might be a resourceful next step in the future development of the field [300, p. 28].

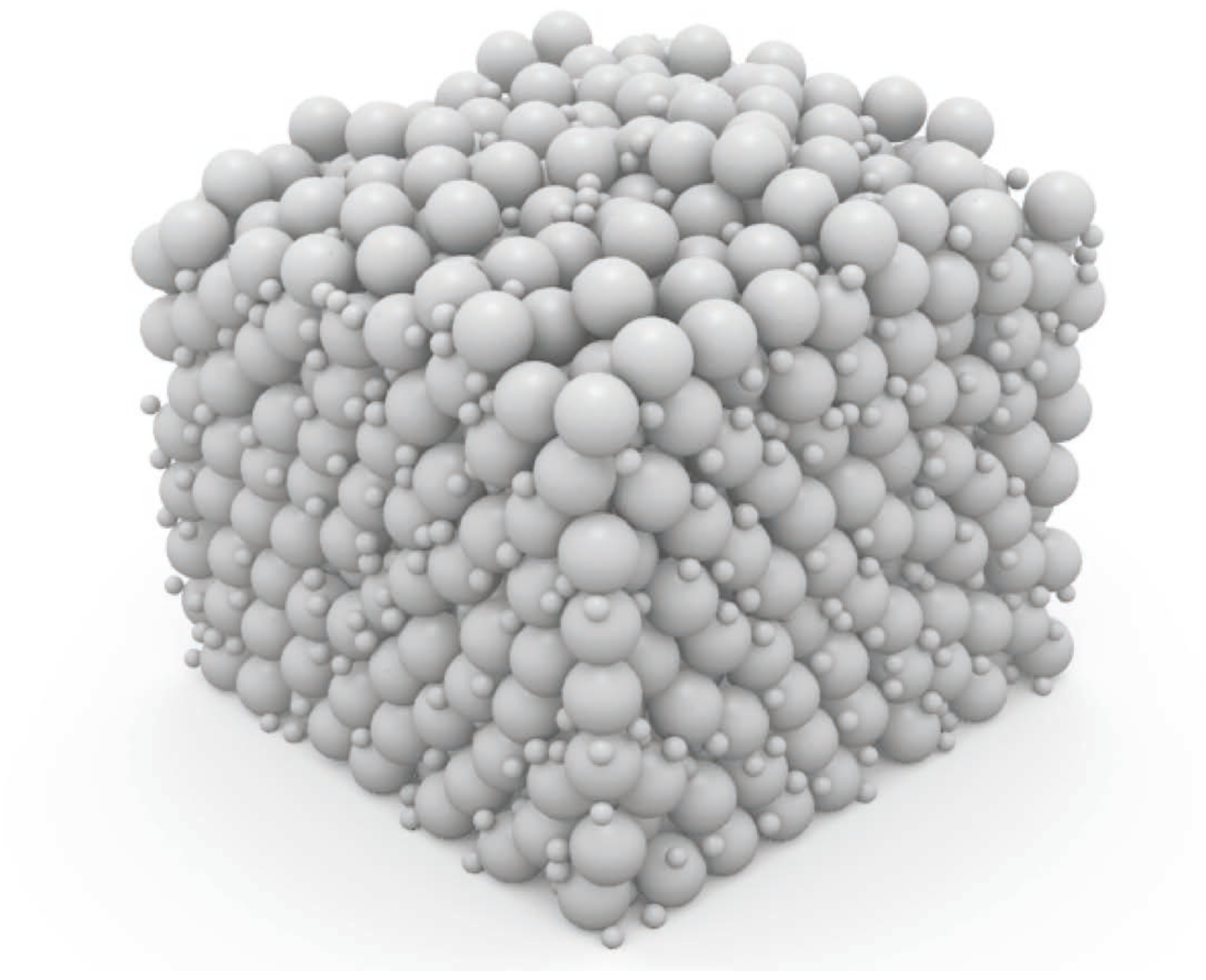

Figure 5.1: Particles optimized for dense packing. Particle geometries which allow dense packing have been optimized using "inverse" methods of design. "Inverse" methods enable the designer to move from effect to cause or from performance of the designed granular material to the form of the particles (see sections 5.2.2.2 and 7.1.1). Marc Z. Miskin, Heinrich M. Jaeger | Jaeger Lab, University of Chicago | 2014 [253]

5

Current state

Designed granular materials in architecture are situated both within the fields of architectural design and granular physics. Each of these two areas will therefore be reviewed in this chapter.

With respect to the field of architecture the aim is to identify relevant precedent work and consequently to establish key lines of research for the thesis. With respect to the field of granular physics it is the goal to give an overview of designed granular materials on the one hand and to identify intersections with architectural design research on the other (see figure 5.1). Both reviews distinguish between conceptual frameworks and applied projects or research. To conclude, the current state of designed granular materials in architecture and granular physics is summarized as well as evaluated and the novel contributions of this thesis are outlined.

5.1 Designed granular materials in architecture

This section introduces the current state of designed granular materials in architecture. On the level of conceptual frameworks, four concepts related to granular architectures are presented. On the level of applied projects and research, six relevant projects are identified and evaluated especially with respect to the design of the particles and the actual tests conducted with them.

5.1.1 Conceptual frameworks

Designed granular materials are comparatively novel in an architectural context. Yet a range of conceptual frameworks already exist, which have been developed in order to systematize these specific "material systems" and consequently make them accessible on a broader conceptual design level. These frameworks have been named "aggregate systems" by Michael Hensel and Achim Menges, "tectonics of indeterminate extension" by Kentaro Tsubaki, "jammed architectural structures" by Fabio Gramazio, Matthias Kohler and Skylar Tibbits and "aleatory architectures" by Sean Keller and Heinrich M. Jaeger [209; 2; 354; 176]. The following sections will introduce these concepts and then situate the framework presented in this thesis within them.

5.1.1.1 "Aggregate systems"

The notion of an architectural granular material in which the individual particle is designed was introduced in 2006 by Michael Hensel and Achim Menges [176; 175; 174]. They outline designed granular materials as a sub-group of "aggregate systems" and introduce basic research trajectories using two relevant project examples, which are further discussed in several key publications from 2008 and 2010 [182; 178; 181]. "Aggregate systems" are part of the overall "Morpho-Ecologies approach" [176, p. 63]. They are seen as one group of three types of "material systems", as discussed in section 4.2 [176, pp. 63–64]. Hensel and Menges define them as architectural systems which consist of large amounts of loose, distinct particles [182, p. 229; 181, p. 77; 178, p. 81; 175, p. 262; 176, p. 64]. "Aggregate systems" made from designed particles in this conceptual approach are a specific sub-group of "aggregate systems" in architecture [182, p. 236; 175, p. 263].

"Aggregate systems" according to Hensel and Menges have distinct characteristics which make them relevant within architectural design research. First and foremost they have the ability to move between solid and static or liquid and dynamic states and are consequently self-organizing systems [182, p. 230; 181, p. 77; 178, pp. 81–82; 175, pp. 262–263]. Based on this and due to the fact that the particles are not bound to each other, these systems allow for continuous reconfiguration and recycling [181, p. 77; 178, p. 81; 174, p. 275; 175, p. 263]. Secondly, Hensel and Menges point out that granular materials have a very distinct load-bearing behaviour, such as anisotropy and the formation of contact force-networks under stress, which can be strategically deployed in an architectural system [182, p. 235; 178, p. 82]. Lastly, "aggregate systems" are rapidly deployable and quick to handle; this not only allows multiple experiments to be conducted but also fast reconfiguration by potential user groups [182, p. 229; 174, pp. 274, 275].

Hensel and Menges highlight that "aggregate systems" are entirely opposed to conventional architectural planning processes [182, p. 229; 181, p. 77; 178, p. 80; 175, p. 262; 176, p. 64]. They state that loose granular materials have been explored only in relatively isolated instances as architectural "material systems", but that a coherent design investigation of them has not been conducted so far [182, p. 229; 181, p. 77; 178, p. 81; 175, p. 262].

Hensel and Menges point out that a granular material's potential instability and dynamic behaviour make it an unexpected subject for architectural design research [182, p. 229]. However, as Hensel and Menges argue, the exploration and instrumentation of the behaviour of granular materials in an architectural context is a promising and possible route; in their eyes it requires a departure from an architecture which imposes form on an inert mass, such as formwork in concrete, towards an approach which observes and deploys the self-organizational characteristics of the granular material [182, p. 230; 181, p. 77; 178, p. 81].

The authors state that, other than in conventional architectural systems where overall geometric form of the structure as well as the position and the connections between elements are precisely defined, working with a granular material challenges the architect to operate with the behaviour of the material; methodologically this denotes a shift from technologies of notation towards tools of observation [182, p. 229; 181, p. 77; 178, p. 82].

One crucial aspect which Hensel and Menges point out and which makes "aggregate systems" distinct from most other architectural systems is their temporality: whereas a conventional architectural structure is planned for permanence and consequent destruction, "aggregate systems" assume numerous evolving stable states during their deployment [182, pp. 229–230, 235; 181, p. 77; 178, p. 82].

Michael Hensel and Achim Menges also outline the basic planning parameters for "aggregate systems" in their conceptual framework. Altogether three parametric realms need to be considered in the process: the particle parameters, the construction principles deployed for the entire configuration and the boundary conditions

[182, p. 235; 181, p. 77; 178, p. 82; 174, p. 275; 175, p. 262; 176, p. 64]. As already indicated in this section, "aggregate systems" challenge the designer to work with methods, tools and techniques which are largely new to the architectural profession; as Hensel and Menges point out, the emphasis is on empirical experiments which are complemented by simulations such as the discrete element method (DEM) or even the finite element method (FEM) or computational fluid dynamics (CFD) [182, pp. 229, 240; 181, p. 77; 178, p. 82].

Comments by Theo Lorenz and Christopher Hight on projects supervised by Michael Hensel and Achim Menges establish a framework for the development of the individual designed particle and its implications as well as questions of human interaction with the reconfigurable granular material [230; 185].

Theo Lorenz reviews the diploma thesis project conducted by Eiichi Matsuda at the Architectural Association School of Architecture (AA) in Diploma Unit 4 under their supervision. Lorenz suggests four directions of future development for "aggregate systems" [230, p. 272]. The first direction focuses on the exploration of geometric parameters in order to calibrate the system behaviour; Lorenz already suggests hooks in addition to the highly non-convex shapes investigated in Matsuda's project [230, pp. 272–273]. The second direction is aimed at materials which allow the particles to vary their characteristics over time [230, p. 273]. The third proposed direction of investigation could aim at mechanisms of more permanent interlocking, which snap into each other under gravity but which still can come apart through pulling [230, p. 273]. The fourth direction, which Lorenz forecasts, enters into the realm of communicating particles, where the individual particle has an integrated intelligence which allows it to react to the sensory data input it receives from the other particles in the system [230, p. 273].

Christopher Hight reviews a studio project conducted by Anne Hawkins and Catie Newell in the GPA Studio at Rice University under Hensel and Menges's supervision (see section 5.1.2.3). He elaborates that "aggregate systems" are a radical departure from the concepts of geometry and detail as they are normally used in architecture: whereas geometry is usually controlled, and architectural detail serves to achieve this control, "aggregate systems" rely on "stored energy" on the level of the detail in the form of friction, which can release itself resulting in an unpredictable overall behaviour [185, pp. 284–285]. Hight suggests that rather than viewing these "aggregate systems" on an architectural scale, they should be investigated as potentially very large-scale urban systems [185, p. 285].

In conclusion, the conceptual framework of "aggregate systems" introduced by Michael Hensel and Achim Menges is a comprehensive proposal to use granular materials as architectural "material systems", highlighting their relevance and novelty within architecture as well as indicating methodological advances and planning parameters.

5.1.1.2 "Tectonics of indeterminate extension"

Kentaro Tsubaki proposes the concept of "tectonics of indeterminate extension" [354; 353; 352]. This notion centres on the idea of structures that are based on deploying the laws of "probability" [354, pp. 187, 193; 353, p. 294; 352, p. 273]. He positions his concept as a counterpoint to developments in the building sector which engages in complex forms by deploying novel precise and rapid digital technologies and computational capacity [354, p. 202; 353, pp. 292, 298; 352, pp. 270, 277]. Tsubaki compares his notion of a probabilistic, indeterminate architectural system versus deterministic architectural systems to the paradigm shift introduced by statistical mechanics versus classical mechanics [354, p. 190; 353, p. 292; 352, p. 270]. He proposes his project "tumbling units" as a prototypical example of such a probabilistic system [354, p. 193; 353, p. 292; 352, p. 270].

The notion of "tectonics of indeterminate extension" introduced by Tsubaki thus specifically emphasizes the probabilistic nature of granular materials in an architectural context.

5.1.1.3 "Jammed architectural structures"

"Jammed architectural structures" are a concept introduced by Gramazio Kohler Research at the Swiss Federal Institute of Technology (ETH) Zurich and the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT) [3; 2]. Whereas the authors themselves do not suggest the application of the notion of "jammed architectural structures" to designed granular materials, the concept itself might still be relevant and transferable to this field. Thus, the conceptual framework of "jammed architectural structures" is considered within this review.

"Jammed architectural structures" utilize the physical phenomenon of "jamming" for the design of full-scale architectural applications [2, p. 28.1]. In a "jamming transition" a granular material transits from a fluid-like to a solid-like state due to confining forces, which is a reversible process [3, p. 85; 2, p. 28.1].

The authors emphasize that "jammed architectural structures" are highly relevant as new architectural construction systems, and name a set of core aspects for this: the "jamming" process is entirely reversible and the structures can be reconfigured [3, pp. 85, 87; 2, pp. 28.1–28.2, 28.10]; the solidification takes place instantly and requires up to no energy in that process [3, p. 87; 2, pp. 28.1–28.2]; the system has self-organisational capacities [2, p. 28.1]; locally occurring or recycled material can be used for the "jamming" process allowing simple materials to be turned into elaborate geometries [2, pp. 28.1–28.2, 28.10]; the structures can be realized at full architectural scale and directly on-site [2, p. 28.2]. Overall, these features render "jammed architectural structures" "sustainable, economical and structurally sound" [2, pp. 28.10–28.11].

The teams from the Swiss Federal Institute of Technology (ETH) Zurich and the Massachusetts Institute of Technology (MIT) outline several key parameters for the research into "jammed architectural structures" [2, pp. 28.1–28.2]. They highlight that the development must occur on a practical, methodological and conceptual level of design research [2, p. 28.2]. In their view, computational methods of design, numerical simulation and "sensory controlled" robotic construction processes need to be integrated in this respect [2, p. 28.2]. For a definition of "sensory control" see section 8.2.1.3.2.

The development thus essentially needs to focus on two aspects: the "material system" itself and the robotic construction procedure, where the material behaviour is at the core of the process and robotic construction informs it and is being informed by it [2, pp. 28.4, 28.10]. The interrelation of these two aspects is governed by three factors: the system precision or imprecision; the interfaces between sets of information; and lastly the integration of diverse research methods and fields [2, p. 28.10].

In conclusion, "jammed architectural structures" as introduced by Gramazio Kohler Research at the Swiss Federal Institute of Technology (ETH) Zurich and the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT) propose an approach to granular materials in architecture which is solely based on the physical process of "jamming" a given granular material, and consequently turning it from a liquid to a solid state. It is therefore a relatively focused conceptual framework. The emphasis is on working with cheaply available bulk material.

5.1.1.4 "Aleatory architectures" for architects

The architect Sean Keller and the physicist Heinrich M. Jaeger introduce the notion of "aleatory architectures" [209]. "Aleatory architectures" integrate knowledge from architecture and structural engineering as well as from granular physics [209, p. 29.2]. Keller and Jaeger outline a range of questions to the architectural, engineering and granular physics communities. In this section only the objectives for architecture are introduced; those that refer to the fields of granular physics and engineering are covered in the related chapter in section 5.2.1.3.

The term "aleatory architectures" was coined by Keller and Jaeger to denote structures which allow for a chance-based formation and reformation on the basis of their composing particles, and consequently call for a novel approach to design where the architect relinquishes control [209, p. 29.2]. The term has its roots in the Latin word "alea" meaning "dice", in other words a game of chance [209, p. 29.3]. Implicit in the term is the concept that the composing particles are designed to specifically react to architectural performance criteria, such as structural or spatial parameters [209, pp. 29.2–29.3]. Pointing to the fact that other disciplines such as music have already embraced chance-based methods, the authors highlight that architecture needs to find its own ways of incorporating the accidental into its design processes [209, p. 29.3].

Keller and Jaeger emphasize that "aleatory architectures" are a challenge to the notion of systematic ordering in architecture since they are based on the statistical behaviour of granular materials [209, p. 29.1]. However, according to the authors, a large amount of structures made from granular materials to date are relatively simple, relying mainly on the angle of repose; yet a range of recent research projects which use particles with a non-spherical shape suggest that characteristics of the granular materials can be calibrated, and consequently a larger range of structural forms becomes feasible [209, p. 29.2]. Keller and Jaeger propose that the inclusion of the accidental into the architectural design process could consequently produce structures which both have a high level of structural performance and convey a novel architectural repercussion [209, p. 29.2].

Keller and Jaeger identify a convergence of both technical and conceptual advances which is enabling the development of "aleatory architectures": on the one hand computational models, robotics and materials sciences have come to a stage where they can be deployed in conjunction with each other; on the other hand the authors state that modernism in architecture and its quest for "aesthetic stability" is slowly being dispersed [209, p. 29.3].

The relevance of "aleatory architectures", which Keller and Jaeger identify, is on the one hand the rapidity with which they can be configured, reconfigured and disaggregated as well as the fact that their material characteristics can be calibrated via the geometry of the individual particle [209, p. 29.3]. On the other hand the strategic use of the so-called "jamming transition" allows for the calibration of stiffness and strength [209, p. 29.2]. Furthermore the very fact that granular materials are not ordered but random might render them more resilient to failure than structures which depend on the exact positioning of their constituent units [209, p. 29.2].

Keller and Jaeger clearly delineate the scope of their conceptual approach: whereas granular materials are investigated in respect to a very wide range of particle types and scales, "aleatory architectures" refer solely to constructions made by and for humans with respect to their physical characteristics and aesthetic qualities [209, p. 29.3]. "Aleatory architectures" are not intended to replace current architectural construction processes and concepts but rather to widen the possible range of approaches [209, p. 29.3].

Keller and Jaeger review the current state of "aleatory architectures", which in general consists of projects using either a structural system in addition to the granular material or those that use particles with designed geometries allowing for a wider range of structural behaviours [209, p. 29.5].

Looking to the future, the authors highlight that development will take place between two poles: on the one hand the ease of construction with granular materials and the cheap availability of already standardized particles, and on the other the deployment of advanced robotics and the manufacturing of not yet standardized granular materials [209, p. 29.9].

With respect to architecture, Keller and Jaeger emphasize the aesthetic aspects of granular materials with their innate heterogeneity and level of detailed resolution being a very distinct characteristic [209, pp. 29.3, 29.5, 29.9]. The structures might align with a larger architectural argument considering the structural characteristics of a construction system as ornamental features in and of themselves and vice versa [209, p. 29.5]. Keller and Jaeger here refer to the writings of Farshid Moussavi and Michael Kubo as well as Nina Rappaport [209, p. 29.5; 260; 298]. The authors emphasize that the idea of a geometrical ordering system is replaced by an order based on the results of physical effects [209, p. 29.5].

The notion of "aleatory architectures" introduced by Keller and Jaeger is a comprehensive proposal to use granular materials as architectural construction and design systems, similar to the conceptual framework of "aggregate systems" presented in section 5.1.1.1. The idea of a chance-based approach is emphasized, like in the concept of "tectonics of indeterminate extension" (see section 5.1.1.2). The need for the integration of architecture, engineering and physics is especially highlighted. Within the context of architecture "aleatory architectures" are considered to introduce and investigate the topic of the aesthetics of chance and structural ornament.

5.1.1.5 Summary and evaluation of conceptual frameworks in architecture

The previous sections have introduced conceptual frameworks for granular materials which have already been established in the realms of architectural construction and design. Four approaches have been summarized (see sections 5.1.1.1 to 5.1.1.4).

Most of these frameworks address a wide range of granular materials and construction systems. Only one of them, "jammed architectural structures", focuses on more specific aspects of granular materials in architecture, namely "jamming" (see section 5.1.1.3). The advantages of granular materials that are pointed out in almost all approaches are their ability to reconfigure and to recycle as well as to be rapidly deployable. Depending on the individual focus, the facts that the behaviour of a granular material can be designed, that a granular material can self-organize, that complex geometries can be achieved from simple materials and that full-scale structures can be erected on site directly are highlighted. The need and value of a collaboration between architects, engineers and granular physicists is generally pointed out.

5.1.2 Project overview and analysis

A range of architectural projects have been conducted with designed granular materials. The following sections will introduce and evaluate them by the categories of particle geometry, particle material and particle system performance. The same categories are used in section 5.2.2.3 in order to analyse projects with designed granular materials in physics, so that a comparison between the results in the two disciplines can be made.

Two full-scale projects, from the Technical University of Vienna and from the University of Tokyo, have not been included [317; 316; 377]. Despite their use of large numbers of custom-made elements, they employ either assembly processes of construction or a binding matrix, which turns them into "material systems" related to but not the same as granular materials.

Several related projects appear to have only been published online and seem to be relatively quick and small explorations of designed granular materials for architectural applications [130; 376; 10; 239; 15; 36; 168; 206; 245; 338; 301]. They are consequently not included in this in-depth project review.

5.1.2.1 Architecture – Project 1

Project credits — *Author:* Kentaro Tsubaki | *Supervisors:* Dan Hoffman, Peter Lynch | *Project type:* M.Arch II thesis | *Institution:* Architecture Department, Cranbrook Academy of Art, Bloomfield Hills, Michigan | *Year:* 1996–97

Project description: One of the first projects using designed particles in a granular material was conducted as a Master's thesis at the Architecture Department of the Cranbrook Academy of Art by Kentaro Tsubaki in 1996–97 and later published in 2008, 2009

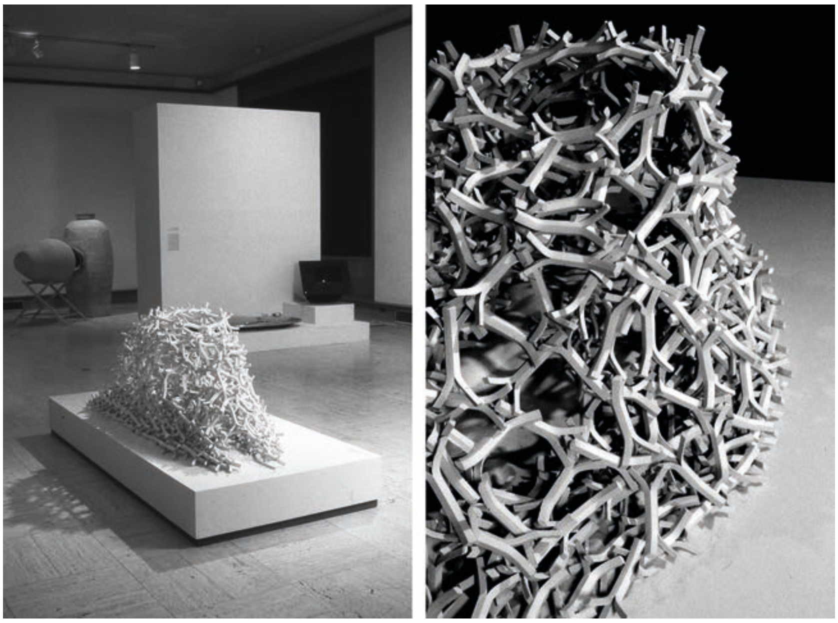

Figure 5.2: Architecture – Project 1. Kentaro Tsubaki | Architecture Department, Cranbrook Academy of Art | 1996–97 [352]

and 2012 [354; 353; 352] (see figure 5.2). The geometry of the unit consists of two tetrapods which are rotated 30 degrees in relation to each other and are connected with a backbone, resulting in a six-armed particle; the tetrapods are intended for interlocking, the backbone is designed to give the units the ability to reach a span [354, p. 195; 353, p. 294; 352, p. 273].

The units are made from ceramic and their final geometry considers fabrication procedures which are specific to this material; however, alternative materials and geometries were tested, such as Masonite or plywood, and assessed with respect to a range of design parameters such as the easy and fast fabrication of one unit [354, pp. 194–195; 353, p. 295; 352, p. 273]. Altogether over six hundred units were fabricated [354, p. 196; 353, p. 295; 352, p. 274]. Both low and large amounts of units were tested; one group of tests investigated what appears to be an assembly system arranging the units from an ordered to a less ordered arrangement [354, p. 198; 353, p. 295; 352, p. 274]. A second test uses the units as a granular material: a box is filled with sand, the units are stacked on the edges and more loosely distributed towards the centre, the sand is drained and a dome remains [354, pp. 199–200; 353, pp. 296–297; 352, p. 275]. The system was installed in two different formations: one spatial dome configuration which moves from an ordered to a disordered arrangement of the units, and one window screen using an ordered arrangement of the elements only [354, pp. 200–202; 353, pp. 297–298; 352, p. 276].

The project has been further pursued by Kentaro Tsubaki at Tulane University in 2013–14 as a supervisor to Richard Peterson [281].

5.1.2.2 Architecture – Project 2

Project credits **—** *Author:* Eiichi Matsuda | *Supervisors:* Michael Hensel, Achim Menges | *Project type:* Diploma Project | *Institution:* Diploma Unit 4, Architectural Association School of Architecture (AA), London | *Year:* 2003–04

Project description: Eiichi Matsuda conducted research into designed granular materials in Diploma Unit 4 at the Architectural Association School of Architecture (AA) from 2003 to 2004, published in 2006 [182; 243; 178; 175] (see figure 5.3). The project investigates spatial formations based on the behaviour of designed granular materials [182, p. 236; 243, p. 81; 178, p. 86]. The initial starting point of the project however was the easy and fast fabrication of the basic particle [175, p. 263]. It was made using three matchsticks joined in the middle to form a three-axial particle geometry [243, p. 81; 175, p. 263]. The base geometry was varied to test changes in degree of interlocking and surface contact between particles [175, p. 263]. Altogether ten thousand particles were made, which were marked on the ends in order to allow for pattern recognition and the analysis of particle rotations [182, p. 236; 243, p. 81; 178, p. 86; 175, p. 263].

Three main groups of experiments were conducted: experiments on horizontal surfaces; experiments with vertical and inclined surfaces; and experiments with removable constraining surfaces [178, p. 86; 175, p. 263].

Defining parameters for the first set of experiments were particle count, particle geometry, speed of pouring, height of the particle emission and roughness of the horizontal plane [243, p. 81; 178, p. 86; 175, p. 263]. The experiments measured on the one hand the maximum pile height before reconfiguration, the angle of repose and the particle spread after collapse [178, p. 86; 175, p. 263]. On the other hand, the density of the granular material in the piles was analysed; this performance criterion was to become one main design parameter throughout the project [178, p. 86; 175, p. 263].

The second set of experiments used vertical and angled surfaces as well as ropes and poles [243, p. 81; 175, p. 263]. These experiments were considered as investigations on how to integrate an actual building context into the construction with the granular material [175, p. 263].

The third set of experiments investigated temporary constraining surfaces, which would be removed after pouring [182, p. 236; 178, p. 86; 175, p. 263]. A pneumatic formwork proved to be most promising: an inflatable was placed between permanent constraining surfaces, the granular material was poured over the inflated pneumatic formwork; when

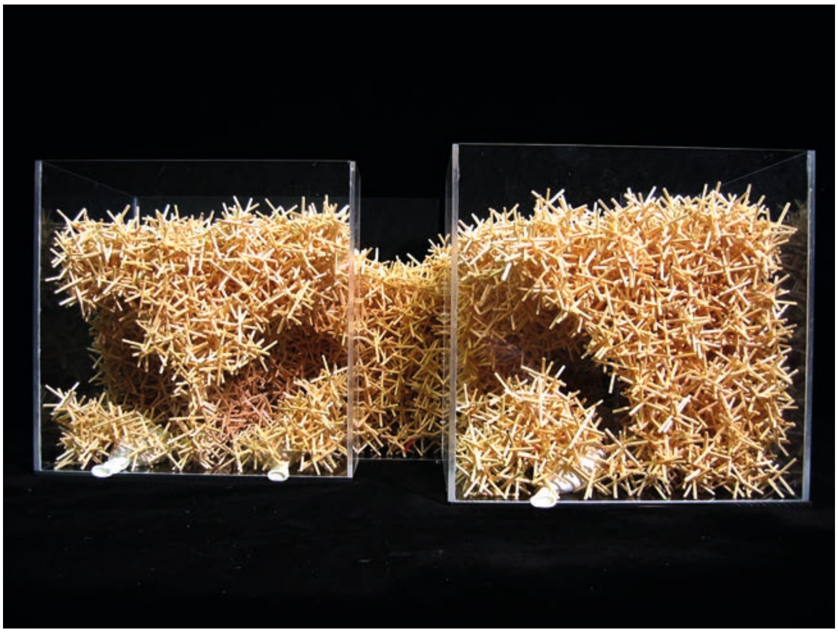

Figure 5.3: Architecture – Project 2. Eiichi Matsuda | Diploma Unit 4, Architectural Association School of Architecture (AA) | 2003–04 [175]

the granular material had subsided the inflatable was deflated, after which a few particles fell out and the granular material subsided again [182, p. 236; 243, p. 81; 175, p. 263]. The resulting structures had a dome-like spatial geometry, which on a micro level is based on a high number of particle contacts and consequently of load-paths; thus the decisive parameters on the particle level are the geometry, mass and roughness of each particle [182, p. 236; 243, p. 81; 175, p. 263].

Parallel tests were conducted on the water run-off in the granular material; these experiments suggested that depending on the density of the granular material water can flow off from particle to particle instead of penetrating vertically to the ground [243, p. 81; 175, p. 263]. The particle geometry and particle sizes as well as the sequence of pouring were calibrated so as to improve the stability; the dome-like spaces consequently had different degrees of density, allowing for the modification of airflow, light and heat [182, p. 236; 243, p. 81; 175, p. 263]. Altogether five particle groups were developed, with which the initial pneumatic experiments were repeated [243, p. 81; 177, p. 24].

The project by Eiichi Matsuda focused mainly on the basic methodology and the identification of crucial parameters for the instrumentation of designed granular materials and their construction processes; questions of scale for architectural purposes were left open [243, p. 81].

5.1.2.3 Architecture – Project 3

Project credits — *Authors:* Anne Hawkins, Catie Newell | *Supervisors:* Michael Hensel, Achim Menges | *Project type:* Studio project | *Institution:* GPA Studio, Rice University, Houston, Texas | *Year:* 2004

Project description: Anne Hawkins and Catie Newell conducted research into designed granular materials in the GPA Studio at Rice University [182; 170; 178; 174] (see figure 5.4). Like Eiichi Matsuda's project it is also based on a highly non-convex particle design, in this case made from a wood sheet material [174, p. 274].

The geometry of the custom-made particles was developed using industrially prefabricated elements which were used to test the granular material's behaviour under gravity, especially the interlocking between particles, depending on different geometries [170, p. 83; 174, p. 274]. Further parameters that influenced the final particle design included in particular the weight for ease of handling, but also the price and speed of fabrication [170, p. 83; 178, p. 87; 174, p. 274]. Several fabrication processes for

Figure 5.4: Architecture – Project 3. Anne Hawkins, Catie Newell | GPA Studio, Rice University | 2004 [174]

the particles were tested, eventually arriving at a nested cut-pattern that allowed five plates at once to be processed on a mitre saw [170, p. 83; 174, p. 274]. Geometrically the produced parts could be assembled from two pieces each in two configurations: an "X" with a height of 350 millimetres and an "A" type with a height of 200 millimetres [170, p. 83; 178, p. 87; 174, p. 274]. Three thousand particles of each of the two types were fabricated [170, p. 83].

The granular material was investigated in test series with large numbers of statistical repetitions, which explored its angle of repose and material density [178, p. 87; 174, pp. 274–275]. The tests also included different formworks, such as the same pneumatic formwork that was used in Eiichi Matsuda's project for the formation of dome-like structures, but also flat containers for the formation of screens [170, p. 83]. Three ways of affecting the granular material were identified: the geometry of the particle; the process of aggregation; and the edge conditions of the granular material during and after processing [178, p. 87; 174, p. 275].

The results of the initial experiment series were tested at a larger scale, focussing on the ability to control the process of aggregation and consequently the performance of the structures [174, p. 275].

One prototype based on the earlier flat-screen experiments, which had been poured in front of a window, explored the transmission of light through the granular material; the test integrated the previous results and used pouring processes and sequences to allow for both structural stability and a modification of the light transmission [170, p. 83; 178, p. 87; 174, p. 275].

Several structural types, such as wall, arch, half-dome and dome were tested both under self-weight and point loads [178, p. 87; 174, p. 275].

Another series investigated the effect of removing particles from a granular structure [178, p. 87; 174, p. 275]. The experiments were all conducted manually pertaining to the idea of human-scale configuration and reconfiguration, each needing no more than thirty minutes to complete [170, p. 83; 178, p. 87].

Based on the mapping of the desired structural, spatial and luminous effects, the granular density and the pouring process can be defined in a subsequent development phase [170, p. 83].

One key aspect of the project was the involvement of spectators in it: first, by directly addressing them; then, by leaving particles unattended in the exhibition areas, which led to the spontaneous formation of granular structures throughout the building [174, p. 275].

Figure 5.5: Architecture – Project 4. Selim Bayer, Kyle Schertzing | EmTech, Architectural Association School of Architecture (AA) | 2009 [182]

5.1.2.4 Architecture – Project 4

***Project credits* —** *Authors:* Selim Bayer, Kyle Schertzing | *Supervisors:* Michael Hensel, Achim Menges, Michael Weinstock | *Project type:* Phase 1 studio work | *Institution:* Emergent Technologies and Design (EmTech), Architectural Association School of Architecture (AA), London | *Year:* 2009

Project description: The project by Selim Bayer and Kyle Schertzing was conducted as a studio project within the Emergent Technologies and Design (EmTech) programme at the Architectural Association School of Architecture (AA) in continuation of the research conducted by Eiichi Matsuda [182, pp. 236–241] (see section 5.1.2.2; see figure 5.5). Particles measuring 900 by 900 by 900 millimetres, 600 by 600 by 600 millimetres and

Figure 5.6: Architecture – Project 5. Luka Piškorec, Sebastian Ernst, Kathrin Dörfler, Fabio Gramazio, Matthias Kohler | Gramazio Kohler Research, Swiss Federal Institute of Technology (ETH) Zurich | 2014 [156]

300 by 300 by 300 millimetres were produced and cast over pneumatic formwork, for example to construct an arch that could support live load [182, pp. 236, 240].

The system was further developed as a canopy proposal, which has not been implemented; the plan was to compact the granular material before releasing the formwork and subsequently to support crucial zones of the structure with ropes [182, p. 240].

5.1.2.5 Architecture – Project 5

Project credits — *Authors:* Luka Piškorec, Sebastian Ernst, Kathrin Dörfler, Fabio Gramazio, Matthias Kohler | *Project type:* Research project | *Institution:* Gramazio Kohler Research, Chair of Architecture and Digital Fabrication, Department of Architecture, Swiss Federal Institute of Technology (ETH) Zurich, Zurich | *Year:* 2014

Project description: At the Swiss Federal Institute of Technology (ETH) Zurich, Gramazio Kohler Research conducted the project "Remote Material Deposition" in 2014 [111; 112; 285; 157; 156]. The first stage of the project, which also includes research on designed granular materials, was conducted by Luka Piškorec, Sebastian Ernst, Kathrin Dörfler, Fabio Gramazio and Matthias Kohler [156].

The main goal of the project was the interactive "sensory controlled" robotic throwing of loam cylinders [111; 112; 285; 157]. However, designed particles were used in the early stages of project development; these particles were made from wood dowels that were each wrapped in male and female parts of Velcro so as to allow for adhesion between them [156] (see figure 5.6).

5.1.2.6 Architecture – Project 6

Project credits* — *Authors: Petrus Aejmelaeus-Lindström, Jan Willmann, Skylar Tibbits, Fabio Gramazio, Matthias Kohler | *Project type:* Research project | *Institutions:* Gramazio Kohler Research, Chair of Architecture and Digital Fabrication, Department of Architecture, Swiss Federal Institute of Technology (ETH) Zurich, Zurich; Self-Assembly Lab, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts | *Year:* 2016

Project description: The project "Rock Print" was conducted as a collaboration between Gramazio Kohler Research at the Swiss Federal Institute of Technology (ETH) Zurich and the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT) [4; 3; 2]. The first publication of the project, which also shows research on potentially designed granular materials, was authored by Petrus Aejmelaeus-Lindström, Jan Willmann, Skylar Tibbits, Fabio Gramazio and Matthias Kohler [2].

The project makes use of industrial bulk material, namely rocks, and string, and explores the "reinforcement" of convex or slightly non-convex particles with "continuous wires" [3; 2; 119].

Figure 5.7: Architecture – Project 6. Petrus Aejmelaeus-Lindström, Jan Willmann, Skylar Tibbits, Fabio Gramazio, Matthias Kohler | Gramazio Kohler Research, Swiss Federal Institute of Technology (ETH) Zurich; Self-Assembly Lab, Massachusetts Institute of Technology (MIT) | 2016 [2]

The deliberate focus was on industrially available bulk materials which are not custom designed [3; 2]. Yet, in the early stages of the project a wider selection of such materials was explored, also including artificially made bulk materials [2, pp. 28.4–28.5] (see figure 5.7). Since these artificially made materials could eventually be controlled with respect to their geometry and material make-up, these early studies are pertinent in the context of this thesis.

Compression tests were conducted on an apparatus which allows a maximum of 100 kilograms and has dimensions of 150 millimetres diameter and 1000 millimetres maximum height [2, p. 28.4]. A cylindrical container was filled with the probe material; the probe was then loaded and the container removed [2, p. 28.4]. The evaluation parameters for these tests were: "buckling length" of the column; "load capacity"; "stiffness"; "congruent behaviour"; and capacity for full-scale architectural applications [2, p. 28.4]. The test series explored four generic geometric groups of particles or construction [2, pp. 28.4–28.5]. The first group of particle geometries chosen consisted of convex particles with a high aspect ratio, such as screws [2, pp. 28.4–28.5]. The second group of particle geometries was composed of chains and strings [2, pp. 28.4–28.5]. The third group collected convex or slightly non-convex particles, such as rock or foam [2, pp. 28.4–28.5]. Lastly, a fourth type of construction element were two-dimensional flat sheets, which were used for layering [2, pp. 28.4–28.5]. These elements were combined with a set of construction techniques, such as layering, mixing and wrapping [2, pp. 28.4–28.5].

The experiment series resulted in two main observations, which were then further developed. First, if the edge condition was confined through a tension element, for example through string, the structures were "most suitable", which very likely means satisfying the previously defined evaluation criteria [2, p. 28.5]. Second, if the particles were "hard" and "form-stable", the overall granular material was again "most suitable" to the established criteria for evaluation [2, p. 28.5].

5.1.2.7 Summary and evaluation of the projects

Altogether six projects have been introduced, specifically analysing which particle geometries and particle materials have been used and how the resulting granular materials were investigated regarding their architectural performance.

In the category of particle geometries, projects 1 to 4 work with highly non-convex shapes (see sections 5.1.2.1 to 5.1.2.4). Only projects 5 and 6 investigate convex particles both with a low and a high aspect ratio, slightly non-convex particles as well as chains and strings (see sections 5.1.2.5 and 5.1.2.6). As a material for manufacturing the particles, mainly wood was deployed, which in one case was covered with the additional material Velcro (see sections 5.1.2.2 to 5.1.2.5). Only project 1 and project 6 use other materials than wood, namely ceramics or foam, metal, string and rock respectively (see sections 5.1.2.1 and 5.1.2.6).

The resulting designed granular materials were mainly investigated with respect to forming spatial elements, namely walls or screens, domes, half-domes and arches (see sections 5.1.2.1 and 5.1.2.4). These were observed under self-weight and loads as well as investigated for their ability to filter environmental influences such as light or water (see sections 5.1.2.2 and 5.1.2.4). Project 5 is focused mainly on developing a "sensory controlled" robotic construction system (see section 5.1.2.5). Project 6 investigates cylindrical probes in compression according to a pre-defined set of evaluation criteria (see section 5.1.2.6).

5.2 Designed granular materials in physics

The current state of designed granular materials in physics is presented in the following sections. On the level of conceptual frameworks, three concepts relating to designed granular materials are introduced. On the level of specific research, the results of two generic approaches are summarized: on the one hand those research approaches that start from the design of the particle geometry, and on the other those that start from the overall performance of the granular material. Consequently, eleven relevant projects are filtered out and evaluated especially with respect to the design of the particles and the actual investigations carried out with them.

5.2.1 Conceptual frameworks

The fact that particle geometry has an effect on the microstructure and consequently the behaviour of granular materials has long been established in granular physics [250, pp. 2, 87; 252, p. 1; 16, p. 48]. Three overarching concepts have been identified which aim to describe and conceptualize the branch of granular physics that deals with the design of particles. They are introduced in the following sections followed by a summarizing evaluation and a positioning of the thesis in the wider field of granular physics.

5.2.1.1 "Granular matter by design"

Heinrich M. Jaeger and his collaborators use the term "granular matter by design" for their research conducted at the University of Chicago [194; 198]. In an overview article aimed at investigating so-called "jammed" states in "granular matter by design", Jaeger also outlines the more generic concepts of "granular matter by design" [194, p. 13]. The basic idea is the calibration of the macro-level properties of a granular material through defining the individual particle geometry and consequently its micro-level structural characteristics [194, p. 18; 198]. The applications that Jaeger considers span from soft robotics to architecture [194, pp. 15–18; 198].

One key aspect which according to Jaeger makes "granular matter by design" a highly relevant strand of research is the fact that the granular material itself can be optimized for novel and specific applications [194, p. 22].

The approaches taken towards the development of "granular matter by design" either start from defining a particle geometry or vice versa from defining the overall performance of the granular material [194, p. 14; 198]. Jaeger emphasizes that the latter approach especially is what can be understood as design, since in his view design involves starting from a desired end result and then in a "top-down" process working towards the system ingredients, namely the geometry of the individual particle [194, pp. 14, 19]. He terms this approach "inverse", referring to related developments in the wider field of materials sciences and engineering [194, pp. 14, 19–21]. A detailed discussion of "inverse" versus "forward" design methods is given in section 7.1.1. Previous research has started either from a given particle shape or by "trial and error" exploration of a set of particle geometries in a bottom-up process; the "inverse" approach in designing granular materials is consequently relatively novel [194, pp. 14, 20].

Jaeger states that technologically the development of "granular matter by design" is supported by the availability of new manufacturing processes, such as 3D printing, by image processing techniques and by the fact that simulating non-spherical particles has become integrated into computational models [194, pp. 18–19, 22]. With respect to a bottom-up – that is, "forward" approach – to designing granular materials, Jaeger outlines a few basic design paradigms: on a basic level the structural characteristics and the mechanical behaviour need to be tuned; geometries can be developed that incorporate more than just one desired material characteristic; however, one particle geometry is unlikely to cover all desired properties; and lastly one might consider that particle groups with entirely novel characteristics can be found [194, p. 19]. However, general guidelines for design or "design rules" do not exist [194, p. 19; 198].

The "inverse" approach according to Jaeger is one first step towards establishing a rule-based system for particle design [194, p. 19]. The challenges which the "inverse" approach aims to tackle are: the multiple control variables for design; the boundary conditions; the matching of an overall granular behaviour to a range of particle geometries; and the introduction of generic "design rules" [194, pp. 19–20]. Computational methods using automated procedures are especially suited for these types of problems [194, p. 20]. In particular, Jaeger refers to evolutionary algorithms as a class of automated methods which are appropriate for the optimization processes that designed granular materials require [194, p. 20]. One crucial aspect of these methods is that the targeted design goals can go beyond currently known behaviours, which means that they can also be used to discover particle geometries that produce novel characteristics in the overall granular material [194, pp. 14, 21, 22]. Another aspect is the fact that in finding an optimized solution the evolutionary method produces many other solutions to similar questions, which might be referred to for another set of design issues [194, p. 21]. However, Jaeger points out that the eventual goal is to find general "design rules" that allow for a smoother calibration of particle geometries in the search space, for example by optimizing two extremes and then interpolating in geometry between them [194, p. 21]. "Inverse" approaches do not need to be applied for particle geometry only but can also be used for the optimization of the processing of a granular material [194, p. 22]. A possible challenge in using evolutionary algorithms according to Jaeger is the fact that an optimized solution can be found, but that the reason for that solution is not known [194, p. 21]. One long-term goal is the optimization of processing methods and boundary conditions as well as the integration of multiple parameters into the particle design for granular materials [194, p. 22].

In conclusion, "granular matter by design", as established by Heinrich M. Jaeger and his collaborators, is an encompassing conceptual framework for the interrelation of particle shape and granular behaviour. One of its key aspects is the introduction of "forward" and "inverse" processes.

5.2.1.2 "Geometric cohesion"

Scott V. Franklin of the Rochester Institute of Technology uses the term "geometric cohesion" to refer to the properties of particle shapes which are extremely aspherical [129; 127; 125, p. 70; 126]. He states that granular materials in most cases need a binding medium in order to stick together; industrial processing of granular materials is based on the very fact that these consist of spherical and thus non-cohesive particles [125, p. 70].

"Geometric cohesion" allows for a granular material to behave more like a solid than like a liquid, for example it can maintain its form [125, p. 70; 126]. According to Franklin, Albert P. Philipse conducted the earliest studies on "geometrically cohesive" granular materials [125, p. 70; 282]. As case studies, Franklin introduces three investigations on rods and "u-shaped" particles [125, pp. 70–71; 158; 351; 88]. Franklin emphasizes that the field is only at the beginning and that both experiments and simulations, specifically molecular dynamics (MD), are needed and indispensable to the analysis of cohesive granular materials [125, p. 71]. Looking ahead Franklin points out that on the physics side a wider range of geometries with cohesive effects is being investigated [125, p. 71]. He also indicates applications for these systems, which could potentially lead to permeable, light and stable structures; however, he does not suggest a specific field for this [125, p. 71].

The concept of "geometric cohesion" as introduced by Scott V. Franklin and his co-workers clearly instrumentalizes particle geometry as the determining factor in the behaviour of a granular material. It is confined to achieving a cohesive granular material and does not encompass a wider approach into a range of possibly operative granular behaviours.

5.2.1.3 "Aleatory architectures" for physicists

As outlined in section 5.1.1.4 Sean Keller and Heinrich M. Jaeger propose the concept of "aleatory architectures" [209]. The concept of "aleatory architectures" is directly related to the notion of "granular matter by design" as outlined in section 5.2.1.1. It aims explicitly at the integration of the disciplines of physics as well as architecture and engineering [209, pp. 29.2–29.3]. The concept in general and its implications for architecture, as the authors outline it, has been introduced in section 5.1.1.4.

In this section the objectives for granular physics and engineering which Keller and Jaeger identify in pursuing "aleatory architectures" are summarized.

One of the core challenges in granular physics has been the reliable forecasting of macro-level behaviour of a granular material based on its composition on a micro level [209, p. 29.4].

This however, according to the authors, is increasingly becoming possible due to advanced computational and manufacturing technologies, thus enabling the investigation of particle shape in relation to its effects on the overall granular material [209, p. 29.4]. Keller and Jaeger point out that one might question whether such statistical systems are suitable for architectural construction with its current building regulations at all [209, p. 29.4]. However their stance is to perceive of "aleatory architectures" as a novel branch which will find its own area in the building sector and therefore entail adjusted regulations [209, p. 29.4].

A key argument of Keller and Jaeger is the use of so-called "inverse" design processes in the development of "aleatory architectures": in their view design procedures need to be able to start from the overall properties of a system and from there develop the composing units on the level below [209, p. 29.4]. This concept has already been introduced in the context of "granular matter by design" in section 5.2.1.1. With respect to the "inverse" design of a granular material the two main aspects to consider are the fact that they are statistical entities and that the definition of the perimeter as well as the handling of the system play a crucial role [209, p. 29.4]. Whereas these "inverse problems" have frequently been addressed with empirical studies in granular physics, digital simulation methods now make it possible to tackle them from a different perspective and are especially suitable for the exploration of the uncharted territory of "aleatory architectures" [209, p. 29.4]. These advancements in digital simulations are further supported by manufacturing processes which allow for the production of a wide range of possible particle geometries [209, p. 29.4].

Another key aspect is the fact, that in constructions made from granular materials the particles can be considered to "autonomously" define their locations in relation to extrinsic load cases [209, p. 29.5]. Here Keller and Jaeger refer to the notion of "material computation" as introduced by Achim Menges [209, p. 29.5; 95]. Consequently the main question is how to develop suitable particle geometries in order to arrive at a stable overall configuration [209, p. 29.5].

"Aleatory architectures" as presented by Sean Keller and Heinrich M. Jaeger address not only designed granular materials, but a rather wide range of architectural research into the use of granular materials as construction systems (see section 5.1.1.4). The proposal is for architects to investigate the aesthetic implications. The fields of engineering and physics are mainly considered to explore the interrelation of macro- and micro-level characteristics of granular construction materials.

5.2.1.4 Summary and evaluation of conceptual frameworks in physics

Three overarching conceptual frameworks of designed granular materials in physics have been pointed out. Two of them, "granular matter by design" and "geometric cohesion", focus solely on designed granular materials for any type of application (see sections 5.2.1.1 and 5.2.1.2). The third concept, "aleatory architectures", additionally encompasses other types of granular materials with an application in architecture only (see section 5.2.1.3). All three approaches point to the relevance of developing novel behaviours in a granular material through the design of the individual particle. As outlined in section 5.1.1.4 "aleatory architectures" also underline the fact that granular materials are reconfigurable, recyclable and rapidly deployable as well as structurally redundant, which makes them a very pertinent field of architectural design research. In the field of physics it is generally accepted that simulations and experiments need to be combined; both methods can rely on advanced technologies in computation and fabrication respectively. Granular architectures, which is the conceptual framework presented in this thesis, relates to all of the three conceptual frameworks which have been identified in granular physics. Its contribution to the field of physics is the establishment of a design system for designed granular materials in architecture, which can serve as a starting point for collaborative research. While in the concept of "aleatory architectures" the contribution of architecture to the research field has been seen mainly in the realm of aesthetics, the approach in granular architectures is to view the architect as an integrator of relevant aspects of the overall research field.

5.2.2 Project overview and analysis

In granular physics the research into the interrelation between particle geometry and granular behaviour is very widely established. Even though not all authors refer to their work as designed granular materials, a lot of the results pertain to this very field. Essentially two approaches are taken: one starts from the particle geometry to explore the behaviour of the resulting granular material, the other starts from the overall behaviour to define a desired particle geometry [194, p. 14]. In materials science the first approach is also referred to as a "forward" approach, going from micro-level properties to macro-level characteristics [199, p. 2732]. Its counterpart is termed an "inverse" method for the design of materials, denoting that from a desired set of macro-level properties the micro-level structure of a material is found [199, p. 2732]. For a detailed discussion of the two terms (see section 7.1.1). The overview is in large parts based on literature reviews by Heinrich M. Jaeger and collaborators as well as related publications by Scott V. Franklin and collaborators and Robert P. Behringer and collaborators [209; 264; 381; 194; 16; 128; 158].

Section 5.2.2.1 will give an overview of research into design that starts with the particle geometry, which is the "forward" approach. Section 5.2.2.2 will review approaches into design that begin by defining the performance of a granular material, which is the "inverse" approach. Section 5.2.2.3 features a series of analyses of those of the research projects, that deal with particle geometries which are related to the ones investigated in this thesis and which analyse parameters that are relevant for architectural construction. In this sense only three-dimensional studies are considered. In section 5.2.2.4 the results of the project review of designed granular materials in physics will be summarized and evaluated with respect to the relevance for the thesis.

5.2.2.1 Overview: Design by particle geometry

The first selection of publications starts from a given particle geometry and explores its effects on the granular behaviour; this method of investigating is referred to as the "forward" approach. This approach is closely bound to available manufacturing techniques: whereas initially only simple and mass-produced particle geometries were viable, such as rods, present-day fabrication techniques such as 3D printing offer a new available spectrum of possible geometries [209, p. 29.4; 194, pp. 18–19]. The following sections introduce three main geometric types: convex, non-convex and double non-convex particles as well as particles with a variable geometry; these terms are defined in chapter 8.

5.2.2.1.1 Geometric type

5.2.2.1.1.1 Convex

In the group of convex particles, spheres and discs are excluded, as they have mainly been used to abstract naturally found granular materials. Thus on the one hand they are not strictly speaking designed particles, and on the other the available relevant literature would be beyond the scope of this thesis. Quite a large range of research projects have investigated ellipsoids [262; 263; 312; 313; 118; 42; 311; 56; 191; 318; 238; 379; 69; 108; 116; 241; 232; 110; 109; 70; 303; 50]. A second focus in the physics community has been on rods and elongated particles [262; 226; 161; 42; 44; 43; 162; 27; 48; 26; 351; 184; 183; 372; 295; 267; 40; 88; 236; 116; 293; 235; 339; 357; 282]. Another large number of contributions has investigated polyhedra or polygons [262; 263; 270; 359; 16; 28; 269; 272; 321; 80; 350; 203; 218; 85; 31; 200; 349; 324; 201; 165; 308; 348; 124; 373; 107; 244]. A smaller fraction of research has gone into frustums [262; 263; 48; 380], glued spheres [35; 283; 214; 292] or superballs [202].

5.2.2.1.1.2 Non-convex

Non-convex particle geometries are comparatively less explored than convex ones. A number of investigations explore many-armed particle shapes [262; 263; 225; 264; 16; 84; 254; 48; 131; 240; 163; 51]. Another geometric approach for creating non-convex particles is the bonding of spheres [35; 29; 233; 247; 283; 166; 307; 214; 213; 220; 291]. Superballs can also form non-convex geometries [202].

5.2.2.1.1.3 Double non-convex

Double non-convex particles form the smallest geometric group of designed particles. One of the sub-groups in this section are hooks or hook-like particles [264; 242; 128; 158].

5.2.2.1.2 Geometric variability

The other group are flexible chains, which due to their flexibility can assume variable geometries [114; 294; 299; 47; 256; 229; 207; 273; 383].

5.2.2.2 Overview: Design by granular material performance

"Inverse" methods of design have also been applied to designed granular materials, mainly using evolutionary algorithms [195; 265; 209; 304; 250; 194; 251; 253; 252; 378; 325; 41]. As outlined in section 3.1.2, "inverse" methods are not considered in the context of this thesis; however, the combination of a "forward" design approach with an "inverse" one is discussed in section 11.1.2.

5.2.2.3 Projects

The following sections will present in greater detail those projects from granular physics, which have a direct relevance for the work presented in this thesis. Particles with aspect ratios below 30 are excluded, as structures made from these particles typically do not become stable. Particles in suspensions as well as regular packings are not analysed. Studies investigating disturbance by an intruder or breakage of particles are also excluded in the project review.

5.2.2.3.1 Granular physics – Project 1

***Project credits* —** *Author:* Albert P. Philipse | *Institution:* Van't Hoff Laboratory for Physical and Colloid Chemistry, Utrecht University, Utrecht | *Year:* 1996

Project description: Albert P. Philipse of the Van't Hoff Laboratory for Physical and Colloid Chemistry at Utrecht University conducted research into the amount of contacts in granular materials with particles of high aspect ratio, which means rods, in 1996 [282]. Comparing rod systems with spheres, Philipse states that in rod systems, contacts are as he calls it "uncorrelated", the granular material consisting of isolated pairs of particles, which is not true for spheres [282, p. 1127]. Philipse's aim is to introduce the "random contact model" and its implications for the packing densities of rods [282, p. 1127]. He applies the theory to "colloidal rods", "fiber composites" and "percolating structures or gels" [282, pp. 1127–1128].

His results show that the contact number is about 5.4 and is not connected to the particle shape within the shape range used for the experiments presented [282, pp. 1132–1133].

This explains why packing density decreases when the aspect ratio increases [282, pp. 1128, 1130, 1132–1133]. Rods with an aspect ratio below 30 have a fluid-like behaviour, but if their aspect ratio moves above 30 they behave more and more like a solid [282, p. 1128]. This change from fluid to solid is only due to the aspect ratio, according to Philipse [282, p. 1129].

5.2.2.3.2 Granular physics – Project 2

***Project credits* —** *Authors:* Joshua Blouwolff, Seth Fraden | *Institution:* Complex Fluids Group, Martin Fisher School of Physics, Brandeis University, Waltham, Massachusetts | *Year:* 2006

Project description: The research presented by Joshua Blouwolff and Seth Fraden from the Complex Fluids Group at Brandeis University investigates the coordination number of granular cylinders [40] (see figure 5.8). The coordination number in a granular material is the number of adjacent particles touching a single particle, and it is an important parameter in assessing the stability of a granular material [40, p. 1095]. Measurements were taken for piles of cylinders [40, p. 1101].

Their results show that the coordination number increases with increasing aspect ratio of the cylinders and ranges between six for aspect ratios around one and ten for aspect ratios equal to or larger than 30; these results are true to theoretical models, although the theoretical minimum would be a coordination number of four rather than six [40, p. 1101].

In the studies conducted, the coordination number did not change with friction, which was unexpected [40, p. 1101]. Blouwolff and Fraden observed so-called "plugs" in granular materials made from rods with an aspect ratio of 50, which are solid enough to be picked up on one end; this corresponds to results by Albert P. Philipse [40, pp. 1100–1101; 282].

According to the authors the "plug" formation does not seem to depend on coordination number alone, but they name friction and flexibility as possible other parameters influencing this phenomenon [40, pp. 1100–1101].

5.2.2.3.3 Granular physics – Project 3

Project credits **—** *Authors:* Sergio A. Galindo-Torres, Fernando A. Alonso-Marroquín, Yucang Wang, Dorival Pedroso, José D. Muñoz Castaño | *Institutions:* MoSCoS School of Mathematics and Physics, University of Queensland, Queensland; CSIRO Exploration and Mining, Technology Court, Pullenvale, Queensland; Golder Geomechanics Center, University of Queensland, Queensland; Grupo de Simulación de Sistemas Físicos, Universidad Nacional de Colombia, Bogotá | *Year:* 2009

Project description: The research was conducted in a collaboration of the MoSCoS School of Mathematics and Physics at the University of Queensland, the CSIRO Exploration and Mining, the Golder Geomechanics Center at the University of Queensland and the Grupo de Simulación de Sistemas Físicos at the Universidad Nacional de Colombia [131]. It is presented in an article which is authored by Sergio A. Galindo-Torres, Fernando A. Alonso-Marroquín, Yucang Wang, Dorival Pedroso and José D. Muñoz Castaño [131].

The aim of the research is to develop a molecular dynamics (MD) simulation for non-convex particles which in turn can be used to characterize these materials [131]. The authors use

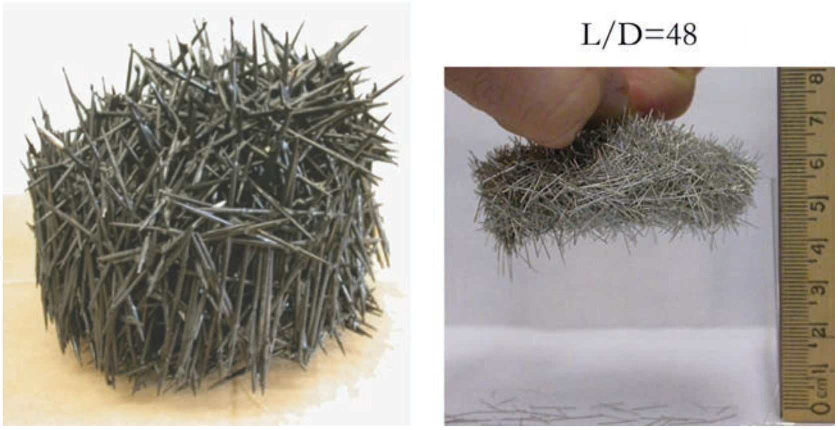

Figure 5.8: Granular physics – Project 2. Joshua Blouwolff, Seth Fraden | Complex Fluids Group, Brandeis University | 2006 [40]

so-named "spheropolytopes" to model the particles, which are polytopes along whose edges a sphere is swept [131, p. 060301.1]. They establish three cases to demonstrate their model: a hopper flow, a triaxial test and sliding along a rough surface [131, p. 060301.1]. The first two case studies are especially relevant within the context of granular architecture. In the first case study hexapods of varying arm length are simulated in a hopper flow [131, p. 060301.3]. The closer the particles are to a sphere, the more they flow [131, pp. 060301.2–060301.3]. At an aspect ratio of 0.25 a critical state is reached below which the particles will always jam; above an aspect ratio of 0.27 the particles will always flow [131, pp. 060301.2–060301.3]. The second case study uses three-axial compression testing [131, p. 060301.3]. The simulations render results on failure stresses, friction angle and dilatancy angle [131, pp. 060301.3–060301.4]. A sample has a failure value after which it enters a so-called critical state [131, p. 060301.3]. The friction angle decreases with decreasing aspect ratio [131, p. 060301.4]. The dilatancy measurements show that granular materials consisting of more spherical particles do not alter their volume as easily as those consisting of more non-convex ones [131, p. 060301.3].

5.2.2.3.4 Granular physics – Project 4

Project credits — *Authors:* Iryna Malinouskaya, Valeri V. Mourzenko, Jean-François Thovert, Pierre M. Adler | *Institutions:* LCD, SP2MI, Futuroscope Cedex; UPMC Sisyphe, Paris Cedex | *Year:* 2009

Project description: The research was conducted in a collaboration of LCD, SP2MI and UPMC Sisyphe and is presented in an article which is authored by Iryna Malinouskaya, Valeri V. Mourzenko, Jean-François Thovert and Pierre M. Adler [240].

The groups investigate the transport characteristics, such as permeability, of packings consisting of "spiky" particles [240]. A relationship between the parameters of a single particle and the properties of the granular material is established [240, p. 011304.15]. The study uses numerical models in which initially packings of the particles are computed and then both the geometric and the transport characteristics are determined; both discretization and anisotropy were included in the model [240, p. 011304.15]. The particle geometry is defined by a sphere or ellipsoid to which other ellipsoids are added to form extensions [240, pp. 011304.2, 011304.15]. The author's results show that the geometrical property of porosity is dependent on the particle parameter of "sphericity" [240, p. 011304.15]. In the presented results particle geometry, especially the "sphericity" of the particle, has also been related to transport properties of the overall granular material at two scales [240, p. 011304.15].

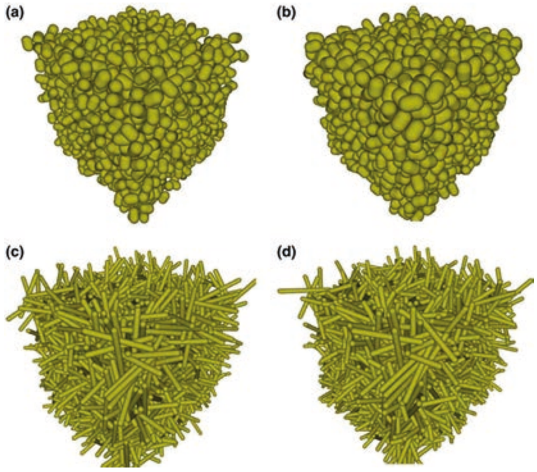

Figure 5.9: Granular physics – Project 5. Alan Wouterse, Stefan Luding, Albert P. Philipse | Van't Hoff Laboratory for Physical and Colloid Chemistry, Utrecht University; Multi Scale Mechanics, Universiteit Twente | 2009 [372]

5.2.2.3.5 Granular physics – Project 5

***Project credits* —** *Authors:* Alan Wouterse, Stefan Luding, Albert P. Philipse | *Institutions:* Van't Hoff Laboratory for Physical and Colloid Chemistry, Utrecht University, Utrecht; Multi Scale Mechanics, Universiteit Twente, Enschede | *Year:* 2009

Project description: The research was conducted by Alan Wouterse, Stefan Luding and Albert P. Philipse at the Van't Hoff Laboratory for Physical and Colloid Chemistry at Utrecht University and at Multi Scale Mechanics at the Universiteit Twente [372]. It investigates "random packings" of "non-spherical granular particles" or in other words rods [372] (see figure 5.9). The aim of the project is to establish a theoretical model for simulation, to find an interrelation between the "particle volume fraction" and the "average contact number (C)" and to evaluate the amount of contacts per particle with respect to the "mathematical caging problem", which is the smallest amount of non-related contacts required to lock a particle [372, pp. 169–170]. The investigation is carried out using simulations only. The authors combine event-driven molecular dynamics (MD) and the mechanical contraction method (MCM) [372, p. 170]. Rods with infinite aspect ratio are simulated [372, p. 175]. The authors mainly aim at establishing a theoretical method, which allows experimental results to be reproduced [372, pp. 170–171, 176].

Based on that established method, the authors present several relevant results [372, pp. 171–177]. One key observation is the fact that the "average contact number (C)" increases up to a count ranging between nine and ten at the "jamming point" [372, p. 176]. The "caging number" has a count of 9 at this stage [372, p. 176]. At even higher aspect ratios the "average contact number (C)" becomes again smaller, which the authors assume is due to the granular material not being entirely "jammed" [372, p. 176]. At constant aspect ratio, the order of the granular material does not increase if the "particle volume fraction" increases [372, p. 176]. The "caging number" approximates 9 at high aspect ratios [372, p. 176].

5.2.2.3.6 Granular physics – Project 6

Project credits — *Authors:* Melissa Trepanier, Scott V. Franklin | *Institution:* Department of Physics, Rochester Institute of Technology, Rochester, New York | *Year:* 2010

Project description: Melissa Trepanier and Scott V. Franklin from the Department of Physics at the Rochester Institute of Technology investigate the collapse of columns made from granular rods [351]. The parameters, which are varied, are both pile heights before collapse and rod lengths [351, pp. 011308.2–011308.3].

A wide range of rod aspect ratios between 2.6 and 47.5 have been tested [351, p. 011308.2].

For rods below an aspect ratio of 24 a pile height is identified above which the cylinder collapses into a cone; below this height there is a transition zone, where either the cylinder remains stable or collapses into a cone; the lower limit height is the value at which the cylinder always remains stable [351, pp. 011308.3–011308.4]. For rod aspect ratios above 24 the piles are in principle always solid [351, pp. 011308.3–011308.4]. Another effect which has been measured is the so-called "runoff distance", which is the spread of the material that flows off a cylinder when it settles into a cone [351, pp. 011308.2–011308.3, 011308.4].

5.2.2.3.7 Granular physics – Project 7

Project credits* — *Authors: Nick Gravish, Scott V. Franklin, David L. Hu, Daniel I. Goldman | *Institutions:* School of Physics, Georgia Institute of Technology, Atlanta, Georgia; Department of Physics, Rochester Institute of Technology, Rochester, New York; School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia | *Year:* 2012

Project description: The research was conducted in a collaboration of the School of Physics and the School of Mechanical Engineering at Georgia Institute of Technology and the Department of Physics at Rochester Institute of Technology [158]. It is presented in an article which is authored by Nick Gravish, Scott V. Franklin, David L. Hu and Daniel I. Goldman [158]. The project explores the characteristics of double non-convex "u-shaped" particles [158] (see figure 5.10). These particle geometries show a behaviour which the authors refer to as "entanglement" or "geometric cohesion" [158]. The concept of "geometric cohesion" is outlined in section 5.2.1.2.

The authors investigated the formation and the collapse of columns and established both simulation and theoretical models to verify their results [158].

Their results show that columns are rigid due to particle rotations and translations being geometrically constricted by the arms perpendicular to the backbone [158, p. 208001.4]. When the arms get longer, an increment in geometric entanglement is countered by a decrement in the density of packing [158, p. 208001.4]. These two characteristics result in the fact that entanglement is densest for particles with a length-to-width ratio of about 0.5 [158, p. 208001.4]. Columns made from these particles are consequently hardest to disentangle [158, p. 208001.4].

Figure 5.10: Granular physics – Project 7. Nick Gravish, Scott V. Franklin, David L. Hu, Daniel I. Goldman | School of Physics, Georgia Institute of Technology; Department of Physics, Rochester Institute of Technology; School of Mechanical Engineering, Georgia Institute of Technology | 2012 [158]

5.2.2.3.8 Granular physics – Project 8

***Project credits* —** *Authors:* Athanasios G. Athanassiadis, Marc Z. Miskin, Paul Kaplan, Nicholas Rodenberg, Seung Hwan Lee, Jason Merritt, Eric Brown, John R. Amend, Hod Lipson, Heinrich M. Jaeger | *Institutions:* Jager Lab, James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois; Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York | *Year:* 2014

Project description: The project was conducted in a collaboration of the Jaeger Lab at the University of Chicago and the Sibley School of Mechanical and Aerospace Engineering at Cornell University [16]. The research is published in an article which is authored by Athanasios G. Athanassiadis, Marc Z. Miskin, Paul Kaplan, Nicholas Rodenberg, Seung Hwan Lee, Jason Merritt, Eric Brown, John R. Amend, Hod Lipson and Heinrich M. Jaeger [16].

The project investigates the interrelation of particle shape and the behaviour of the respective granular material under stress with a specific focus on confining pressure [16] (see figure 5.11). The authors' aim was to establish a set of generic insights that are valid for packed frictional particles with varying geometries [16, pp. 49, 57].

A wide range of particle shapes with both convex and non-convex geometries was tested [16, p. 57]. The main measurements taken were the packing density, the Young's modulus and the yield stress, which have been graphed in a comprehensive analysis [16, pp. 49, 51–55]. The yield stress as well as the Young's modulus get higher with increasing confining pressure [16, p. 57]. Stiffness and strength are dependent on each other for all tested particle geometries [16, p. 57]. If the confining pressure

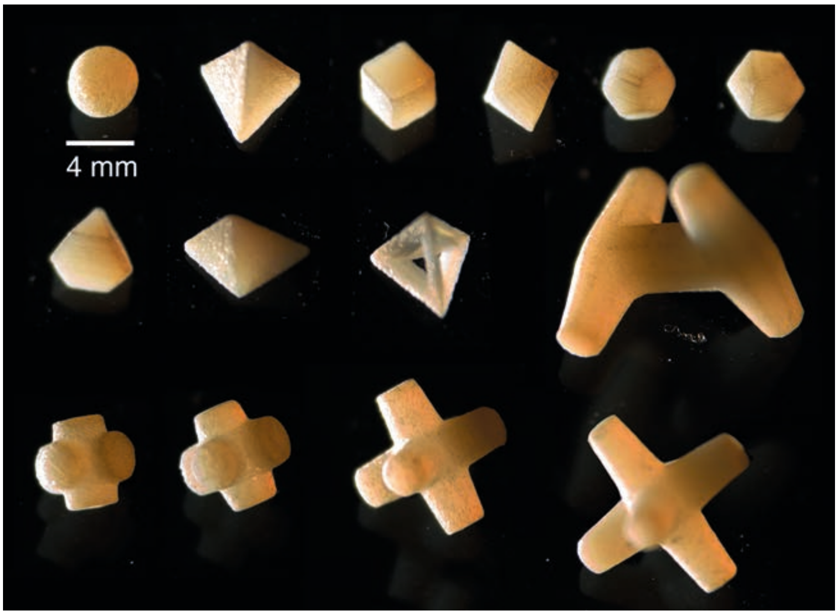

Figure 5.11: Granular physics – Project 8. Athanasios G. Athanassiadis, Marc Z. Miskin, Paul Kaplan, Nicholas Rodenberg, Seung Hwan Lee, Jason Merritt, Eric Brown, John R. Amend, Hod Lipson, Heinrich M. Jaeger | Jaeger Lab, University of Chicago; Sibley School of Mechanical and Aerospace Engineering, Cornell University | 2014 [16]

is constant, the yield stress and the Young's modulus can be calibrated by particle shape; however, a higher confining pressure reduces the effect of particle shape on the Young's modulus [16, pp. 55–57].

With respect to the interrelation of stiffness, confining pressure and particle shape, two strands of particle geometries can be distinguished as a function of their "sphericity" [16, p. 57]. The first group are polyhedral particles which have a range of contact possibilities, especially large face-to-face contacts if subjected to compression [16, p. 57]. The second group are particles with arm extensions, such as hexapods, which can exclusively form point contacts [16, p. 57]. Several of these particle geometries have been further characterized for their "granular plasticity" [262; 263]. The authors position their results within the field of soft robotics based on jamming, highlighting the unique capacity of a granular material to move from a soft to a rigid state [16, p. 57]. Specifically for these applications, particles that are polyhedral offer a large range of stiffness, whereas particles with arms are relatively insensitive to variations in confining pressure [16, p. 57].

5.2.2.3.9 Granular physics – Project 9

Project credits — *Author:* Scott V. Franklin | *Institution:* School of Physics, Rochester Institute of Technology, Rochester, New York | *Year:* 2014

Project description: Scott V. Franklin from the School of Physics at the Rochester Institute of Technology presents research on the rheological behaviour of so-called "u-shaped" particles under tension [128].

Generally speaking a granular material made from "u-shaped" particles can withstand tensional forces [128, p. 5804.4]. Franklin investigates both the generic behavioural pattern and the influence of the length of the probe on the probability of failure [128, p. 5804.4]. Under tension the material elongates, with some connections failing and others forming, leading to a behaviour similar to the well-known stick-slip phenomenon; the forces at which these ruptures occur vary widely [128, p. 5804.4]. The probability of failure increases with increasing length of the probe [128, p. 5804.4]. Franklin argues that both phenomena are due to an effect which is referred to as the "Weibullian weakest-link theory" [128, p. 5804.4]. This model states that the granular material consists of groups forming units on a lower hierarchical level; the overall strength of the material depends on its weakest sub-group [128, p. 5804.4]. Consequently longer probes have a higher probability of weak links than shorter ones and thus break more easily [128, p. 5804.4].

5.2.2.3.10 Granular physics – Project 10

Project credits* — *Authors: Kieran A. Murphy, Lea K. Roth, Nikolaj Reiser, Darius Choksy, Clare E. Singer, Heinrich M. Jaeger; Dan Peterman | *Institution:* Jaeger Lab, James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois; Dan Peterman, Chicago, Illinois | *Year:* 2015–16

Project description: The research presented in this project was conducted at the Jaeger Lab at the University of Chicago and is published in several articles which are authored by Kieran A. Murphy and Heinrich M. Jaeger in varying co-authorships with Lea K. Roth, Nikolaj Reiser, Darius Choksy and Clare E. Singer [265; 261; 264] (see figure 5.12). It aimed to develop a granular material for architectural constructions, especially for arches and columns with high aspect ratios, which uses only the particle's geometry as the defining parameter [264, pp. 26.1, 26.8–26.9]. The two characteristics that were identified as critical were easy flow of the material during construction and unconfined rigidity under applied external loads [264, pp. 26.1, 26.8–26.9].

The family of shapes which were developed are termed "Z", "U" and "Z90" relating to their geometry resembling these letters in the alphabet [264, p. 26.2]. Packings which are made from this group of particles are not only rigid under self-constraint but also become even more rigid under pre-strain

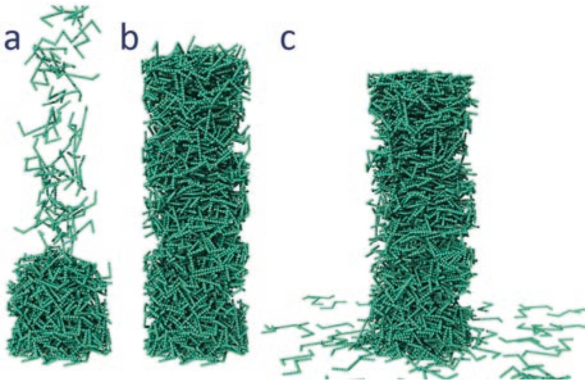

Figure 5.12: Granular physics – Project 10. Kieran A. Murphy, Lea K. Roth, Nikolaj Reiser, Darius Choksy, Clare E. Singer, Heinrich M. Jaeger; Dan Peterman | Jaeger Lab, University of Chicago; Dan Peterman, Chicago | 2016 [264]

[264, pp. 26.8–26.9]. The parameter "γ", which is used to define the orientation of one of the arms, can be deployed to calibrate the behaviour of this group of particle shapes [264, pp. 26.2, 26.8–26.9]. "Z90" particles are in comparison most rigid when no pre-strain is applied; in a granular material consisting of "U"-shapes, chains form that are hard to disentangle; "Z"-shapes can be poured best and show the highest stiffening under strain [264, pp. 26.2, 26.5 , 26.6, 26.8–26.9].

Simulations showed that the specific characteristics of these particle types are caused by their anisotropy [264, pp. 26.7, 26.8–26.9]: upon pouring they sort themselves at a 90-degree orientation to gravity with their core axis, so that mainly stress along the vertical, gravitational axis can be transferred [264, pp. 26.6–26.7, 26.8–26.9]. Compared to rods which show similar anisotropy in orientation and distribution of forces, the arms angling off the central spine seem essential to prevent particles slipping past each other, which is important for the targeted behaviour of self-constraint [264, pp. 26.7, 26.8–26.9].

In collaboration with the artist Dan Peterman, the team from Jaeger Lab realized a freestanding column composed of "Z" particles, which was able to bear a live load, as well as an arch composed of "Z90" particles [261].

5.2.2.3.11 Granular physics – Project 11

Project credits — *Authors:* Lingyi Meng, Shuixiang Li, Xiaohu Yao | *Institutions:* Department of Mechanics Engineering, School of Civil and Transportation Engineering, South China University of Technology, Guangzhou; Department of Mechanics and Aerospace Engineering, College of Engineering, Peking University, Beijing | *Year:* 2017

Project description: The project is presented by Lingyi Meng, Shuixiang Li and Xiaohu Yao of the Department of Mechanics Engineering at the South China University of Technology and of the Department of Mechanics and Aerospace Engineering at Peking University [225].

It investigates the "maximally dense random packing (MDRP)" for "intersecting spherocylinders" [225] (see figure 5.13). The "maximally dense random packing (MDRP)" is defined as the packing state at which the highest density is achieved without increasing order [226, p. 177]. "Intersecting spherocylinders" are spherocylinders which are joined in their mid-point at a 90-degree rotation to each other [225, p. 50]. The "maximally dense random packing (MDRP)" for both "2d" and "3d" "intersecting spherocylinders" with varying aspect ratios is investigated [225, pp. 50–51]. In order to obtain the packings a "geometrically based relaxation algorithm" was deployed, which does not consider mechanical forces but shows good consistency with previous simulations and experimental results [225, p. 52]. In conclusion "2d intersecting spherocylinders" have a higher packing density than "3d intersecting spherocylinders" with the same aspect ratio of the arms [225, pp. 53, 56]. The packing density decreases generally with an increase in aspect ratio of the arms [225, pp. 53, 56]. The "specific volume", which is the "reciprocal of the packing density", increases with an increase in aspect ratio of the arms [225, pp. 53, 56]. If compared to non-intersecting "spherocylinders", "2d intersecting spherocylinders" have a higher packing density, if aspect ratios of the arms are small [225, pp. 55–56]. The two curves for "specific volume" of non-intersecting "spherocylinders" and "2d intersecting spherocylinders" intersect at an aspect ratio of 1.25, which indicates similar packing density but suggests different "contacts and local arrangements" [225, pp. 56–57].

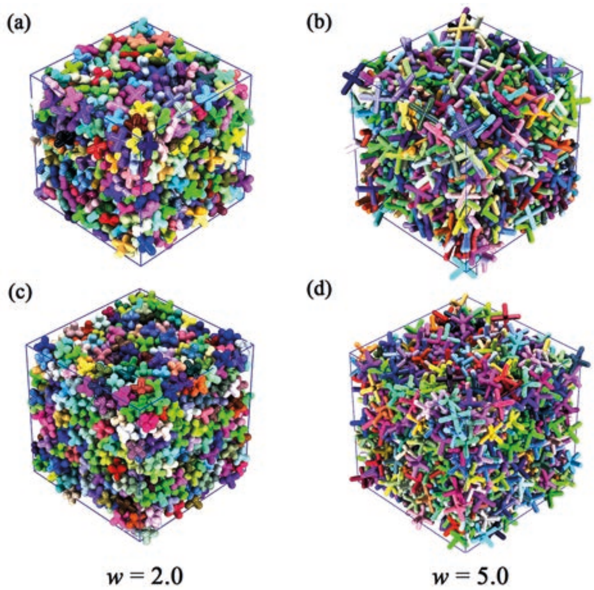

Figure 5.13: Granular physics – Project 11. Lingyi Meng, Shuixiang Li, Xiaohu Yao | Department of Mechanics Engineering, South China University of Technology; Department of Mechanics and Aerospace Engineering, Peking University | 2017 [225]

5.2.2.4 Summary and evaluation of the projects

The project selection from granular physics presented in the preceding sections has been made with respect to the projects' relevance within the context of this thesis (see section 5.2.2.3).

These projects can be summarized and evaluated with respect to the particle geometries, materials and granular material performances, which have been investigated.

With respect to particle geometry, projects 1, 2, 5 and 6 are focused on convex, cylindrical shapes (see sections 5.2.2.3.1 to 5.2.2.3.2 and 5.2.2.3.5 to 5.2.2.3.6). Projects 3, 4, 8 and 11 investigate highly non-convex or non-convex geometries, where the non-convexity is achieved by arm extensions from a convex base shape (see sections 5.2.2.3.3, 5.2.2.3.4, 5.2.2.3.8 and 5.2.2.3.11). Project 8 also looks at a wide range of convex geometries (see section 5.2.2.3.8). Projects 7, 9 and 10 investigate double non-convex shapes, which are essentially two-dimensional hooks (see sections 5.2.2.3.7, 5.2.2.3.9 and 5.2.2.3.10). Project 10 however lays the emphasis on yet another particle geometry, which are two- or three-dimensional "Z-shaped" particles (see section 5.2.2.3.10).

Particle materials are greatly varied in projects 1, 2 and 6 (see sections 5.2.2.3.1, 5.2.2.3.2 and 5.2.2.3.6). Projects 8 and 10 work with resin or acrylic (see sections 5.2.2.3.8 and 5.2.2.3.10). Projects 7 and 9 deploy steel (see sections 5.2.2.3.7 and 5.2.2.3.9). Other than in the architectural examples, some investigations focus on simulation studies only, which allows the testing of extreme material values, such as particles with no static friction (see sections 5.2.2.3.3, 5.2.2.3.4 and 5.2.2.3.11).

The performance criteria on the basis of which the overall granular material is evaluated, relate to established characterization parameters for materials in general or granular materials in particular. These encompass fluidity versus solidity of a probe, coordination number, packing density, yield stress and Young's modulus, friction angle, dilatancy angle, porosity, conductivity, permeability, entanglement, tensile strength, extension length, rigidity of a probe or strain stiffening of a probe (see sections 5.2.2.3.1 to 5.2.2.3.11). Projects 6, 9 and 10 additionally investigate aspect ratios of the entire probe (see sections 5.2.2.3.6, 5.2.2.3.9 and 5.2.2.3.10).

5.3 Contributions of granular architectures

The preceding sections have given an overview of existing conceptual frameworks and projects, which strategize and investigate designed granular materials in both architecture and granular physics. The following two sections highlight the contributions which this thesis on granular architectures makes to the current state.

5.3.1 Contributions to architecture

In the field of architecture, a range of already established conceptual frameworks are pertinent to this thesis. In particular, the concepts of "aggregate systems" and of "aleatory architectures" have direct relevance for the work presented in this thesis (see sections 5.1.1.1 and 5.1.1.4). Other than these two related conceptual frameworks, the research for this thesis on granular architectures has focused solely on designed granular materials as a form of "designer matter (DM)", thus excluding non-designed granular materials.

In this context, the thesis proposes a first comprehensive design system for both particle systems and construction systems for designed granular materials in architecture. The projects presented in sections 5.1.2.1 to 5.1.2.6 show initial investigations into architectural prototypes.

However, full-scale realizations of structures consisting of designed granular materials have not yet been conducted. The two case studies therefore demonstrate the first integration of selected categories of the proposed design system at full architectural scale.

5.3.2 Contributions for granular physics

In granular physics a range of conceptual frameworks for designed granular materials has been established (see sections 5.2.1.1 to 5.2.1.3). They are relatively widely framed with respect to either their fields of application or the types of granular materials considered. Granular architectures can contribute to these frameworks on a conceptual level, with a specific focus on designed granular materials in architecture only. The emphasis here would be to view the architect as both a designer and an integrator of the relevant research aspects (see section 5.2.1.4).

Several detailed research projects have investigated designed granular materials in physics (see sections 5.2.2.3.1 to 5.2.2.3.11). In that process a couple of design systems for particles have been developed (see section 5.2.2.4). The proposed comprehensive design system for designed granular materials in architecture, which integrates both particle systems and construction systems, will work as an interface between architecture and physics for both "forward" and "inverse" design processes.

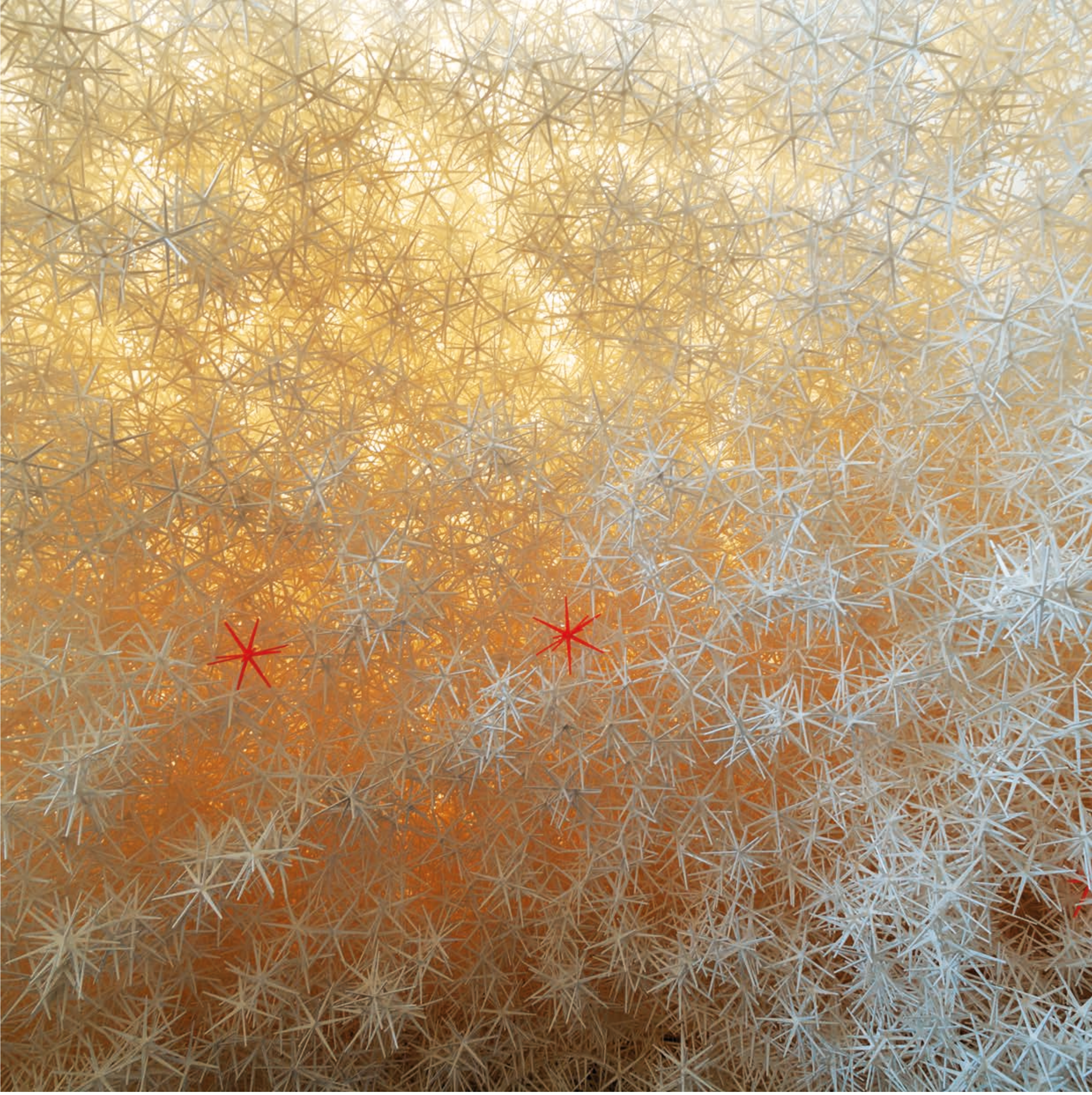

Figure 6.1: Decapods. A single-curved wall measuring circa 2000 millimetres in height has been constructed from decapods. The decapods are one of the first particle geometries to have been designed in the research development phase. They have a diameter of circa 115 millimetres and are produced by injection moulding. Karola Dierichs | ICD, University of Stuttgart | 2012 [98]

6

Research development

The research on granular architectures presented in this thesis has been developed through a series of articles investigating different approaches to the practical, methodological and conceptual level of working with designed granular materials in architecture (see figure 6.1). These development stages will be introduced in the following sections with respect to their role in the eventually implemented approach to the research. Only published work is presented in this chapter. Both individual and collaborative research as well as supervised student research are included.

The research development of this thesis has been conducted under the overarching term "aggregate architectures". "Aggregate architectures" are thus the direct precursor of granular architectures. The renaming of the field has been undertaken due to a refinement in terminology, where aggregates are referred to more specifically as additives in concrete, and granular materials are referred to more generically as systems with high numbers of particles (see appendix B and section 1.1.1). "Aggregate architectures" are based on the notion of "aggregate systems" (see section 5.1.1.1).

The following sections introduce the practical, methodological and conceptual developments of "aggregate architectures".

6.1 Practical

On the practical level initial versions of the overall design system were developed.

The 2010 article *Natural aggregation processes as models for architectural material systems* introduces a first definition of "aggregate architectures", a current-state overview as well as a first sketch of a design system for "aggregate architectures", which is based on the notions of "aggregate systems" as outlined in section 5.1.1.1 [92]. The initial "development system" for granular materials in architecture proposed in this article is composed of the "system" itself, comprising aspects of particle and construction systems, and the "evaluation of architectural performance" of this "system" [92, pp. 24–25]. It is therefore distinct from the design system presented in chapter 8, which does not include the architectural evaluation criteria, but only the particle and construction systems themselves.

A first more comprehensive version of the design system presented in chapter 8 was developed in 2016 in the article "Towards an aggregate architecture: designed granular systems as programmable matter in architecture" [102]. It defines "particle system" and "fabrication system", the latter term being equivalent to the construction system presented in chapter 8 [102, pp. 25.4–25.6]. The "particle systems" are distinguished by "geometry" and "material" [102, pp. 25.4–25.5]. The "fabrication systems" are categorized into "robotic fabrication" and "formwork" [102, pp. 25.5–25.6]. Similar to the design system catalogue presented in appendix A, the article introduces a set of case study projects to verify the proposed design system [102, pp. 25.6–25.12]. A range of articles focus on more specific investigations of particle systems and construction systems. These will be outlined in the following two sections.

6.1.1 Particle systems

An initial parametric particle model for the analysis and design of the particles was developed in 2012 [95; 96]. This parametric particle model is described in greater detail in the article *Functionally graded aggregate structures: digital additive manufacturing with designed granulates* [96]. The parametric particle model is based on the notion of "convex and concave hulls" [96, pp. 297–299]. It is based on four analysis steps for a particle geometry: the "boundary box", the "convex hull", the "overall concave hull" and the "detailed concave hull" [96, pp. 297–299]. After an analysis of already developed particle geometries, a new one is presented that is based on "sheet material fabrication" and allows for "functional grading" of the thermal characteristics of the granular materials composed of these designed particles [96, pp. 299–300].

The terminology of "convex, non-convex and double non-convex" to describe the basic geometric particle types has been introduced in the article "Granular morphologies: programming material behaviour with designed aggregates" [99, pp. 88–89]. It also shows some results of the packing tests based on the parametric particle model presented in sections 9.1.1.1.1.1 and 9.1.2 [99, pp. 88–89].

The particles, developed based on the parametric particle model introduced in section 9.1.1.1.1.1, were characterized in collaboration with the Department of Physics and Center for Nonlinear and Complex Systems at Duke University. The results were grouped together in the three following articles. "Packings of 3D stars: stability and structure" is a collaborative article under the lead of the Department of Physics and Center for Nonlinear and Complex Systems at Duke University; it shows a characterization of three types of 3D printed particles and of one type of injection moulded ones [381]. "Vibrational collapse of hexapod packings" is a collaborative article led by the Department of Physics and Center for Nonlinear and Complex Systems at Duke University; it investigates the failure of columns made from hexapods which are exposed to vibration [382]. The particles have different degrees of friction and the columns have different aspect ratios and are constructed on bases with different degrees of friction [382]. "Structure of hexapod 3D packings: understanding the global stability from the local organization" is another collaborative article under the lead of the Laboratoire de Mécanique et Génie Civil at the Université de Montpellier and the Department of Physics and Center for Nonlinear and Complex Systems at Duke University; it investigates the dependency of contacts on the arm length of hexapods and relates these to the stability of the overall packing [32].

Additionally, particles with variable geometry have been developed both within research and teaching. A first hygroscopically actuated particle was published in "Granular morphologies: programming material behaviour with designed aggregates" [99, pp. 88–89].

The overview article *Smart granular materials: prototypes for hygroscopically actuated shape-changing particles* presents and discusses three prototype projects investigating hygroscopically actuated particles with a variable geometry [106]. These were conducted in order to establish an initial approach towards systematization of research into such particles [106].

6.1.2 Construction systems

In the field of construction systems the main focus was laid on the use of robots and on the development of suitable "end effectors" as well as models for "sensory control". For a definition of "end effectors" see section 8.2.1.2, for a definition of "sensory control" refer to section 8.2.1.3.2.

The 2012 overview article "Aggregate structures: material and machine computation of designed granular substances" and the article *Functionally graded aggregate structures: digital additive manufacturing with designed granulates* present a robotic pouring process, which is based on a six-axis articulated robot equipped with a singling-out magazine emitter head [95, pp. 80–81; 96, pp. 300–302].

Following on from these first investigations into robotic construction with designed granular materials, a patent on *Herstellung Architektonischer Strukturen aus Aggregaten Konkaver Gebilde* was registered for robotic construction with granular materials consisting of non-convex particles [104].

The integration of "sensory control" into the construction process with designed granular materials has been investigated in several directions, including optical distance sensing, optical luminance sensing and thermal sensing.

The article *Robotic pouring of aggregate structures: responsive motion planning strategies for online robot control of granular pouring processes with synthetic macro-scale particles* uses a rigid body dynamics (RBD) simulation as a basis for the development of robotic distance interaction models with a granular material consisting of highly non-convex particles [105].

Luminance sensing for the "sensory controlled" removal of particles from a structure using a six-axis articulated robot has been investigated in the Master's thesis project of Desislava

Angelova [13; 89, pp. 11–13; 99, pp. 90–91]. The article *Graded light in aggregate structures: modelling the daylight in designed granular systems using online controlled robotic processes* comprehensively presents this Master's thesis project including luminance studies and first investigations on a gripper "end effector" [13].

The overview article "Granular construction: designed particles for macro-scale architectural structures" includes research and teaching conducted at the Institute for Computational Design and Construction (ICD), especially with respect to autonomous construction processes at full scale [103]. It separates "autonomous construction" into the fields of "autonomous machines" and "autonomous particles" [103, pp. 92–93]. The former denotes robotic systems that deploy increasing levels of "sensory control"; the latter considers the possibility of shape-changing particles being designed to perform construction-relevant tasks [103, pp. 92–93]. This second aspect refers back to initial ideas of a particle with sensing capacity becoming a "transformative machine" [99, p. 90].

6.2 Methodological

On the methodological level, a major emphasis has been on the development of methodological frameworks. Another key aspect has been the exploration of tools and techniques for the investigation of designed granular materials in architecture.

6.2.1 Methodological frameworks

On a methodological level, "aggregate architectures" require the architect to observe and interreact with the structures rather than to precisely plan them [102, pp. 25.2, 25.3; 99, p. 88; 95, p. 77]. Both physical and numerical modes of investigation need to be used as observational tools, and the precise methods are frequently adapted from the field of granular physics [102, pp. 25.2, 25.3, 25.4; 99, p. 88; 95, pp. 78–79]. Ideally physical and numerical modes of investigation need to be integrated with each other [95, pp. 79, 80].

Several terms which frame the numerical-physical realms have been outlined: analogue versus digital, experiment versus simulation and "material computation" versus "machine computation" [98, pp. 303–304; 94, pp. 464–465; 97, pp. 702–703; 95, pp. 78–79; 93, pp. 2–3; 90, p. 3; 91, pp. 373–374].

6.2.2 Tools and techniques

An overview of tools and techniques for experiments and simulations is given in the article entitled *Material computation in architectural aggregate systems* [91] (see section 7.2.1).

In the following paragraphs, several articles are presented which show the detailed exploration of a set of different such tools and techniques for both experiments and simulations.

A first discrete element method (DEM) simulation model was implemented and presented in the article *Interrelation of experiment and simulation in the development of aggregate architectures* in collaboration with the Institute of Engineering and Computational Mechanics (ITM) at the University of Stuttgart, using models from a seminar "Material Computation: Aggregate Architectures" on particle geometries conducted in 2010 [90].

Material und machine computation als Grundlage experimenteller Ästhetik in der Aggregat Architektur presents analytical results from the 2010 seminar as well as rigid body dynamics (RBD) and discrete element method (DEM) simulations as a basis for aesthetic assessment of "aggregate architectures" [93].

A benchmark of a rigid body dynamics (RBD) gaming software application for the simulation of robotic pouring is discussed in the article *Material and machine computation of designed granular matter: rigid-body dynamics simulations as a design tool for robotically-poured aggregate structures consisting of polygonal concave particles* [97].

A first implementation of the discrete element method (DEM) using a state-of-the-art software package is presented in *Aggregate architecture: simulation models for synthetic non-convex granulates* [98]. Both a polygonal and a multi-sphere particle modelling approach are tested and benchmarked; a wall is used as a basic prototype demonstrator of the "material system" [98].

The first dome construction from highly non-convex particles and its scan as well as a basic discrete element method (DEM) simulation and statistical simulation series are presented in the article *Simulation of aggregate structures in architecture: distinct-element modeling of synthetic non-convex granulates* [101].

Modelling aggregate behaviour presents a detailed description of the discrete element method (DEM) simulation model used for the arch [89, pp. 8–11]. This model was first shown in the overview article "Granular morphologies: programming material behaviour with designed aggregates" [99, p. 90].

Non-convex designed aggregates as architectural material systems is a poster presentation of the discrete element method (DEM) model of the dome with a larger number of particles than deployed in *Simulation of aggregate structures in architecture: distinct-element modeling of synthetic non-convex granulates* [100].

The collaborative article *Packings of complex shaped particles in cylinders* conducted under the lead of the Institute for Multiscale Simulation (MSS), Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg introduces a steepest-descent model for simulating the packings of 3D printed non-convex particles [347]. *Feedback- and data-driven design for aggregate architectures: analyses of data collections for physical and numerical prototypes of designed granular materials* is an article on the Master's thesis project by Gergana Rusenova, which integrated simulation analyses obtained with the discrete element method (DEM) into an inflatable formwork for designed granular materials [306].

6.3 Conceptual

The notion of an "aggregate architecture" is based on Michael Hensel and Achim Menges's fundamental concepts of "aggregate systems", as introduced in section 5.1.1.1. During the development of the research presented here, several articles have served to establish and refine the conceptual framework for "aggregate architectures" [103; 102; 99; 95].

"Aggregate architectures" have been defined as architectural "material systems", as outlined in section 4.2. "Aggregate architectures" encompass solely designed granular materials [103, p. 90; 102, p. 25.1; 99, p. 87; 95, pp. 76–77]. They have been described as working on three different trajectories, those of "time", "space" and "specificity" [95, pp. 76–77, 80].

Their relevance lies in the fact that they can be re-constructed rather than demolished, reconfigured rather than statically arranged and calibrated on the level of material behaviour rather than taken as a given material entity [103, p. 90; 102, p. 25.3; 99, pp. 87, 88; 95, pp. 76, 77].

Due to these properties, "aggregate architectures" are introducing novel concepts within the context of architectural design: whereas architecture is usually considered permanent, "aggregate architectures" are time-dependent; they show emergent behaviour rather than a definite form; they can be calibrated in their characteristics on the level of the individual particle geometry [103, p. 90; 102, pp. 25.3, 25.12; 99, pp. 87, 91; 95, pp. 77, 81].

6.4 Summary of the research development

In summary the research development has served to lay the foundations for both the design system and the case studies on the practical, methodological and conceptual level of design.

On the practical level, key aspects of the design system have been developed: with respect to particle systems the geometric sub-groups of convex, non-convex and double non-convex have been described and tested; with respect to construction systems, mainly several approaches to robots, "end effectors" and control paradigms have been explored.

On the methodological level, the notions of experiment and simulation as well as of analogue and digital processes have been discussed in several iterations. A set of tools and techniques have been explored. During that exploration photographic techniques for experiments and the discrete element method (DEM) for simulations have proven especially valuable.

On the conceptual level of design, several overview articles have laid out the relevance of designed granular materials for architecture as being recyclable, reconfigurable and designable. The consequence for the architect is the fact that he or she needs to work with a time-dependent, emergent system, where the main control he or she has of the system is the design of the particles of which the granular material is composed.

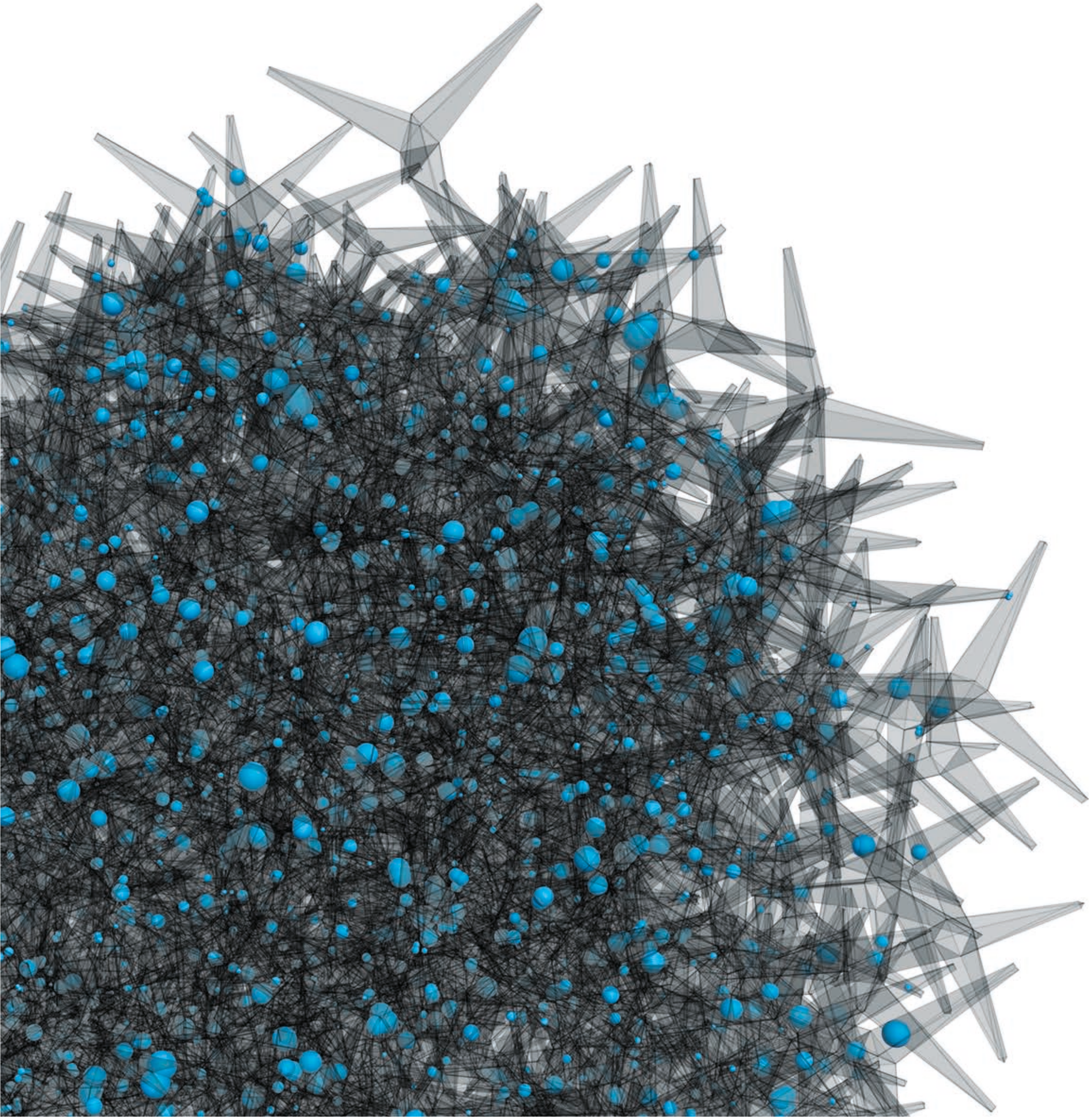

Figure 7.1: Simulation of non-convex particles. The discrete element method (DEM) allows contacts to be analysed in a simulation of tetrapods of type 50/4/20/0.2 (see figure 1.1 and section 9.1.2.3.3). Simulations have been used mainly in the statistical series of the two case studies in order to gain an understanding of the micro-mechanical behaviour of the designed granular materials deployed. Karola Dierichs with ITASCA Education Partnership (IEP) Research Program | ICD, University of Stuttgart | 2018

7
Methods

In this chapter, methods will be introduced in terms of methodological frameworks, tools and techniques as well as in terms of the actual applied research methodology (see figure 7.1).

Whereas the methodological frameworks define overarching notions rooted in the field of the philosophy of science, tools and techniques describe the concrete means by which the investigations are conducted. The applied research methodology is the integration of both the overarching methodological frameworks with the actual tools and techniques within a coherent research agenda.

Consequently the following sections begin with an overview of the methodological frameworks of "forward" and "inverse" strategies for material design, of experiments and simulations and of the notions of the analogue and the digital (see section 7.1). Next, tools and techniques that have been used in the course of the presented research are introduced while referring them to the general methodological framework (see section 7.2). The closing section gives an overview of the two main tracks of investigation or research methodology: the development of a design system on the one hand and its application in two integrative case studies on the other. These two tracks are based in the previously introduced methodological frameworks and draw from the selected tools and techniques (see section 7.3).

7.1 Methodological frameworks

Methodological frameworks discuss the approach to a problem rather than the subject matter of a research question. They aim at a methodological meta-level rather than proposing actual solutions in terms of tools or techniques. Three strands are introduced: "forward" versus "inverse" design, experiment versus simulation and analogue versus digital forms of information.

The notion of "forward" and "inverse" design proposes a framework for moving between causes and effects in the development of a novel system [194; 199]. The two notions of experiment and simulation distinguish the foundation based on which an "object" and a "target" system are interrelated [369]. This is paired with the notions of analogue and digital forms of processing, which distinguish whether information is passed on in a continuous or in a discretized form [319]. To conclude, the research presented here is situated within the framework of experiments and simulations for "forward" design processes, using both analogue and digital means of observation.

7.1.1 "Forward" versus "inverse" design

The terms "forward" and "inverse" methods refer to the direction in which causes and effects are interrelated when approaching a specific research question [199, p. 2732]. In the context of the research presented here, the two terms mainly relate to the way in which new materials are developed [199, p. 2732]. They also denote a scalar progression between micro-, meso- and macroscopic properties in the development of a material [199, p. 2732]. Other than Pedro M. Reis, Heinrich M. Jaeger and Martin van Hecke, Avni Jain seems to refer to the terms micro-, meso- and macroscopic as dimensional [199, p. 2732; 300, p. 26] (see section 4.3.1).

The "forward" process moves from cause to effect, from micro to macro [199, p. 2732]. It can be conducted either through exploring probes of a material and deducing its macroscopic characteristics or by collecting data from preceding investigations and combining them to investigate new properties of a system [194, pp. 14, 18–19; 199, p. 2732].

The "inverse" process moves from effect to cause, from macro to micro; this means that a set of macro-characteristics are defined and the micro-level structural and material make-up are determined accordingly [250, p. 49; 194, pp. 14, 19; 199, p. 2732]. A more specific understanding of the term "inverse" is given by Marc Z. Miskin [250, p. 49]. He states that "inverse" procedures allow for a range of causes to be sought for a range of effects within the same problem class [250, pp. 49, 87]. This makes them different from mere optimizations, which allow singular effect–cause interrelations [250, pp. 49, 87]. This implies that a range of solutions is found for a relatively more open search space, which must consequently be ordered and evaluated [250, p. 60].

"Forward" strategies have the advantage that they can serve to build data collections, to which "inverse" strategies can revert rather than having to determine them from scratch [199, p. 2736]. First and foremost though, "forward" processes are invaluable for problems which fall outside the bounds of established physical theories [199, p. 2736]. If predictive "inverse" strategies have failed to produce a valid result, "forward" strategies can be used to understand the problem at hand and improve the theoretical numerical models [199, p. 2736]. Furthermore "forward" strategies can usefully serve to define the search space for "inverse" ones: that is, they suggest a certain geometric group of particles that might be interesting for "inverse" optimization [198].

A point of critique for "forward" strategies is the fact that they can be considered to be mere "trial and error" procedures [194, p. 14].

One of the advantages "inverse" approaches offer is the solution of previously unsolvable questions in materials science [194, pp. 21–22; 250, pp. 87, 88]. They also expand the scope of the designer and researcher to work with desired effects rather than known causes [250, p. 88]. These methods can also be used to target material characteristics that lie outside the known spectrum [194, p. 21]. The catalogue of solutions which is produced in the search for a specific question can be referred to when addressing a different research problem [194, p. 21].

Challenges encountered by the "inverse" method are rooted mainly in the accuracy and scope of the numerical models which are at its core: the models need to be accurate and the range of problems to be addressed needs to lie within the field of known physics [250, p. 88; 199, p. 2736]. Furthermore, the outcome of "inverse" strategies always needs the "forward" validation which matches the actual with the intended material characteristics [199, p. 2736]. Also, like in many other approaches, "inverse" methods do not per se answer the question of why a certain solution exists; they just state the fact that it does [194, p. 22]. Lastly, there is no guarantee that the results that come from an "inverse" optimization really are the best solution: they are merely a "hypothesis" of the best match [250, p. 88].

The integration of "forward" and "inverse" approaches is inevitable and can provide new discoveries, especially if results do not match and "forward" methods need to be used to improve the numerical models implemented in "inverse" strategies [250, p. 88; 199, p. 2736].

A core paradigm in the methodological discussion of "forward" and "inverse" processes is the question of what design actually denotes. One school of thought considers only "inverse" processes as actual design [250, pp. 61, 87–88; 194, pp. 14, 19]. "Forward" processes are seen as scientific investigation of either given or new particle shapes [250, p. 88; 194, pp. 14, 18]. Another approach is to consider design research as the equivalent interrelation of cause and effect, or of "form" and "performance" [180, pp. 32, 34]. Frequently starting bottom-up from material experiments, these design processes oscillate between the empirical findings of the material realm and an analytical evolutionary model [248, p. 56; 179, p. 22; 176, p. 63]. One can talk of a "co-evolution" of "form" and "performance" as opposed to singular engineering optimizations [179, p. 23]. This approach is considered a method both for scientific research and for design [180]. One might consider the establishment of a "parametric model" as research, and its instrumentalization as design [180, p. 33].

In the context of the thesis presented, design is merely understood as the interrelation and consequent application of form and performance, or of cause and effect. This can occur either through "forward" or "inverse" modes of investigation. Ideally and eventually both should be integrated. However, since the research field of designed granular materials in architecture is in its infancy, only "forward" methods have been used in the course of this research, in order to establish the relevant design systems. These can in turn serve as an input for "inverse" processes of investigation. In this definition, the difference between designer and scientist does not lie in the direction of investigation, but in the intention under which these investigations are conducted: are they meant to discover cause–effect interrelations, which would be considered science, or are they meant to apply these interrelations for the development of a functional object, which would be considered design? Ultimately one should speak of design research, where these two intentions are integrated.

7.1.2 Experiment versus simulation

Since the thesis is conducted mainly through experiments and simulations, the delineation of these two terms is very relevant. The exact definition of the two terms "experiment" and "simulation" is a point of discourse in the field of the philosophy of science, especially with respect to their epistemological relevance [370; 369; 279; 259; 123; 258; 368; 159; 257].

Francesco Guala gives an account on "models, simulations and experiments" [159]. He defines a model as the underlying "structure" corresponding to a theory; models can be both static and dynamic, where only dynamic models can be deployed as simulations [159, pp. 60–62]. Model, simulation and experiment are all of the same class of scientific devices, since they are mediators between how the world is perceived and what the world actually is [159, pp. 72–73].

In Guala's definition the difference between simulation and experiment is ontological, that is different in kind, not epistemic, that is different in validity [159, pp. 62–67]. Here he refers to the work by Herbert A. Simon [159, p. 66; 322]. In a simulation there is an "abstract" and "formal" correspondence between "simulating" and "simulated system" [159, pp. 66–67, 73]. In an experiment the "target" corresponds in a "deep" and "material" manner to the "experimental system" [159, pp. 66–67, 73]. Both experiment and simulation can produce new information, but simulations require a different kind of background knowledge than experiments [159, pp. 70, 71, 73].

Mary S. Morgan delineates the two notions of "model experiments" and "laboratory experiments" [259; 258; 257]. In Morgan's definition a "model experiment" creates an "artificial world", whereas a "laboratory experiment" reconstructs "part of the real world" in an "artificial environment" [259, p. 321; 257, p. 49]. A "model experiment" is based on "mathematical" "inputs, intervention and outputs"; a "laboratory experiment" works with "material" "inputs, intervention and outputs" [258, p. 221; 257, p. 49].

Morgan introduces several other categories for distinguishing between model experiments and laboratory experiments, such as the "demonstration method" or the "controls" [259, p. 321; 258, pp. 221, 225, 231; 257, p. 49]. She clearly claims that "laboratory experiments" are epistemologically more valid than "model experiments", since their ontological correspondence to the goal system might lead to epistemological relevance [259, pp. 323, 326; 258, pp. 230–231; 257, p. 54]. Morgan also describes a third class of "hybrid experiments", where "inputs" are "quasi-material" or "semi-material" and "interventions and outputs" are "non-material"; simulations fall into this category [258, pp. 225, 231, 232–233; 257, p. 49].

Evelyn Fox Keller gives a chronological account of how both the definition and the epistemological value of "computer simulations" has evolved [123]. She observes that simulations have shifted from executing defined mathematical tasks based in theory, to testing new aspects of an existing theory, to establishing and testing models which are not based on theory [123, pp. 202, 212].

In the process they progressed from ontological and epistemological "inferiority" to ontological and epistemological validity [123, pp. 202, 212].

Wendy S. Parker takes the stance that simulations can in certain cases be considered experiments [279]. Questioning the fact that the discourse on experiments and simulations mainly revolves around "materiality" as a discerning factor, she states that "computer simulation studies" are "material experiments" in their own right [279, pp. 484, 495]. In Parker's definition a simulation is a representative model of something else, which has a set of phases organized in time [279, pp. 486–487, 495]. An experiment is an act of inquiry where a researcher can interact with the system in order to observe how the characteristics are altering [279, pp. 487, 495]. "Computer simulations" are not an experiment by this definition, but "computer simulation studies" are experiments, as there is an act of intervention on the physical system, which is the computer [279, pp. 488, 495]. In this respect Parker disagrees with Guala, who claims that the distinction between experiment and simulation can be made by assessing whether there is a "material" or a "formal" interrelation between system and "target" [279, pp. 484, 485–486, 494]. She also challenges Morgan's statement that "simulation studies" are "nonmaterial", and proposes instead that they are a "material experiment" [279, pp. 484, 488–491, 495].

As regards Morgan's claim that experiments have higher epistemic relevance, Parker suggests that both experiments and computer simulations can render pertinent results; in both cases the validity of the inferences lies in how accurate the relation between the "experimental system" and the "target system" is [279, pp. 484, 491–494, 495]. Parker states that the focus on "material" or "formal" sameness, with "material" sameness considered to have a higher epistemic value, is not quite addressing the point; in her view pertinent similarity is the key, although ontological sameness can in many situations – especially when the "target" is not very well known – provide the best information [279, pp. 484, 491–494, 495].

Eric Winsberg gives a definition of experiment and simulation in the article "A tale of two methods" [369]. Winsberg states that both experiment and simulation have an "object" and a "target", the "object" being the system that a researcher is working on, the "target" being the system which she or he actually wants to gather information about [369, pp. 579, 583]. The results which both experiment and simulation produce should have a value which is also true outside the modelling environment [369, p. 579]. The main distinction between experiment and simulation, which Winsberg arrives at, lies in the foundation on which the similarity between "object" and "target" is built: in an experiment "object" and "target" pertain to the same type of system; in a simulation the models which are used in the "object" for the "target" system must be correct [369, pp. 585, 587–588]. It is thus the type of argument for a valid relationship between "object" and "target", as well as the type of underlying knowledge the assumption is based on, which makes experiment and simulation distinct from each other [369, pp. 586, 588].

Two aspects of the underlying foundation allow a differentiation to be made between experiment and simulation [369, p. 588]. First, the underlying knowledge required for a simulation concerns mainly the "target"; in an experiment the main focus is on the "object" and how it can be managed [369, p. 588]. Second, in a simulation the arguments for the legitimacy of the system are extrinsic, whereas those for an experiment are intrinsic, looking at the "object" and how well it has been controlled [369, p. 588]. One of the main goals of the philosophical discourse is the epistemology of experiment and simulation. In that context Winsberg states that it is relevant to determine how these two operations are similar and how they are different [369, pp. 583–584]. Winsberg claims that experiments are not epistemologically more relevant than simulations, yet that they are merely different from simulations in that respect [369, pp. 584, 590–591]. The reliability of information gained from a simulation merely depends on the quality of the underlying information and the researcher's aptitude in using it [369, p. 591]. Winsberg traces the assumption that experiments are epistemologically superior to simulations to the fact that they often precede them, since experiments are often used to build the theoretical models that a simulation is founded on [369, p. 591]. However, he highlights that this notion of the experiment preceding the simulation dates back to times in scientific research where first principles needed to be established, which does not pertain to many current-day phenomena for which reliable models have been developed [369, p. 591].

Winsberg positions his argument within the discourse of the philosophy of science, mainly referring to work by Morgan, Guala and Parker [370; 369; 279; 258; 159; 257]. The notion brought forward by Nigel Gilbert and Klaus G. Troitzsch, that experiments explore nature in a direct manner and simulations investigate a model, is too simplistic in Winsberg's view [369, pp. 576–579, 584; 138, p. 14]. He counters that both experiment and simulation use representative systems, and that both experiment and simulation generate new knowledge [369, pp. 577, 578]. However, he takes on Guala's and Morgan's notion that experiments and simulations have an "object" and a "target" and that both systems need to define the soundness of using the "object" to draw conclusions on the "target" [369, pp. 579, 584]. He objects to Morgan's and Guala's claim that experiments have a "deep, material" interrelation of "object" and "target" while simulations have merely an "abstract and formal" one [369, pp. 579–580, 584–585]. As a counterpoint Winsberg notes that in both experiment and simulation the "object" itself is material in the first place, meaning that it is a physical experimental setup or a physical computer set to perform a simulation [369, pp. 579–582, 584]. He equally criticizes Guala's and Morgan's definition of confining this to relevant sameness, since this definition is based on considering both systems in terms of success only [369, pp. 579–582, 584]. In that sense unsuccessful experiments or simulations would not be included in Morgan's and Guala's framework, but they should be according to Winsberg [369, p. 581]. In Winsberg's view Parker's definition of experiment and simulation merely describes them so that they are two aspects of one thing, like "a car and driving" [369, p. 582]. Winsberg counters that the difference between experiment and simulation must be more substantial [369, pp. 583–584]. He agrees however with Parker that the statement of experiments being epistemically stronger is not correct; epistemic relevance depends on the "quality" of underlying information [369, p. 591].

It is evident from the preceding review that the delineation of experiment and simulation is all but evident or generally established. However, Winsberg's definition appears to be most appropriate for the research conducted in the framework of this thesis for two reasons. First, it is clearly delineated and refined on the basis of related definitions, such as those given by Guala and Morgan. Second, it does not try to introduce novel definitions of the two terms, like those presented for example by Parker, Fox Keller or Morgan, which are certainly methodologically relevant yet do not lie within the scope of this thesis. The two notions of experiments and simulations will consequently be used in the sense of the definition established by Winsberg.

7.1.3 Analogue versus digital

In the context of this thesis experiments and simulations are conducted using either analogue or digital means.

The terms "analogue" and "digital" need definition despite or maybe precisely because of their ubiquitous use. The word "digital" is etymologically derived from the Latin word "digitus" meaning "finger" or "toe" [228, pp. 193–194; 331]. The Latin "digitus" as well as the German word "Zeiger" both stem from the same Indo-European root "*deik", meaning "pointer" [228, p. 193]. The current-day meaning of the term "digital" as having something to do with ciphers, counting and measuring, is thus based in the fact that fingers were often used as counting and measuring devices [228, p. 202].

The term "analogue" in current-day English denotes something which refers to or uses data that are shown by a physical measurable entity which can be continuously altered [328]. It is derived from the Greek word "analogia" meaning "correspondence", "similarity", "relationship" or "comparison" [326, pp. 215–216; 328]. Its earliest use was in mathematics [326, p. 216].

The general understanding of "digital" is consequently the cipher-based, discrete, discontinuous representation of information [228, p. 204]. "Analogue" refers to continuous forms of representation based on similarities [228, p. 204].

After the use of "digit" as a technical term by Charles Babbage in 1837 and later in a patent by Clair D. Lake in 1921, the introduction of the word "digital" is first documented in a patent by Charles Campbell from 1938, and the coupling of digital and analogue only became established around 1945, for example in Douglas R. Hartree's reports on his first experiences with ENIAC, the first American digital computer [228, pp. 204–205; 319, pp. 10–11; 167, p. 500; 55, p. 9; 219, p. 2; 30, p. 21]. Due to this genealogy the notions of analogue and digital experienced at least three connotations in their wake [319, pp. 11–12]. Firstly, analogue and digital became a universal paradigm seemingly applicable to almost any phenomenon in the realm of cybernetics [319, p. 11]. Secondly, the notion of digital was confined to a binary logic especially through the works of John von Neumann [319, pp. 11–12]. Thirdly, the two terms were valued quite strongly with the connotation that the digital was able to simulate any analogue phenomenon due to the fact that in its abstraction it was more efficient [319, pp. 11–12]. Departing from its use in the technical realm, the notions of analogue and digital have been transferred to other fields, such as communication theory and popular culture, which frequently coincides with a transformation or transfer of the original meaning of the two terms [319, pp. 14–28; 228, pp. 208–214].

In his essay *Analog/digital – Opposition oder Kontinuum?* Jens Schröter introduces three key theoretical approaches to the notion of analogue and digital [319]. The three theories are Niklas Luhmann's system-theoretical, Friedrich Kittler's media-archaeological and Nelson Goodman's symbol-theoretical approach respectively [319, p. 26; 210; 234; 144; 143]. They are embedded in the realm of media theory, which has contributed significanly to the understanding of what "analogue" and "digital" actually denote [319, p. 20]. Schröter points out that this entails that the definition of what "medium" actually is affects how analogue and digital are delineated [319, p. 20]. Schröter summarizes Luhmann's definition of the "medium" as consisting of elements which can have both analogue, continuous and distinct, digital interrelations [319, pp. 20–22; 234, p. 53]. In this definition analogue and digital are markers of a "continuum" of elements that the "medium" is composed of [319, pp. 21–22; 234, p. 53].

He contraposes Luhmann's theory with that of Kittler [319, pp. 22–24]. Kittler defines a "medium" as a "technique for saving, processing and transferring of information" [319, p. 22; 210, p. 170]. He distinguishes between "pre-technical" and "technical" "media", the latter of which can be categorized as either "analogue media" or "digital technology" [319, p. 22; 210, p. 172]. The distinction according to Kittler lies in the fact that "analogue media" are based on "continuous functions", whereas "digital technology" uses "discrete scans" to process data [319, p. 22; 210, p. 185]. "Analogue" and "digital" refer in this case not to how elements in a "medium" are interrelated, but rather to how "forms" are registered [319, p. 22]. Schröter concludes that in Kittler's theory analogue and digital are an "opposition" rather than a "continuum" [319, p. 22]. A symbol-based theory of the analogue and the digital is presented by Goodman [319, pp. 24–28]. The definition is not based on the material storage "medium" but rather on the composition of the signs [319, p. 26; 143, pp. 159–164]. A sign is analogue if all aspects of a "character" are "constitutive" [319, p. 27; 143, p. 160]. A sign is digital if some aspects of a "character" can be excluded based on an independent repository [319, p. 27; 143, p. 161]. In this definition any sign can be both digital and analogue [319, p. 27; 144, p. 169].

Schröter uses these three theoretical directions to indicate that the distinction between analogue and digital is not clearly defined but rather a field of open investigation and discourse [319, p. 28].

In the context of this thesis, analogue processes are understood as those based on continuous information sets, digital processes as those based on discretized sets of information. In that respect the reading of "analogue" and "digital" is close to that of Kittler, who views them as two opposing means of managing data.

7.1.4 Summary and evaluation of the methodological frameworks

The methodological frameworks have introduced three aspects of research methodology. The first one describes the direction in which cause and effect are interrelated, which can be either "forward" from cause to effect or "inverse" from effect to cause (see section 7.1.1). The second aspect addresses the principle behind the research, which can be either an experiment or a simulation. While the discourse on the exact delineation of these terms is open, in the context of this thesis it is Eric Winsberg's definition that is adopted (see section 7.1.2). The third aspect describes the medium of investigation which can be either analogue or digital. While these two terms are also discussed in their exact definition, in the context of this thesis analogue processes are seen to work with continuous data, digital ones with discretized data (see section 7.1.3).

Within this thesis solely "forward" design methods have been used. The aim is to integrate the findings with "inverse" modes of investigation in a next step. Both experiments and simulations are deployed and analogue as well as digital media are applied in the process of investigation.

7.2 Tools and techniques

An overview of the applied tools and techniques of experiments and simulations as well as for designed granular materials is given in the following sections. The methods mainly stem from the field of granular physics and have been adapted to architectural applications accordingly.

7.2.1 Tools and techniques for experiments

A categorization of experimental methods was presented in 2010 as a precursor to this thesis [91]. Five aspects of setting up, capturing and analysing experiments were introduced: the "experimental setup", "boundary conditions", "particle marking", "photographic data capture" and "image processing" [91, pp. 375–376] (see sections 7.2.1.1 to 7.2.1.5). In the context of this thesis the last two aspects – that is, sections 7.2.1.4 and 7.2.1.5 – are expanded to data capture and data processing, to encompass a wider range of tools and techniques. The five aspects will be used in the following sections in order to introduce the basic experimental tools and techniques applied in the course of the research presented here. Detailed descriptions will be given in the context of each individual case study or feasibility test in chapter 9 or the appendix A respectively.

7.2.1.1 Experimental setup

The experimental setup is defined by the type of forces and environmental factors that have an effect on the system, such as gravity or vibration, as well as by the techniques of gathering data which are to be extracted from the system [91, p. 375].

7.2.1.2 Boundary conditions

The boundary conditions of a given experiment describe in the first place the dimensionality of the cell, meaning whether it is two or three dimensional [91, p. 375]. In the second place they refer to the geometry and the material properties of surrounding side and ground planes as well as any eventual formwork [91, p. 375].

7.2.1.3 Particle marking

Particle markings are deployed to observe individual particles or groups of particles [91, p. 375]. These can be either axial lines or full-cover dye coats [91, p. 375].

7.2.1.4 Data capture

Developing techniques for capturing data from the experiments is especially relevant and a range of different principles has been tested [91, pp. 375–376]. Generally speaking these tools and techniques fall into the realm of digital imaging, and one might note that in this instance the experiment moves from using analogue to using digital means, as has been discussed in section 7.1.3.

7.2.1.5 Data processing

Data processing techniques are used to further analyse the information gathered from the experiments [91, p. 376].

7.2.2 Tools and techniques for simulations

Several models for the simulation of granular materials exist [290]. Each of them addresses a different problem with respect to granular behaviour and its analysis and thus needs to be carefully chosen pertaining to the overarching research hypotheses. The following paragraph briefly introduces the model behind the simulations which have actually been used. The summary is based on the 2005 monograph by Thorsten Pöschel and Thomas Schwager entitled *Computational Granular Dynamics: Models and Algorithms* [190; 290].

Molecular dynamics (MD) simulations solve Newton's equation of motion for many-body systems, which means that they are based on the calculation of forces and torques [290, p. 13]. The method was originally developed by Berni J. Alder and Thomas E. Wainwright in 1957 for the computation of gases consisting of hard spheres [290, p. 14; 6]. Fundamental work for the application of this method specifically for granular materials has been conducted among others by Peter A. Cundall, Peter K. Haff, Hans J. Herrmann and Otis R. Walton [290, p. 14; 132; 358; 164; 79; 77]. Michael P. Allen and Dominic J. Tildesley have written one of the standard frameworks on molecular dynamics (MD) [290, p. 14; 8].

The algorithm at its core computes forces and torques, pairing one particle with all other particles in the many-body system which the granular material represents [290, p. 14]. Three other numerical problems have to be addressed in a molecular dynamics (MD) simulation: the addition of the total forces and torques in the system, the integration of the equations describing motion, and the collection of data based on the calculated particle paths [290, p. 15]. Boundary conditions, such as wall roughness, need to be modelled accurately in order to correspond to the actual physical conditions [290, pp. 15–16]. A molecular dynamics (MD) simulation is preceded by setting the "initial conditions" of the model, meaning the coordinates, velocities, Euler angles and angular velocities conditions [290, p. 16]. These initialization algorithms do not need a high degree of refinement, since they are used only once at the beginning of the simulation and the behaviour of the system in the long run is not dependent on them [290, p. 17]. The easiest and computationally most efficient model for particles is a disc in two dimensions or a sphere in three dimensions; this is due to the fact that collision can easily be detected by the distance of the sphere centres being smaller than the sum of the sphere radii [290, p. 17]. However, more complex geometries can be modelled using the multi-sphere method or triangles with springs to model a single particle [290, pp. 75–86, 86–108]. A set of other modelling methods for the particles exist, such as ellipsoids [290, pp. 108–110]. The particle model needs to be chosen to allow for both an accurate system behaviour and reasonable computational time [290, p. 108].

Several methods for integration have been developed such as the Gear algorithm [290, p. 26]. In conclusion, a molecular dynamics (MD) algorithm consists of six steps: the "initialization", the "predictor", the computation of "forces", the "corrector", the "data extraction" and the "program termination" [290, pp. 27–28]. Compared to other methods, molecular dynamics (MD) simulations are computationally expensive as relatively small time-steps are required to gain accurate results [290, p. 14].

The discrete element method (DEM) develops molecular dynamics (MD) for specific application in the field of granular materials [290, p. 14; 79]. For the simulations a state-of-the art software package has been used which is based on the distinct element method, which is a sub-group of the discrete element method (DEM) [78, p. 106].

7.3 Applied research methodology

Within the research presented here, two methodological research trajectories have been pursued: a design system with complementary feasibility tests (see chapter 8 and appendix A) as well as integrated architectural prototypes and pavilions which are complemented by statistical test series (see chapter 9).

7.3.1 Design system

7.3.1.1 Design system categories

The design system was developed based on and in parallel to the feasibility tests. It establishes the basic system categories for particle systems and construction systems as well as the relevant system parameters for each.

7.3.1.2 Feasibility tests

A wide range of feasibility tests were used to develop and explore the different aspects of the design system. The tests were conducted as part of the doctoral research and as taught seminars, workshop projects and Master's theses. Appendix A lists the projects within the respective section of the established design system and gives a brief overview of the hypothesis, the applied tools and techniques as well as the results.

7.3.2 Case studies

7.3.2.1 Full-scale architectural prototypes and pavilions

The full-scale architectural prototypes and pavilions serve to test and confirm or refute the scalability of a given granular system and to study full-scale structural and spatial effects. Each of the cases addresses a different relevant aspect of designed granular materials. As the methodological approach varies greatly from project to project, the exact tools and techniques used will be outlined in the respective project section.

7.3.2.2 Statistical experiments and simulations

The statistical experiment and simulation series are directly related to the cases studies. They each test one core aspect of a respective pavilion in a controlled setting. Apart from providing crucial data for the full-scale architectural prototypes and pavilions, the model of a complementary statistical series is also seen as a test of how to integrate architectural research, which is frequently rapid and qualitative, with thorough quantitative research as it is conducted in granular physics.

7.4 Summary of the methods

The methods have been presented in terms of methodological frameworks, tools and techniques and the actual research methodology applied in the thesis. With respect to methodological frameworks, "forward" design approaches are used as a basis for the development of a comprehensive design system for designed granular materials in architecture. These are investigated using experiments or simulations deploying analogue or digital media (see section 7.1).

Tools and techniques describe both the actual experimental and simulation methods used in the course of this thesis (see section 7.2). Experiments can be described by their experimental setup, boundary conditions, particle marking, data capture and the way data are processed. Simulations are based on different mathematical models, one of which has been applied in the context of this thesis, namely the discrete element method (DEM).

The applied research methodology combines the development of a design system for both particle and construction systems with case studies consisting of full-scale architectural prototypes and pavilions as well as statistical experiments and simulations (see section 7.3).

8

Design system

The design system describes the basic categories for both the particle systems in section 8.1 and the related construction systems in section 8.2. It is therefore a foundation both for the research conducted in this thesis, but also for potential collaborative projects within a wider research community in architecture as well as granular physics. Each category is introduced through a generic definition and the related sub-categories or parametric models respectively. All categories are complemented by feasibility tests, which are presented in appendix A.

A first version of the design system was presented in 2016 in the article "Towards an aggregate architecture: designed granular systems as programmable matter in architecture" [102].

8.1 Particle systems

The particle system is defined as a large number of elements which are not bound and between which only short-range repulsive forces are active; it is consequently a granular material (see section 1.1.1).

In the context of this thesis only designed granular materials are considered. In such a designed granular material both the individual particle and the overall particle mix in the particle system are designed. This means that their geometry, material characteristics and mixing grade have been developed with respect to the architectural performance of the particle system. The particle systems can thus be further distinguished on the level of the individual particle as well as that of particle mixes. Determining the values for the parametric models in the particle system is consequently key to calibrating the architectural behaviour of a designed granular material.

8.1.1 Particle

The particle is the smallest component element of a particle system. The individual particle can be categorized by its geometry as well as by its material characteristics. Both aspects, geometry and material, can be used separately or in combination to calibrate the overall behaviour of the granular material and consequently its performance with respect to structural and building physics criteria in architecture.

8.1.1.1 Geometry

Geometry is defined as that branch of mathematics that deals with points, figures and their respective characteristics in a dimensionally defined space [65; 364]. The geometry of a particle thus describes the characteristics of the points and resulting figures that compose a three-dimensional object, which is the particle. The geometry of an individual particle is described through its dimensions and geometric type as well as its possible time-dependent variability between the geometric types. In a designed granular material particle geometry is one of the key factors in defining the behaviour of the overall granular material. It mainly works through introducing new types of contact between particles, which lead to new types of force transfer through the system. The respective geometric model needs to integrate considerations of both the behaviour of a granular material and manufacturing constraints for mass production.

8.1.1.1.1 Dimension

See section A.1. The dimension of a particle is defined as the longest diameter of its convex hull. Thus, the basis for determining the dimension of a particle is the diameter of its convex hull. The convex hull is defined as the smallest convex polygon or polyhedron that encompasses every one of a defined set of points; it is the overlap of all convex polygons or polyhedra for the set of points [355; 361]. The convex hull of a particle is consequently the convex polygon that envelopes all points which define the particle's geometry. Determining the dimension of a designed particle is relevant in two respects: on the one hand it is key to defining

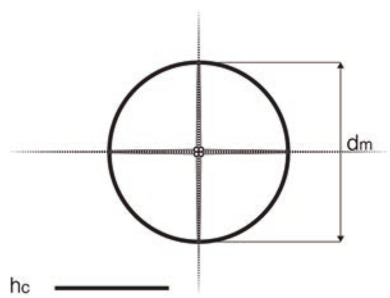

Figure 8.1: Dimension of a particle. Karola Dierichs | ICD, University of Stuttgart | 2018

the interrelation between the dimension of the particle and the size of the overall structure, and on the other the dimensions of particles are one of the bases for establishing size-graded particle mixes (see section 8.1.2).

Parametric model: The diameter of a particle is the longest diameter d_m of the convex hull h_c of the set of points p_p describing the particle geometry p_g (see figure 8.1).

8.1.1.1.2 Geometric types

The geometric type of a particle is defined as the overarching group of its geometric features, effecting a typical and distinct set of behaviours in the granular material composed of such particles. Three main geometric types are introduced here: convex, non-convex and double non-convex particles. All of these have a set of possible sub-types which have partly been explored in granular physics and partly in architecture, both in this thesis and within the wider research community (see chapter 5). The distinction between convex, non-convex and double non-convex particle systems seems a fundamental one at this stage of research, as they each show qualitatively different and typical forms of granular behaviour. Establishing the geometric type of a designed particle allows the basic properties of a designed granular material, such as its ability to flow or to transfer loads, to be defined.

8.1.1.1.2.1 Convex

See section A.2. A convex polygon or polyhedron encloses all lines connecting all pairs of points in a given set [361; 62]. A convex particle geometry consequently encloses all lines connecting all pairs of points which define the particle as a three-dimensional object. Particles belonging to this type very generally have the capacity to flow. Sub-types are spheres and polyhedra

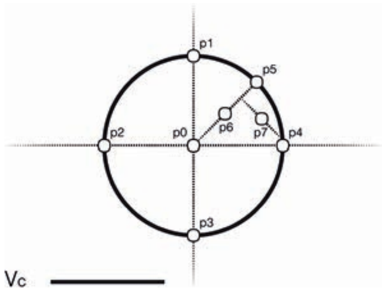

Figure 8.2: Section through a convex particle. Karola Dierichs | ICD, University of Stuttgart | 2018

as well as their elongated form of ellipsoids and rods (see section 5.2.2.1). On the one hand of the spectrum would be the spheres, which remain fluid in all orientations and do not even have an angle of repose, if the spheres have no friction. On the other end of the spectrum, if the aspect ratio becomes very high, the particles can become solid through geometric interlocking and flow only in the longitudinal orientation. The ability of a designed granular material to flow is highly relevant either during construction, if the material needs to be poured, or if particles are used as a formwork which needs to flow out once the structure has set (see section 8.2.3.2.1). An example for convex particles is given in section A.2.

Parametric model: A particle is called convex if its three-dimensional volume V_c contains all lines p_l connecting all points p_p pertaining to the particle geometry p_g (see figure 8.2).

8.1.1.1.2.2 Non-convex

See section A.3. A non-convex polygon or polyhedron does not enclose all lines connecting all pairs of points in a given set [360; 61]. As a result it has at least one internal angle which is larger than 180 degrees [360; 61]. A non-convex particle geometry

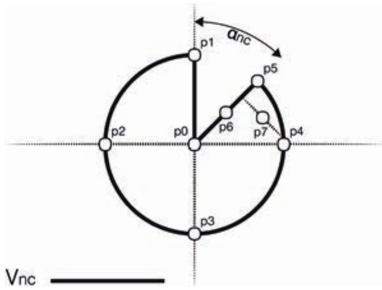

Figure 8.3: Section through a non-convex particle. Karola Dierichs | ICD, University of Stuttgart | 2018

consequently does not enclose all lines connecting any pair of points which define the particle as a three-dimensional object. Sub-types are many-armed particles like tetrapods, hexapods or octapods, but any indented particle geometry made for example from glued spheres is also classified as non-convex (see section 5.2.2.1). Depending on the degree and the amount of non-convexity, particles belonging to this type all show a tendency of geometric interlocking through the increase in contacts and thus a limited ability to be easily poured. An interrelation of the degree of non-convexity and the resulting solidity of the granular material needs to be numerically established. In the context of this thesis, particles with an internal angle which lies between 250.53 degrees for tetrapods and 289.47 degrees for octapods are referred to as highly non-convex. Designed granular materials consisting of such highly non-convex particles can among others have an angle of repose of 90 degrees. The increase in solidity in a designed granular material, which is consisting of non-convex particles, is crucial if the material is to be used as a construction material, which requires at least a certain phase of stability.

Parametric model: A particle is called non-convex if its three-dimensional volume V_{nc} does not contain all lines p_l connecting all points p_p pertaining to the particle geometry p_g (see figure 8.3). The degree of non-convexity can be established through the largest internal angle a_{nc} of the non-convex volume V_{nc}.

8.1.1.1.2.3 Double non-convex

See section A.4. A double non-convex particle geometry has been defined as being non-convex on two geometric scales of the particle, such that hooks are formed [102, p. 25.4]. Particles pertaining to this type do not flow if exposed to gravitational pull, since they display a very high degree of entanglement. They cannot be dissolved except by vibration or manual separation. Particles with a double non-convex geometry are the least fluid geometric type. They are thus on the one hand very promising as a more permanent construction material, and on the other the most intricate type to handle during construction.

Parametric model: A particle is called double non-convex if its three-dimensional volume V_{dnc} does not contain all lines p_l connecting all points p_p pertaining to the particle geometry p_g and if this non-convexity occurs on two length scales of the particle geometry p_g (see figure 8.4). The degree of double non-convexity can be established through the largest internal angle a_{dnc} of the double non-convex volume V_{dnc}.

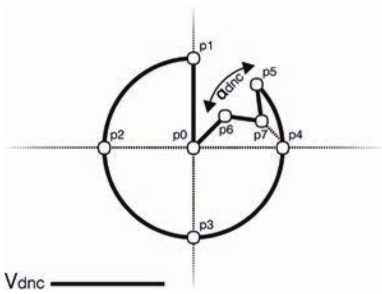

Figure 8.4: Section through a double non-convex particle. Karola Dierichs | ICD, University of Stuttgart | 2018

8.1.1.1.3 Geometric variability

Geometric variability of a particle is defined as its ability to change from one geometric type to another geometric type as a function of time. This geometric change can be brought forward by changes in environmental conditions, such as humidity or heat, if a material which is actuated by these conditions is used for the fabrication of the particle. Consequently, one can distinguish between non-variable and variable particle geometries. The establishment of the possibility for a time-based variability between geometric types is relevant, as it allows for the integration of a range of particle behaviours characteristic of each distinct geometric type into one and the same designed granular material.

8.1.1.1.3.1 Non-variable

See section A.5. A particle's geometry is non-variable if it does not change over time. Non-variable particle geometries are relevant if fundamental knowledge about a specific geometric type needs to be established in isolation.

Parametric model: The geometry of the particle at time instance 1 $p_g[t_1]$ is the same as the geometry of the particle at time instance 2 $p_g[t_2]$ (see figure 8.5).

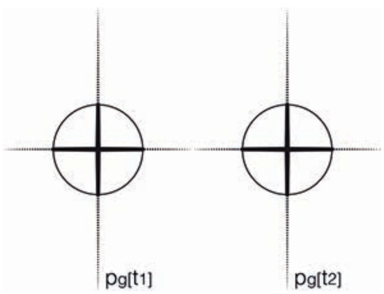

Figure 8.5: Particle with a non-variable geometry. Karola Dierichs | ICD, University of Stuttgart | 2018

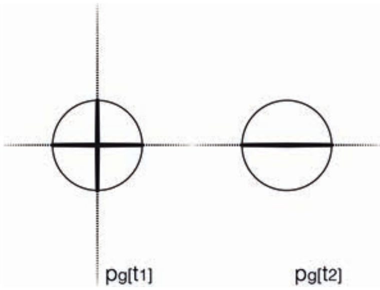

Figure 8.6: Particle with a variable geometry. Karola Dierichs | ICD, University of Stuttgart | 2018

8.1.1.1.3.2 Variable

See section A.6. A particle's geometry is variable if it does change over time. Variable particle geometries are relevant as they allow the most suitable granular behaviours for each construction phase to be integrated.

Parametric model: The geometry of the particle at time instance 1 $p_g[t_1]$ is not the same as the geometry of the particle at time instance 2 $p_g[t_2]$ (see figure 8.6).

8.1.1.2 Material

The material of the individual particle is defined as the substance which the particle is made of. A particle geometry can be made from a range of different materials or even a combination of materials, which each have distinct properties. Sub-categories of material properties which are relevant for the architectural behaviour of the overall granular material are the mechanical as well as the thermal and optical characteristics of the respective substance. Alongside the geometry of the particle, the material which a particle is made of is another factor that can be used to tune the characteristics of the overall designed granular material. This category is specifically relevant to the selection of suitable manufacturing processes for the particles.

8.1.1.2.1 Mechanical properties

See section A.7. Mechanical properties are used to describe the strength and stiffness of a given material [20]. This encompasses amongst others compressive and tensile strength as well as elasticity, plasticity and ductility [20; 39, pp. 154–158]. Tuning the mechanical properties of a given particle type leads to the calibration of the mechanical properties of a designed granular material composed of these particles.

Parametric model: The mechanical property of the material of the particle p_{mp} is set in proportion to the mechanical property of the overall granular material m_{mp}.

8.1.1.2.2 Thermal and optical properties

See section A.8. Thermal and optical properties are summarized into one sub-category since they both address the filtering of environmental influences. Thermal properties of a material describe how heat is stored and transferred and how it affects the material. Optical properties of a material define how light penetrates through and reflects from a material. If the thermal and optical properties of a given particle geometry are changed, the thermal and optical characteristics of the designed granular material composed of these particles are adjusted. These two categories thus allow for the integration of aspects of building physics into structures made from designed granular materials.

Parametric model: The thermal property of the material of the particle p_{tp} is set in proportion to the thermal property of the overall granular material m_{tp}. The optical property of the material of the particle p_{op} is set in proportion to the optical property of the overall granular material m_{op}.

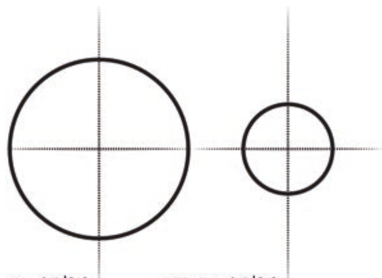

Figure 8.7: Mixing ratios for a particle mix. Karola Dierichs | ICD, University of Stuttgart | 2018

8.1.2 Particle mixes

See section A.9. Particle mixes are understood as percentage combinations of particles with different geometric and material characteristics. This can thus be a mix of particles with different dimensions, geometric types or time-based variability, a mix of particles with different mechanical, thermal or optical properties or any combination thereof. If a range of particle geometries or particles with different material characteristics have been developed, then the percentage mixing or grading of these different particle types can provide a fast and economical manner of further defining and tuning the overall properties of a designed granular material. When mixing particles with different properties, one aspect to consider is the ease and speed of separating the different particle types after they have been deployed.

Parametric model: The particle mix m_p is defined by the individual particle types $p_t[n]$ and their mixing ratios in percent (see figure 8.7).

8.2 Construction systems

Construction systems are defined as the principles and means through which a designed granular material is configured, reconfigured and recycled after use. They can be categorized into locally effective, globally effective and boundary construction systems.

Designed granular materials are a form of "designer matter (DM)". Consequently they are considered to do a large part of their configuration and reconfiguration through their innate capacities. Under that premise construction systems must be developed only if needed and in direct response to the characteristics of the respective granular material. In this sense, the following section will introduce the design system for the construction systems developed in the context of this thesis.

8.2.1 Locally effective construction systems

Locally effective construction systems work only on a part of the designed granular material, not the entire structure. Essentially a wide range of machines can be devised to be a locally effective construction system for designed granular materials. However, the focus in the context of this thesis has been on industrial robots specifically as they facilitate numerically precise construction and allow the integration of "sensory controlled" processes. Several types of industrial robots as well as effectors and control paradigms are applicable to the construction processes with granular materials. The subsequent sections will give an overview of these industrial robot types, effector types and control paradigms. They will highlight their overall relevance within the processes of formation, reformation and recycling of designed granular materials. Operating locally on a designed granular material is applicable to the configuration, reconfiguration and recycling of a respective structure. Compared to globally effective construction systems (see section 8.2.2), local ones can more easily be enlarged in scale, since the respective machine does not need to embrace the entire granular structure. Furthermore, local manipulation can be used to modulate the designed granular material at a finer resolution.

8.2.1.1 Industrial robots

See section A.10. Industrial robots can be used for the local manipulation of a designed granular material. An industrial robot is a multifunctional operator for the automation of industrial processes, which can be programmed and reprogrammed [22; 193, p. 3]. It has a minimum of three axes of operation and can be either static or "mobile" [22; 193, p. 3]. An industrial robot has a certain level of autonomy [193, p. 2]. The basic distinction of industrial robots into static and "mobile" can be further refined [193, pp. 3, 10–12]. Based on the joint type and their axial directionality static robots are distinguished into "rectangular" or "Cartesian robots", "cylindrical robots", "polar" or "spherical robots", "pendular robots", "articulated robots", "SCARA robots", "spine robots" and "parallel robots" [23; 193, pp. 10–11]. "Mobile robots" can be categorized into "wheeled robots", "legged robots", "biped robots", "crawler robots", "humanoid robots",

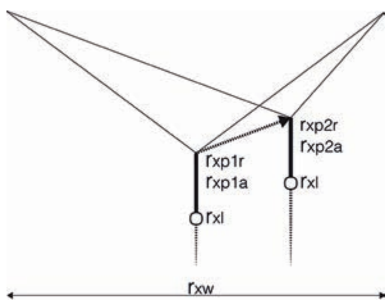

Figure 8.8: Parameters for a cable-driven parallel robot. Karola Dierichs | ICD, University of Stuttgart | 2018

"mobile platforms", "omni-directional mobile mechanisms" and "automated guided vehicles (AGVs)" [193, pp. 11–12]. The choice of industrial robot is relevant to the type of local operations which are possible on a designed granular material. These operations are specified by "rated load", "pose accuracy", "path accuracy", "pose repeatability" and "path repeatability" as well as the robot "working space" [193, pp. 16, 24, 26–27].

Parametric model: The specific model of the industrial robot r_x is classified by its performance, meaning by its "rated load" r_{xrl} in grams, its "pose accuracy", "path accuracy", "pose repeatability" and "path repeatability" $r_{xp1a}, r_{xp2a}, r_{xp1r}, r_{xp2r}$ in millimetres and its "working space" r_{xw} in millimetres (see figure 8.8).

8.2.1.2 "End effectors"

An "end effector" is a tool attached to the "mechanical interface", which is the plane made for this purpose at the end of the "manipulator" [19; 193, p. 9]. The "end effector" enables the industrial robot to perform its specific operations [19; 193, p. 9]. Sub-categories which are relevant for construction with designed granular materials are singling-out "end effectors" and clustering "end effectors".

The decision on the "end effector" influences how a designed granular material is processed. This encompasses mainly the amount of material which is handled at a given time, as well as the possible speed and frequency of application.

8.2.1.2.1 Singling-out "end effectors"

See section A.11. Singling-out "end effectors" emit one particle at a point in time, ideally always with the same particle orientation and flow rate. If particles are emitted individually at a constant flow rate and orientation, very fine-grained structures are possible.

Furthermore this type of "end effector" lends itself to rigorous testing of granular behaviours since the emission is highly repeatable between different sets. This "end effector" type is mainly used for the addition of particles to a structure. The individual removal of particles from a structure for reconfiguration or recycling is possible; shape recognition algorithms for individual particles would need to be integrated.

Parametric model: The singling-out "end effector" e_s is characterized by particle flow per time unit $f_p[t]$ and particle orientation p_o.

8.2.1.2.2 Clustering "end effectors"

See section A.12. Clustering "end effectors" emit more than one particle at a time, usually with varying orientations and particle count per cluster. Grippers are a typical example for clustering "end effectors". This "end effector" type allows for the bulk processing of designed granular materials and can easily be used for both configuration and reconfiguration and for the eventual recycling processes. Due to the fact that the particle orientations and the amount of particles per cluster vary, clustering "end effectors" are creating another statistical parameter in the overall system. Any quantitative testing of the construction process must account for this fact as another statistical variable in the overall system.

Parametric model: The clustering "end effector" e_c is characterized by average particle count per cluster c_p.

8.2.1.3 Control

The "control program" defines the abilities, operations and reactions of an industrial robot or respectively of a robot system [193, p. 18]. A range of "control programs" is possible, such as "pose-to-pose control", "continuous path control", "trajectory control",

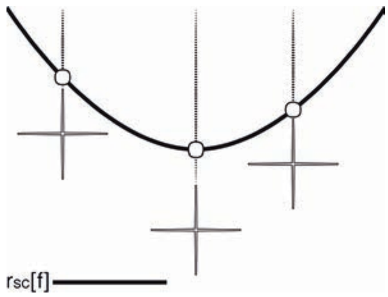

Figure 8.9: Non-"sensory control" of a robot. Karola Dierichs | ICD, University of Stuttgart | 2018

"master–slave control", "sensory control", "adaptive control", "learning control", "motion planning" or "compliance" [193, pp. 19–20]. For the purpose of working with designed granular materials it is mainly relevant to distinguish whether an industrial robot is "sensory controlled" or not. "Sensory control" denotes that the robot's program is altered based on data which are received about the operation at hand [24; 193, p. 19]. These data are gathered from integrated sensors [24; 193, p. 19].

Establishing the control paradigm in which the industrial robot operates is very relevant with respect to the design principles which can be developed for a structure made of designed granular materials. If non-"sensory control" is used, then the design is predetermined at the beginning of the construction process. If "sensory control" is applied, then the design can change during the construction process.

8.2.1.3.1 Non-"sensory control"

See section A.13. Non-"sensory control" denotes that the industrial robot's actions are not modified based on input data received from sensors, but that a predefined control program is executed without alteration; it is the opposite of "sensory control" as defined in

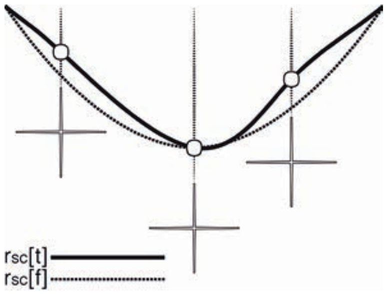

Figure 8.10: "Sensory control" of a robot. Karola Dierichs | ICD, University of Stuttgart | 2018

[24; 193, p. 19]. Non-"sensory control" can be highly relevant if basic construction principles for designed granular materials need to be tested quickly.

Parametric model: The robot's "sensory control" r_{sc} is switched off, which is described by the parameter $r_{sc}[f]$ (see figure 8.9).

8.2.1.3.2 "Sensory control"

See section A.14. "Sensory control" denotes that the industrial robot's actions are modified based on input data received from sensors, such as a camera or pressure sensor [24; 193, p. 19]. The interaction model of the industrial robot and the granular material need to be defined. "Sensory control" can be relevant on different levels of the design and construction process. It can range from path correction over goal-oriented design models to the conceptualization of continuously emerging formations.

Parametric model: The robot's "sensory control" r_{sc} is switched on, which is described by the parameter $r_{sc}[t]$ (see figure 8.10).

8.2.2 Globally effective construction systems

Globally effective construction systems affect the granular material as a whole rather than in local parts. The granular material is considered as a mass, much like what can be observed in natural processes where a global force acts on the entire material. Globally effective construction systems can be highly efficient in the preparation of a granular material before testing but also during its configuration and reconfiguration. Three types of globally effective construction systems – namely vibration, revolution and the calibration of humidity or heat – will be introduced in the following sections.

Globally affecting a designed granular material can be a very reliable and efficient manner of construction, since one operation of the construction system affects all particles at once. However, this requires that the actual construction system embrace the entire designed granular material, which can be very complex.

8.2.2.1 Vibration

See section A.15. Vibration denotes the time-based periodic alternation of positions of units within a system [25]. The induction of vibrations into a granular material is one of the most

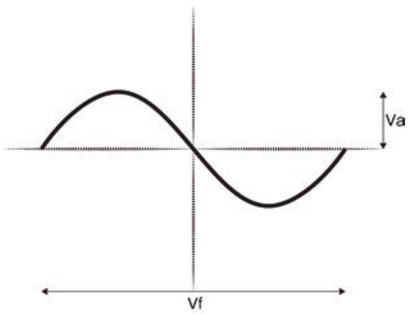

Figure 8.11: Parameters of vibration as a construction system. Karola Dierichs | ICD, University of Stuttgart | 2018

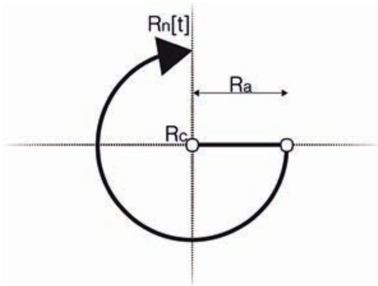

Figure 8.12: Parameters of revolution as a construction system. Karola Dierichs | ICD, University of Stuttgart | 2018

effective manners of influencing the entire system. It is mainly used in the equalization of small-scale samples, but it can also have formative and reformative effects or induce size segregation. Concrete vibrators might be adapted in order to scale these processes up.

Parametric model: Vibrations v are characterized by their frequency v_f and amplitude v_a [25] (see figure 8.11).

8.2.2.2 Revolution

See section A.16. Revolution is the movement of a body around a central axis [21]. The revolution of a granular system is usually achieved by spinning a container which is filled with the designed granular material. Revolution leads to the rotary distribution of the material but can also induce segregation of two different types of granular material [115, pp. 155–156, 171–176].

Parametric model: Revolution R is described by the position of its centre R_c, the length of the revolutionary axis R_a and the number of revolutions per time unit $R_n[t]$ (see figure 8.12).

8.2.2.3 Humidity or heat

See section A.17. The calibration of the ambient conditions in an enclosed space can be used as a globally effective construction system. Especially either relative humidity (RH) or temperature (T) can be regulated to achieve specific behaviours in designed granular materials consisting of particles which are responsive to these two ambient conditions (see section 8.1.1.1.3). Calibration of the ambient conditions allows for a very finely graded interrelation of the respective ambient parameters, the particle geometry and the resultant behaviour of the overall designed granular material.

Parametric model: Relative humidity RH is measured in percent. Temperature T is measured in Kelvin or Celsius.

8.2.3 Boundary construction systems

Boundary construction systems are defined as those elements of the design system which establish the outer or inner confines of a designed granular material.

Boundary construction systems can be categorized into containers and formwork. In most cases boundary construction systems are required in order to construct with designed granular materials, both to solidify the outer confines during construction and to introduce spatial enclosures within the granular material.

8.2.3.1 Containers

Containers define the outer confines of a granular material. Essentially any stable confining structure can be used as a container, much as in concrete casting. In the course of this thesis, however, it is mostly packaging boxes and bent sheets that have been effectively used as containers for construction with designed granular materials. Containers are in some cases necessary to keep the granular material stable during construction.

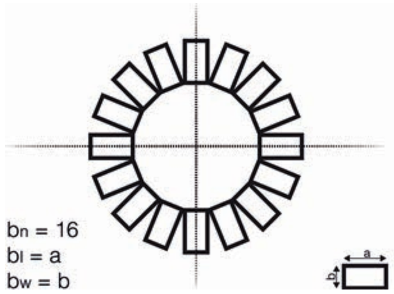

Figure 8.13: Modular cuboids as a container. Karola Dierichs | ICD, University of Stuttgart | 2018

8.2.3.1.1 Modular cuboids

See section A.18. Most boxes for logistics are by mathematical definition a cuboid, which is a polyhedron with six rectangular faces [63; 66]. The packaging boxes of designed granular materials can be used as an outer boundary for the construction process. Tension elements such as cables or clip joints are needed between the boxes in order to prevent them from giving way to the pressure of the granular material during settling. Using the packaging material of the designed granular material itself is an economic, reusable and modularly variable container option.

Parametric model: A box container system c_b is defined by the length b_l, width b_w and height b_h of the individual box as well as the overall amount of boxes b_n (see figure 8.13).

8.2.3.1.2 Developable surfaces

See section A.19. A developable surface has zero Gaussian curvature and is also a ruled surface [363]. It can be transformed from a plane and back into a plane without deformation [363; 64]. Cones and cylinders are instances of developable surfaces [64]. For the construction of containers for designed granular materials thin wood laminates can be bent or rolled in order to

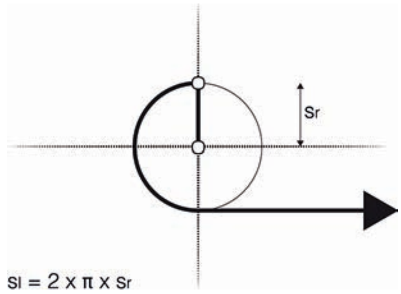

Figure 8.14: Developable surface as a container. Karola Dierichs | ICD, University of Stuttgart | 2018

achieve a curved outer confining structure. The advantage is that these sheets can be transported in a flat state and then bent or rolled upon installation using tension elements such as belts. Like the modular cuboids defined in section 8.2.3.1.1 these sheets are reusable in a range of different formations.

Parametric model: The developable surface container system c_s is determined by the length of the surface s_l, the width of the surface s_w, the height of the surface s_h and the bending radius of the surface s_r (see figure 8.14).

8.2.3.2 Formwork

Formwork is defined as that element of the design system which determines the inner boundaries of a designed granular material. The particles themselves can be used as formwork. These can be either of a different or of the same geometric type as the final structure. Additionally, custom-tailored elements can be used. Formwork is needed in order to articulate spatial enclosures in a designed granular material.

8.2.3.2.1 Different type of particles as formwork

See section A.20. Particles which have different characteristics than the overall granular material can be used as formwork. This

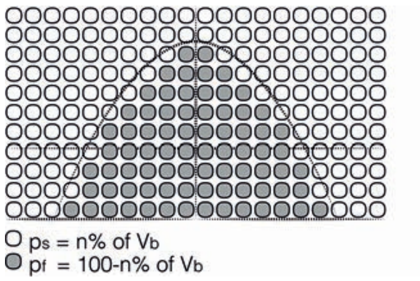

Figure 8.15: Different type of particles as formwork. Karola Dierichs | ICD, University of Stuttgart | 2018

can include for example particles that have a lower degree of interlocking or entanglement and thus flow out of a structure more easily. Using two designed granular materials in combination, one as the formwork and one as the structure, has the advantage that spatial articulations can be very varied, fine-grained and scalable in comparison with the two other formwork principles (see sections 8.2.3.2.2 and 8.2.3.2.3). First, a designed granular material which functions as a formwork for the other can be changed in distribution from construction to construction, thus leading to very diverse spatial formations. Second, it can also be distributed on different spatial scales of the structure, allowing for large, medium and small openings and recesses. Lastly, the overall system can be extended in scale quite easily by simply adding more material.

Parametric model: The interior space is defined by the geometry in which the formwork particles are distributed p_{fg}. The structure particle type p_s and the formwork particle type p_f are measured in percent of the total built volume V_b (see figure 8.15).

8.2.3.2.2 Same type of particles as formwork

See section A.21. If the container is designed to have parts which can be released prior to the rest, even a granular material consisting of only one particle type can have portions

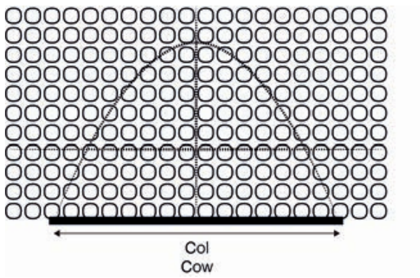

Figure 8.16: Same type of particles as formwork. Karola Dierichs | ICD, University of Stuttgart | 2018

that act as formwork and others that remain as a structure. The principle uses the so-called "clogging" phenomenon, where a granular material forms stable arches over an outflow hole [115, pp. 10–12]. This strategy thus uses both container and granular behaviour as a formwork strategy. The advantage of this formwork principle is the fact that only one type of designed granular material is needed. However, it much depends on the release mechanism in the formwork, which can become challenging once structures are scaled up.

Parametric model: This formwork principle is defined by the opening in the container c_o and its length c_{ol} and width c_{ow} as well as the velocity of release of the opening lid r_v (see figure 8.16).

8.2.3.2.3 One-piece formwork

See section A.22. Formwork can also be made from a secondary "material system" which is not a granular material, such as inflatables or developable sheets. Other than the particle formworks defined in sections 8.2.3.2.1 and 8.2.3.2.2, these secondary "material systems" are deployed in one piece and are thus referred to as a one-piece formwork. The final form of a one-piece formwork is not variable; however, the formwork can be reused and has a good ratio of transportation volume

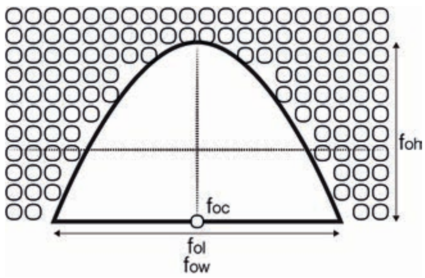

Figure 8.17: One-piece formwork. Karola Dierichs | ICD, University of Stuttgart | 2018

to deployed volume, if inflatables or developable sheets are used. While on the scale of laboratory tests balloons can be applied as a one-piece formwork, tailored inflatables need to be designed and fabricated on a large construction scale.

Parametric model: The one-piece formwork f_o is determined by its centre point f_{oc}, length f_{ol}, width f_{ow} and height f_{oh} (see figure 8.17). If an inflatable formwork is used, the radii of the principal curvatures need to be taken into account as f_{or1} and f_{or2} [39, p. 117].

8.3 Summary of the design system

The design system for designed granular materials has been introduced. It encompasses both the particle systems themselves and the related construction systems.

The categories for particle systems have been presented in section 8.1. On the level of the individual particle both the geometry and the material of a particle significantly affect the overall behaviour of a designed granular material. One of the basic geometric characteristics is the convex hull of a particle, which is used to define its maximum dimension. Furthermore, three main geometric types – convex, non-convex and double non-convex – have been identified. These can be either non-variable or variable in geometry over time. On the level of the material from which a particle is fabricated, the mechanical, thermal and optical properties of this material can be deployed to calibrate the overall structural and building physical behaviour of a granular material. On the level of the overall granular material, particle mixes need to be considered with respect to the architectural performance of the system.

Construction systems have been outlined in section 8.2. They can be categorized into locally effective, globally effective and boundary construction systems. Locally effective construction systems operate on parts of a granular material. A locally effective construction system is categorized by the type of robot, "end effector" and control paradigm which are used. Globally effective construction systems affect the granular material as a whole. A globally effective construction system can be driven by vibration or revolution, but also by climatic parameters, such as humidity or heat. Boundary construction systems can be used to articulate outer and inner boundaries of an architectural structure made from granular materials. Systems which define outer boundaries are referred to as containers for the overall structure; systems which articulate the internal spatial formations are defined as the formwork.

The proposed system for designed granular materials in architecture aims to be a basis and a starting point both for applied architectural projects which integrate a range of system categories, and for scientific research which investigates a smaller range of system categories in depth.

The following chapter 9 will introduce two case studies which demonstrate both of these applications of the design system: on the one hand full-scale architectural structures are implemented, and on the other these full-scale and sometimes rough implementations are complemented by more rigorous statistical series of experiments and simulations.

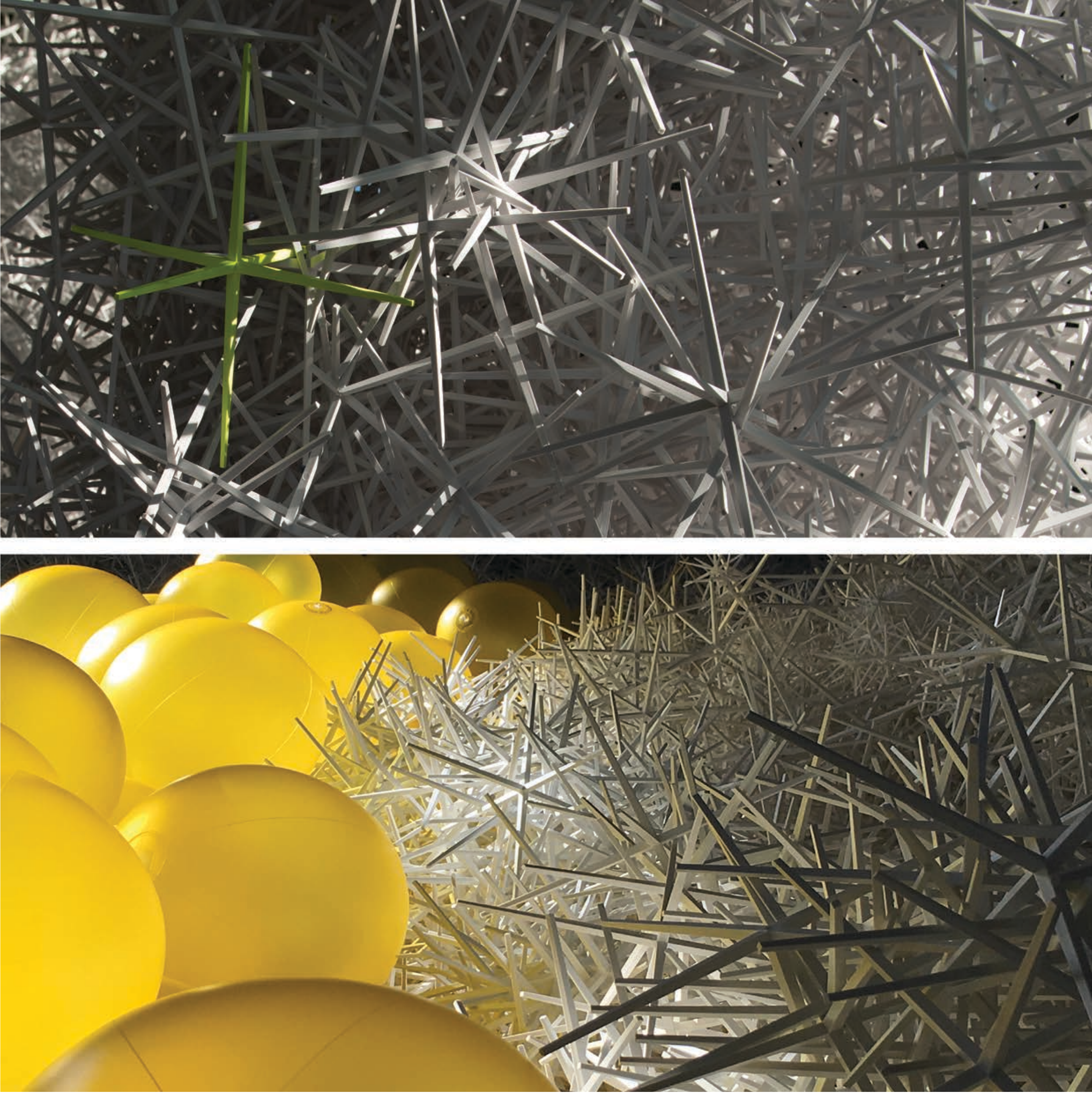

Figure 9.1: Designed granular materials of case study 1 and case study 2. Case study 1 uses highly non-convex particles and case study 2 is based on a combination of highly non-convex and convex particles. The highly non-convex particles are in both cases mainly hexapods, the convex ones are spheres. Both case studies were constructed in situ with a cable-driven parallel robot. Karola Dierichs | ICD, University of Stuttgart | 2015–18

9
Case studies

The two case studies conducted in the context of this thesis are the ICD Aggregate Pavilion 2015 as case study 1 and the ICD Aggregate Pavilion 2018 as case study 2 (see figure 9.1). Both case studies are presented and evaluated with respect to their practical, methodological and conceptual contributions to architectural design of and with granular materials.

On the practical level of design the case studies investigate different aspects of the design system both with respect to particle systems and construction systems. With respect to particle systems, case study 1 highlights the ability of a single-grade granular material to be tuned to a specific characteristic, in this case a vertical angle of repose. Case study 2 shows an application of two designed granular materials with different characteristics being applied in one structure, one particle type being the formwork for the other. With respect to construction systems, both case studies work with a cable-driven parallel robot which is developed from case to case to suit the specific project requirements.

On the methodological level the two case studies introduce on the one hand statistical experiment and simulation series of single relevant system categories of the overall project in order to investigate and demonstrate how a more rigorous scientific approach can be merged with faster-paced and frequently rough architectural production processes. On the other hand the two case studies aim to show how different aspects of the design system presented in chapter 8 can be integrated in a full-scale architectural application. The statistical series are presented with respect to their underlying hypotheses, methods and results. The project applications are shown in terms of their component system categories as well as their integrated results both in the development and realization stages.

On the overarching conceptual level the two case studies will each be discussed with respect to the three aspects of relevance for designed granular materials in architecture which have been presented in chapter 2: granular materials can be recycled, granular materials can be reconfigured and granular materials can be designed. The third aspect, namely the fact that granular materials can be designed, is key in the conceptual context of this thesis, whereas the first two aspects pertain to all granular materials and are thus accompanying facets for any project working with these systems, be they designed or not. The three aspects will therefore be discussed in inverse order.

Each case study will be generally introduced with respect to its aim and relevance for the thesis. Consequently, the first main section of each case study presents the actual architectural application. This section shows both the integrated project and the relevant system categories. The integrated results are presented in their project development and project realization stages. System categories are distinguished as either primary or secondary.

Primary system categories are those features in the proposed integrated design system which are the main focus of investigation within the scope of this specific project. Secondary system categories are features in the integrated design system which are not the focus of research in this case yet have been integrated into the project and have been in most cases the result of previous investigations. The second main section of each case study is a detailed account of the related statistical experiments and simulations, outlining their hypotheses, methods and results. To conclude, the case studies are evaluated on the practical, methodological and conceptual level of design.

9.1 Case study 1

ICD Aggregate Pavilion 2015

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The ICD Aggregate Pavilion 2015 was realized on the campus of the University of Stuttgart, Germany in 2015 [249; 103; 284; 102] (see figure 9.2). Its main aim was to explore vertical structures which are made from designed granular materials: whereas non-designed granular materials most frequently have an inclined angle of repose, designed granular materials consisting of highly non-convex particles can form 90-degree angles [209, p. 29.5; 102, pp. 25.5, 25.7; 381, pp. 24.1–24.2]. Related to this main strand of research was an investigation of how the packing density depends on the geometry of the highly non-convex particles, as well as an analysis of their load-bearing capacities. With respect to the construction system, the ICD Aggregate Pavilion 2015 showcases the initial implementation of a custom-made cable-driven parallel robot for construction with designed granular materials within the context of this thesis. Compared to case study 2, case study 1 has a relatively simple layout on the practical, methodological and also conceptual level, as will be discussed in section 9.1.3.

Its main value on the practical level lies in being a first full-scale prototype demonstrating fundamental parameters of the

Figure 9.2: ICD Aggregate Pavilion 2015. The ICD Aggregate Pavilion 2015 was realized in a public square on the campus of the University of Stuttgart. Karola Dierichs | ICD, University of Stuttgart | 2015 [102]

design system: a mainly single-grade designed granular material consisting of highly non-convex particles and a cable-driven parallel robot equipped with a clustering "end effector". On the methodological level, it is also a first attempt to integrate more rigorous scientific statistical experiments and simulations with full-scale architectural prototypes. On the conceptual level, case study 1 simply sets the example that designed granular materials allow their behaviour to be tuned through the design of the individual particle, in this case moving from a sloped to a vertical angle of repose. The following sections introduce both the overall project and the statistical experiment and simulation series.

9.1.1 Application

9.1.1.1 Integrated project

The ICD Aggregate Pavilion 2015 was developed in two phases. Phase 1 encompassed testing of vertical spatial structures made from granular materials consisting of highly non-convex particles as well as the development of the cable-driven parallel robot (see section 9.1.1.1.1). Phase 2 was the actual realization of the pavilion on site, which was conducted in several iterative sessions of construction and deconstruction (see section 9.1.1.1.1). The following sections present the results of these two project phases.

9.1.1.1.1 Project development

For the ICD Aggregate Pavilion 2015 both the particle and the construction system were developed from scratch. They are therefore described in greater detail in this section. However, they were also implemented in whole or in part within the other case study, where only the advancing developments will be outlined. Both particle and construction system were consequently tested in scaled and full-scale prototyping before they were integrated into the actual project application.

9.1.1.1.1.1 Parametric particle model

The parametric particle model was developed in order to form different particle geometries which are all based on the same parameters. This allows the comparison of performance criteria between

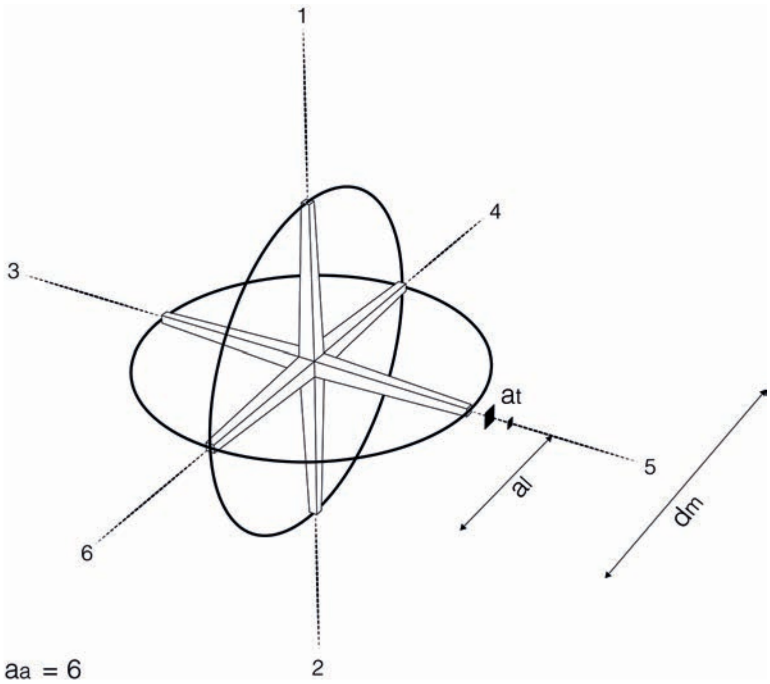

Figure 9.3: Parametric particle model. The parametric particle model defines the longest diameter of the convex hull, the arm amount, the axis length and the arm taper. Karola Dierichs | ICD, University of Stuttgart | 2014

granular materials consisting of these different particle geometries. For that purpose, the parametric particle model combines a set of different parameters which are all key to the design of one particle. The parametric particle model is based on equal distance points on a sphere, which are strictly speaking only fulfilled by the axes of Platonic solids projected on an enveloping sphere [365]. Consequently, in the context of this project, the Platonic solids have been chosen as a basis for the parametric particle model. The main geometric operation is the formation of arm extensions based on the cumulation of these Platonic solids; cumulation denotes the perpendicular extrusion of a face of the Platonic solid [362]. Based on this simple geometric operation, the parametric particle model allows the specification of four parameters: the longest diameter of the convex hull d_m, the arm amount a_a, the axis length a_l and the arm taper a_t (see figure 9.3).

Longest diameter of the convex hull (d_m): The longest diameter of the convex hull d_m has been defined in section 8.1.1.1.1 as part of the particle system. It is measured in millimetres. It is relevant as a parameter for the particle model as it provides a measure of scale for the particle geometry. Two particles can have identical values for arm amount, axis length and arm taper as a relative parameter to the measurements of each particle's core Platonic solid, yet still be different in dimension.

Arm amount (a_a): The arm amount (a_a) is defined as the amount of face extrusions from the base solid. It consequently depends on the amount of faces of the respective Platonic solid. The so-called "solid angle" depends on the amount of arms, which is measured by the function for the steradian as 4pi/a_a [366].

Axis length (a_l): The axis length (a_l) is the cumulation distance of the respective face. It can be described as a relative value using multiples of the distance between the centre point of the core Platonic solid and the centre point of the faces of the core Platonic solid. It can also be described as an absolute value in millimetres. The axis length of the individual particles is one of the main parameters by which the overall behaviour of the granular material can be calibrated.

Arm taper (a_t): The arm taper (a_t) is the reduction in diameter of the cross section of one arm along its length. It is set as a relative value of the longest diameter of the cross section at the tip of the arm over the longest diameter of the cross section at the core solid. In the context of this thesis it has not been set with respect to any specific performance criterion (see section 9.1.2.2.1). The arm taper (a_t) can however be a very relevant parameter for the calibration of the slope of an injection mould, which is important for the pieces to be able to move out of the mould easily.

The particles are name-indexed based on these four parameters: the first number indicates the convex hull diameter, the second the arm amount, the third the axis length, and the last the edge length at the arm tip, which defines the arm taper. As an example particle 50/6/20/0.5 has a convex hull diameter of 50 millimetres; it has six arm extensions: each arm has an axis length of 20 times the centre point to the face centre point of the base polyhedron; the product of the edge length at the tip of each arm over the edge length at the base of each arm is 0.5.

9.1.1.1.1.2 Particle mass production

Based on the 3D-printed series of particles which will be presented in detail in section 9.1.2, the injection moulds were developed in two planning phases considering cost and attainable construction volume.

First planning phase: A first estimate for injection moulding was based on the sub-series of particles with variations in arm amount. This selection was made due to the fact that the arm amount changes the geometric makeup of the mould. This tends to be more costly than a change in size of a given geometry (see figure 9.4). Particle 50/6/20/0.5 and particle 50/8/20/0.41 were scaled up two times, for particle 50/4/20/0.2 the axis length was doubled, because otherwise the taper would have been too extreme in this latter case. The twice scaled-up version of particle 50/6/20/0.5, labelled with the index 100/6/20/0.5, has a convex hull diameter (d_m) of 100 millimetres, an arm amount (a_a) of 6, an axis length (a_l) of 50 millimetres and an arm taper (a_t) of 0.5. The cost of the mould has been estimated at 17900.00 Euros and the cost per particle at 0.38 Euros, if 100 particles are produced. The version of particle 50/4/20/0.2 in which the axis lengths have been doubled is named 100/4/40/0.2. It has a

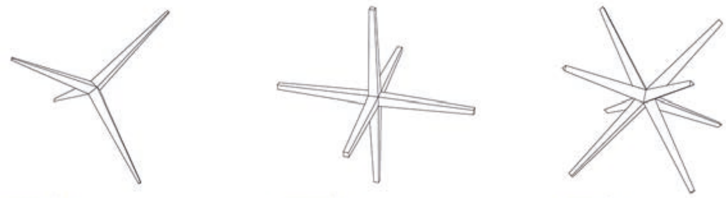

Figure 9.4: Particle geometries for the first offer. Particle geometries in the first injection moulding offer comprised a tetrapod, a hexapod and an octapod. Karola Dierichs | ICD, University of Stuttgart | 2014

convex hull sphere diameter (d_m) of 100 millimetres, an arm amount (a_a) of 4, an axis length (a_l) of 50 millimetres and an arm taper (a_t) of 0.20. The cost of the mould is 19000.00 Euros, the cost of a particle per amount of 100 particles is 0.37 Euros. Particle 50/8/20/0.41 in its scaled-up version is labelled as particle 100/8/20/0.41. It has a convex hull sphere diameter (d_m) of 100 millimetres, an arm amount (a_a) of 8, an axis length (a_l) of 50 millimetres and an arm taper (a_t) of 0.41. For this particle geometry the cost per mould is 30500.00 Euros and the cost per particle per amount of 100 particles is 0.39 Euros. All three moulds are the same type of tool, which is an open-close mould with one component of plastic and one cavity using a sprue gate. The moulds have a guaranteed number of 100000 shots, which corresponds to the guaranteed number of shots per year. The quoted material is white acrylonitrile butadiene styrene (ABS), but a recycled polystyrene was used for the final serial production. The particles are initially quoted for an electro-eroded structure with a roughness of 22 corresponding to the German engineering standards described in the norm VDI 3400. This small comparison shows that an increase in geometric intricacy leads to much higher production cost, with the eight-armed version having a 1.6 times higher cost for the mould than the six-armed one. In addition, the statistical series conducted in section 9.1.2 shows that the most effective calibration of packing density for example can be conducted by varying the axis length (a_l) and not the arm amount (a_a). The increase in cost for a mould with an increased arm amount (a_a) at this stage is not justified and has been excluded from the options.

Second planning phase: Based on these results a second cost estimate was made for two particle geometries with six arms and varying axis lengths (a_l) as well as a four-armed geometry (see figure 9.5). This selection was based on the one hand on the relatively low production cost of these geometric types, and on the other on the increase in packing density and compressive strength of the tetrapods (see section 9.1.2.1.2). Particle 50/6/20/0.5 is scaled up three times and is named particle 150/6/20/0.5. It has a convex hull diameter (d_m) of 150 millimetres, an arm amount (a_a) of six, an axis length (a_l) of 75 millimetres and an arm taper (a_t) of 0.5. The cost per mould is 23200.00 Euros and the cost of one particle per amount of 100 particles is 0.499 Euros. Particle 100/6/40/0.5 scaled up three times is labelled as particle 300/6/40/0.5. This particle has a convex hull diameter (d_m) of 300 millimetres, an arm amount (a_a) of six, an axis length (a_l) of 150 millimetres and an arm taper (a_t) of 0.5. The cost of the mould for this particle geometry is 29700.00 Euros and the cost of one particle per amount of 100 particles is 0.99 Euros. Particle 100/4/40/0.2 scaled up three times is named particle 300/4/40/0.2. It features a convex hull diameter (d_m) of 300 millimetres, an arm amount (a_a) of four, an axis length (a_l) of 150 millimetres and an arm taper (a_t) of 0.2. The cost of a mould for particle geometry 300/4/40/0.2 is 31700.00 Euros. The cost of one particle per amount of 100

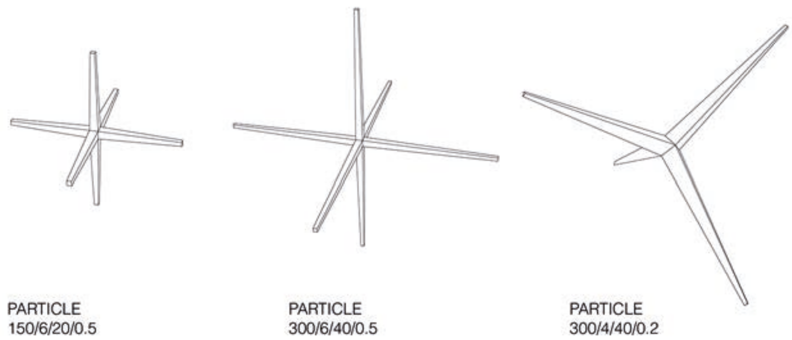

Figure 9.5: Particle geometries for the second offer. Particle geometries in the second injection moulding offer were based on the results from the first offer and comprised two hexapods with different arm lengths and a tetrapod. Karola Dierichs | ICD, University of Stuttgart | 2014

particles is 0.92 Euros. The three moulds have the same type of tool as the previous quote, meaning an open-close mould with one component of plastic and one cavity using a sprue gate. Again the moulds have a guaranteed number of 100000 shots, corresponding to the guaranteed number of shots per year. The quoted material is white acrylonitrile butadiene styrene (ABS), however the final production was conducted with recycled polystyrene. Since the particles show a wall thickness of up to 7.5 millimetres, the use of a propellant is required to avoid sink marks. The particles are initially quoted for an eroded structure of VDI 3400 reference 22; the eventual eroded structures were VDI 3400 reference 23. All three moulds have been produced, enabling the serial production of three different particle geometries with clearly quantifiable features (see figure 9.6). The cost for the intended volume of 30 cubic metres is 90565.00 Euros for particle 150/6/20/0.5, 43065.00 Euros for particle 300/6/40/0.5 and 56540.00 Euros for particle 300/4/40/0.2. That calculation indicates on the one hand, that higher axis length allows the intended

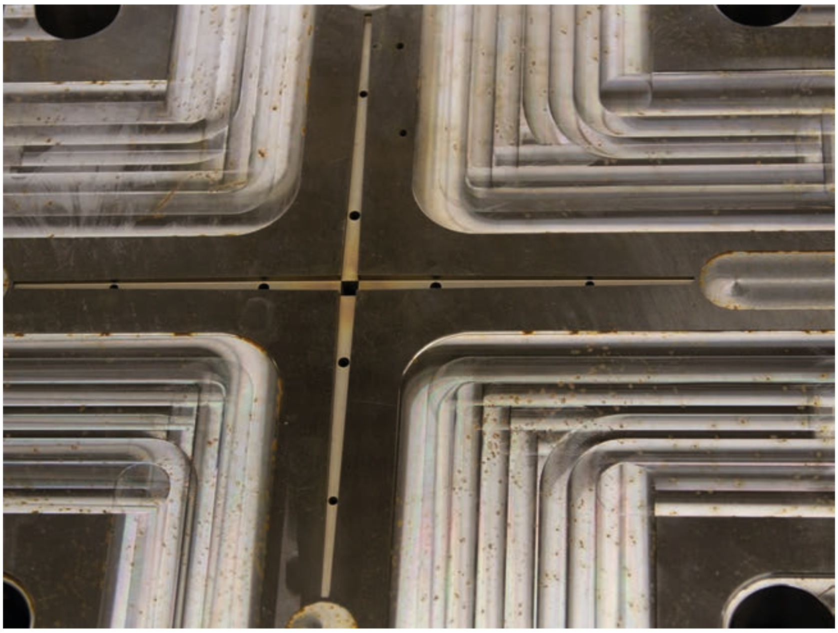

Figure 9.6: Injection mould. The mould for particle 300/6/40/0.5 was produced using computer numerically controlled (CNC) processes. Karola Dierichs | ICD, University of Stuttgart | 2015

building volume of 30 cubic metres to be produced at lower cost. On the other hand, it shows that the roughly twofold increase in packing density for particle 300/4/40/0.2 can be offset by lower cost per particle of this type leading to an increase in cost of only 1.3 for the intended volume of 30 cubic metres.

9.1.1.1.1.3 Prototyping of vertical structures

Several scaled prototypes were tested prior to the final project realization of the ICD Aggregate Pavilion 2015. These prototypes investigate vertical structures, in this case columns. Wall prototypes were also developed in this phase and are selectively presented in section A.18. All of these vertical structures investigate a 90-degree angle of repose as the main novel feature of the designed granular material. The tests were conducted in a rapid manner, using the models as initial sketches. The following sections consequently do not present quantitative results with statistical repetition but rather qualitative ideas and assessments thereof. Columns were investigated both on table-top and on full construction scale. Based on the fundamental observation that designed granular materials made from highly non-convex particles can display a 90-degree angle of repose and thus form columns, three sub-aspects of such columns were examined: (i) columns of different aspect ratios, which are non-hollow – that is solid – and non-layered; (ii) columns with layers of different particle geometries; and (iii) hollow columns. Only ten repetitions of each test were conducted in most cases, since these are still meant to be relatively fast feasibility investigations. If any aspect needed to be validated, a higher number of repetitions of each test became necessary.

(i) Columns of different aspect ratios: The first series of tests investigated columns of three different aspect ratios. These were, other than the two subsequent test series, non-hollow and non-layered but of one and the same particle type. All tests were conducted with particle 50/6/20/0.5. The particles were manually poured into a cylindrical container, which subsequently was removed. The containing cylinders all had a height of 500 millimetres, and their respective widths were 200, 150 and 100 millimetres, leading to column aspect ratios of 2.5, 3.3 and 5. The tests evaluated whether a column stands or falls on removal of the surrounding cylindrical container. All of the ten columns with aspect ratio 2.5 did not collapse, three out of ten columns with aspect ratio 3.3 fell and none of the columns with aspect ratio 5.0 stayed standing (see figure 9.7).

(ii) Layered columns: Based on the column series with aspect ratio 3.3, meaning with 150 millimetres width at 500 millimetres

Figure 9.7: Columns of different aspect ratios. Columns which had different aspect ratios were made from a designed granular material consisting of hexapods. They were tested in ten iterations for stability under self-load. Karola Dierichs | ICD, University of Stuttgart | 2014–17

height, a complementary test series was conducted. This series investigated how a base layer of tetrapods might affect the stability of a column. Since the columns at aspect ratio 3.3 showed some but not total collapse upon removal of the container, these proportions are suitable for validating the hypothesis. The tetrapods, meaning particles of type 50/4/20/0.2, were filled into the cylinder to form a bottom layer of circa one to two particles thickness. The rest of the cylinder was filled with the hexapods, meaning with particles of type 50/6/20/0.5. This series was likewise evaluated on the criterion of whether a column stands or falls on removal of the outer cylinder. Two out of ten columns collapsed, which is one less than in the non-layered series of the same aspect ratio. This leads to the indication that a bottom layer of tetrapods slightly improves the stability of the column.

(iii) Hollow columns: The third series of tests investigated hollow columns, meaning that an outer and an inner cylinder were used so as to form an inner empty space in the column. For this series, the columns with aspect ratio 2.5, meaning with 200 millimetres width and 500 millimetres height, were chosen. As they were the most stable ones of the three proportions tested in (i), they were suitable to verify how that stability is affected by a hollow core. Two cylinders with different diameter were used as inner formwork: one with 100 millimetres, leading to an average wall thickness of 50 millimetres, and one with 50 millimetres, leading to an average wall thickness of 75 millimetres. Only one particle type was used, namely the hexapods, particle 50/6/20/0.5. The particles were filled in manually between the outer and inner cylinder. The inner and then the outer cylinder were subsequently removed. In this case twenty repetitions were conducted of each test, so as to verify the difference between the columns with an inset of 100 millimetres and those with an inset of 50 millimetres. Again, the evaluation criterion was whether a column is stable and stands or is unstable and collapses. For the series with an inner cylinder of 100 millimetres diameter, two out of 20 hollow columns did not stand. For those with an inner diameter of 50 millimetres, one in twenty tests collapsed. There is thus a slight destabilization to be observed when the columns have a hollow core; this destabilization increases as expected, if the walls are thinner.

9.1.1.1.1.4 Cable-driven parallel robot – Iteration 1

The cable-driven parallel robot was custom-made for the full-scale construction with designed granular materials. The following two sections explain the hard- and software elements on a generic level. The specific configuration of the robot is described in section 9.1.1.1.2.2 in connection with the actual project application.

Hardware system: The cable-driven parallel robot hardware system consists of (i) steel cables, (ii) two "end effector" plates, (iii) four motors, (iv) four pulleys, (v) a control cabinet and (vi) a control computer [231, pp. 17–19].

(i) The steel cables are the "links" of the cable-driven parallel robot [193, p. 8].

(ii) They hold an "end effector" plate, which comes in a three- or four-point version depending on the amount of motors used in the system [231, p. 19].

(iii) The motors are servomotors and are used to run winches, which roll and unroll the steel cables. The robot can be run with all four, three or even two motors [231, p. 19]. All motors are placed on the ground and fastened or weighed down [231, pp. 18–19].

(iv) Four pulleys are attached to high points on top of each motor [231, p. 19]. The cables run from the winch up to the pulley and from there to the "end effector" plate [231, p. 19].

(v) The four motors are controlled through drivers contained in a control cabinet [231, p. 17]. The cabinet allows for an additional three axes, which can be occupied either by motors or controls on the "end effector" [231, p. 10]. It also has output pins for tools, such as an electrical gripper [231, p. 12].

(vi) The drivers are controlled by data sent from a personal computer, which can be connected to the control cabinet via a universal serial bus (USB) port.

Software system: In this implementation the cable-driven parallel robot is managed through (i) a control interface and (ii) a custom-written control model in a parametric modelling software package.

(i) The control interface is available on the market and thus not custom-written. A custom-made interface for the cable-driven parallel robot was implemented in the course of case study 2 and is presented in section 9.2.1.1.1.6. The interface allows the setting of the "axes", the "steps per unit", the "declaration", the "speed", the "resume delay", the "output pin" for the "relay control", the "inputs" and the "home position" [231, pp. 9–14].

(ii) A custom-made control model is set up for the cable-driven parallel robot in a parametric modelling software package. It has three elements: (ii.i) the geometry of the movement trajectories, (ii.ii) the calculation of the required cable length for these trajectories and (ii.iii) the G-code generation [231, pp. 8–9].

9.1.1.1.1.5 Summary of the project development

The project development for case study 1, the ICD Aggregate Pavilion 2015, encompassed the introduction of a parametrically defined particle geometry, the investigation of processes for particle mass production as well as the prototyping of vertical structures (see sections 9.1.1.1.1.1 to 9.1.1.1.1.3). In parallel a custom-made cable-driven parallel robot was built (see section 9.1.1.1.1.4).

9.1.1.1.2 Project realization

Departing from the project developments presented in the preceding section 9.1.1.1.1, the ICD Aggregate Pavilion 2015 was realized in summer 2015 on the campus of the University of Stuttgart. The following sections present the integrated project. Starting from a brief site description, the installation of the cable-driven parallel robot on site is outlined followed by a specification of the main architectural element of vertical columns. To conclude, the ICD Aggregate Pavilion 2015 is presented based on its integration in the site, robotic construction and final design.

9.1.1.1.2.1 Site

The site of the ICD Aggregate Pavilion 2015 is located on the campus of the University of Stuttgart, Germany. It is an open-air seating area between two high-rise buildings, which is surrounded by four trees.

The site was selected partly since the four surrounding trees already in situ could perform as installation points for the cable-driven parallel robot (see figure 9.8). It also provided large seating boulders which the proposed structure could be built on and for which it could form new temporary enclosures.

9.1.1.1.2.2 Cable-driven parallel robot on site

The four pulleys of the cable-driven parallel robot were installed on one tree each, the corresponding motors with winches situated and fastened beneath them. The fixing points had a height of anchor 1 at 3369.8 millimetres, anchor 2 at 3346.83 millimetres, anchor 3 at 3525.18 millimetres and anchor 4 at 3333.39 millimetres respectively (see figures 9.8 and 9.9). The actual construction space measured 5024.579 millimetres by 5156.234 millimetres with an effective potential operation height of the robot of

Figure 9.8: Cable-driven parallel robot installation 1. The cable-driven parallel robot was installed between four trees and equipped with an electrical gripper as a clustering "end effector". Karola Dierichs | ICD, University of Stuttgart | 2015

2393.8 millimetres, which is the average of the anchor heights minus 1000 millimetres safety margin. An electrical radial gripper was integrated in the robotic system and fitted with 3D-printed fingers. For a detailed description of the gripper and fingers (see section 9.1.1.2.2). The installation of the cable-driven parallel robot on existing fixing points allowed the entire project

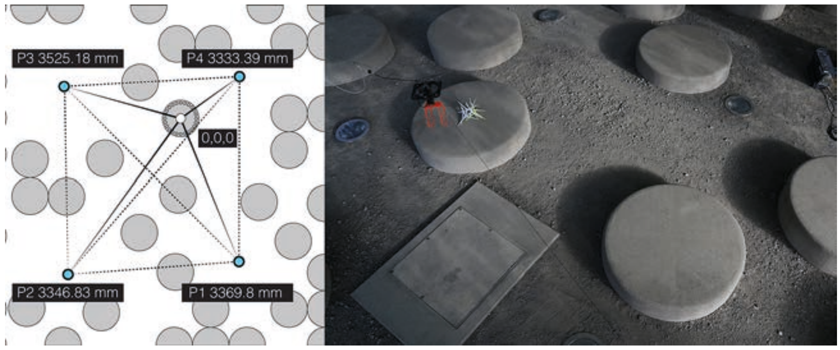

Figure 9.9: Design model of the ICD Aggregate Pavilion 2015. The trees on site define the height of the four anchor points. The zero point of the model is chosen on the centre of one of the boulders. Karola Dierichs, Ondřej Kyjánek, Martin Loučka | ICD, University of Stuttgart | 2015

to be conducted very quickly. The setting-up of the robot was completed within one day. The consequent definition and confinement of the "working space" provided a clear constraint to the design which could be implemented in this specific location.

9.1.1.1.2.3 Design model

The basic prototype of the ICD Aggregate Pavilion 2015 is a vertical column. It is non-hollow, with an aspect ratio of 2.7 at 4000 millimetres to 1500 millimetres and uses a layering percentage of circa 5.05 per cent of particle 300/4/40/0.2 at the bottom and circa 94.95 per cent of particle 300/6/40/0.5 on the top (see figure 9.10). As outlined in section 9.1.1.1.1.2, particle 300/6/40/0.5 has a convex hull diameter (d_m) of 300 millimetres, an arm amount (a_a) of six, an axis length (a_l) of 150 millimetres and an arm taper (a_t) of 0.5. One column contains circa 3020 particles of this type.

Particle 300/4/40/0.2 has a convex hull diameter (d_m) of 300 millimetres, an arm amount (a_a) of four, an axis length (a_l) of 150 millimetres and an arm taper (a_t) of 0.2. In one column 321

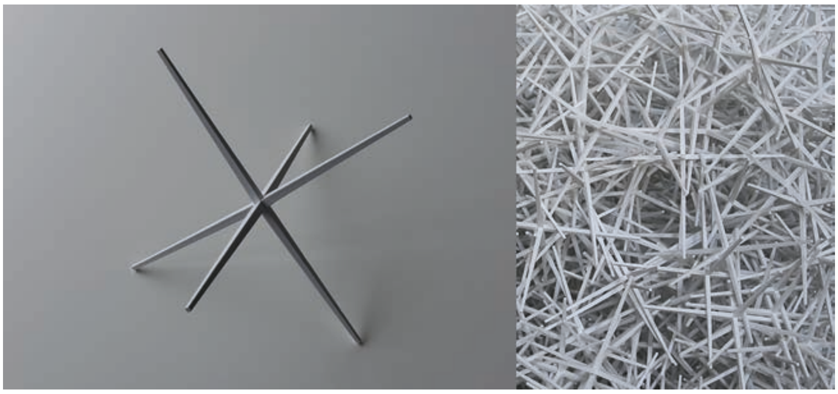

Figure 9.10: Particle type for the ICD Aggregate Pavilion 2015. The main particle type for the ICD Aggregate Pavilion 2015 was type 300/6/40/0.5, which is a hexapod that can interlock to form stable structures with a 90-degree angle of repose. Karola Dierichs | ICD, University of Stuttgart | 2015

particles of this type are contained. The construction of the columns was mainly conducted manually. The application of the cable-driven parallel robot was tested for several key tasks in the construction process. Using manual construction one column was installed in about 45 minutes average by three persons. No container was used in the construction process, the basic outline being given by the concrete boulders on site. The construction tests with the cable-driven parallel robot were limited to the construction height of 2393.8 millimetres. Parcels of particles were prepared at a pickup point, where the cable-driven parallel robot could collect them with the gripper. The parcels were deposited in concentric circles starting along the edge of the concrete boulders.

9.1.1.1.2.4 ICD Aggregate Pavilion 2015

The ICD Aggregate Pavilion 2015 aimed to investigate vertical structures made from designed granular materials. It consisted of five columns within the open-air seating area, which has been introduced in section 9.1.1.1.2.1. The design investigated how the introduction of vertical elements could temporarily change the existing courtyard. The columns acted as vertical confinements both visually and spatially. The horizontal confinement in this specific location was given by the surrounding trees forming a cover over the seating area. The selection of the five boulders out of the total 20 boulders installed as seats in the yard was given mainly by the construction space of the cable robot. The spatial effect of the vertical structures was the formation of a temporarily enclosed space in the centre of the otherwise open seating area. Given the solidity of the columns, the enclosure was not only spatial, but also visual. This allowed the formation of framed views rather than an open vision of the surrounding campus.

9.1.1.1.2.5 Summary of the realized project

Case study 1, the ICD Aggregate Pavilion 2015, is the first out of two case studies. The final project was realized in an existing open-air seating area (see section 9.1.1.1.2.1). The cable-driven parallel robot was installed in situ on four trees (see section 9.1.1.1.2.2). A set of five columns was constructed on existing seating boulders (see section 9.1.1.1.2.3). These columns formed new and temporary visual and spatial enclosures on site (see section 9.1.1.1.2.4).

9.1.1.2 System categories

The ICD Aggregate Pavilion 2015 integrated a range of the categories of the design system outlined in chapter 8. The following sections will introduce the system categories deployed in the final realization of the pavilion. A distinction is made between primary system categories and secondary system categories, with the former being key to the overall relevance of the case study and the latter being supportive, but not key factors. The selection is geared towards highlighting the core conceptual goal of the ICD Aggregate Pavilion 2015, namely to demonstrate how the behaviour of a designed granular material can be calibrated to achieve novel constructional characteristics, which in this case is a 90-degree angle of repose.

9.1.1.2.1 Primary system categories

The primary system categories integrated from the design system in case study 1 are non-convex particle geometries (see section 8.1.1.1.2.2) and industrial robots in the form of a cable-driven parallel robot (see section 8.2.1.1). The following paragraphs summarize the detailed information pertaining to these system categories.

Non-convex particle geometry (see section 8.1.1.1.2.2): The core system category which is implemented in the ICD Aggregate Pavilion 2015 is the use of a highly non-convex particle geometry. This allows a 90-degree angle of repose in the designed granular material, which enables it to depart from the sloped mounds known from granular materials like sand. Two particle geometries are used in the final production. The largest percentage are six-armed particles of the type 300/6/40/0.5, or hexapods, which have a convex hull diameter of 300 millimetres, an axis length of 150 millimetres and an arm taper of 0.5. For a detailed description of the model (see section 9.1.1.1.1.1). A smaller percentage are four-armed particles of the type 300/4/40/0.2, or tetrapods, with a convex hull diameter of 300 millimetres, an axis length of 150 millimetres and an arm taper of 0.2.

Industrial robots (see section 8.2.1.1): A second key system category of the ICD Aggregate Pavilion 2015 is the development and application of a cable-driven parallel robot for the distribution and redistribution of the granular material. This specific robot type was selected mainly because it enables a large "working space" and in-situ construction. "Rated load" as well as "path" and "position" "accuracy" and "repeatability" are sufficient for the task. In this iteration, the cable-driven parallel robot has a "rated load" of 10000 grams. "Pose accuracy" and "path accuracy" are in the centimetre range and "pose repeatability" and "path repeatability" in the millimetre range. The overall "working space" can measure circa 28754 millimetres by 28754 millimetres in plan, and its height is calculated to be 1000 millimetres below the height of the anchor points.

9.1.1.2.2 Secondary system categories

The secondary design system categories which were considered during the realization of case study 1 are the particle dimensions (see section 8.1.1.1.1), the use of non-variable particle geometries (see section 8.1.1.1.3.1), the mechanical properties of the particles' material (see section 8.1.1.2.1), the use of particle mixes (see section 8.1.2), a clustering "end effector" (see section 8.2.1.2.2), non-"sensory control" of the robot (see section 8.2.1.3.1), the use of globally effective construction systems (see section 8.2.2) as well as the use of boundary construction systems (see section 8.2.3). The following paragraphs summarize these secondary system categories.

Dimensions of the particles (see section 8.1.1.1.1): While the initial particle series, shown in section 9.1.2, and the three injection-moulded forms have different particle dimensions, the final structure of the ICD Aggregate Pavilion 2015 was made of particles with the same dimension of 300 millimetres only. The size of particles was limited by the fabrication constraints of the selected injection moulding process. The largest feasible size was chosen so as to achieve a maximum construction volume at minimum cost. In conclusion the total volume cost per 30 cubic metres for large particles versus that for small particles is about half as high. A particle with a convex hull diameter (d_m) of 150 millimetres, an arm amount (a_a) of six, an axis length (a_l) of 75 millimetres and an arm taper (a_t) of 0.5 has a cost per mould of 23200.00 Euros, and a cost per piece at a series of 100 pieces of 0.499 Euros. Based on the statistical series in section 9.1.2, one cubic metre has about 4500 particles, which leads to a cost per cubic metre of 2245.50 Euros, and a cost of 90565.00 Euros per intended 30 cubic metres including the mould. Compared to that a particle with a convex hull diameter (d_m) of 300 millimetres, an arm amount (a_a) of six, an axis length (a_l) of 150 millimetres and an arm taper (a_t) of 0.5 has a cost per mould 29700.00 Euros, cost per piece at a series of 100 pieces of 0.99 Euros. One cubic metre contains about 450 particles, consequently the cost per cubic metre 445.50 Euros and the cost per intended 30 cubic metres with mould is 43065.00 Euros.

Non-variable particle geometry (see section 8.1.1.1.3.1): Given that case study 1 aims to establish fundamental principles for architectural design with highly non-convex particle geometries, the focus has been placed on investigating non-variable particle geometries only. The particles are made from recycled polystyrene plastic, which has no variable behaviour based on changes in ambient conditions.

Mechanical properties of the particle material (see section 8.1.1.2.1): The injection-moulded particles are made from recycled polystyrene. The material was recycled through re-grinding leftovers produced during injection moulding – the so-called sprue. Propellant was added to reduce sink marks. Plastics were chosen as a material mainly on the basis of a suitable fabrication process for large particle series, which is injection moulding.

Particle mixes (see section 8.1.2): The designed granular material was not graded in either size or material makeup. Controlled particle mixing can be considered a further form of advanced system development for the ICD Aggregate Pavilion 2015. This was not relevant at this stage of fundamental research. It would first and foremost require a production process which allows the production of a wider range of particle characteristics, for example particle sizes, to base the grading on. Though actually two different geometric types of particles were used in each column, namely tetrapods and hexapods, this cannot be strictly considered mixing as the types were not mixed throughout the structure but layered: the tetrapods formed the base layer of about 7.5 per cent and the hexapods formed the rest of the column with about 92.5 per cent.

Clustering "end effector" (see section 8.2.1.2.2): The "end effector" fitted to the cable-driven parallel robot was a clustering one: in this specific case a radial gripper fitted with custom-made fingers which grab around ten particles. The tool was electronically actuated and integrated into the cable-driven parallel robot's control code. The gripper as a clustering "end effector" is one of the most efficient manners of constructing with designed granular materials, since it can both add and remove material from a structure. The specific fingers developed for this case study are designed to grab a comparatively small amount of particles, which still allows relatively accurate construction of for example circular geometries. An electric radial gripper was integrated into the cable-driven parallel robot. The gripper has two jaws, a total torque of 250 Newtoncentimetres, an opening angle per gripper jaw of 90 degrees, a repetition accuracy of 0.06 degrees, a weight of 730 grams, a maximum load of 140 Newtons, maximum torque in x, y, z of 2.5 Newtonmetres, 5.0 Newtonmetres, 5.0 Newtonmetres and a moment of inertia of 3.0 kilograms per square centimetre [140]. The gripper fingers were custom 3D printed from a polyamide (PA) 2200. They have two fingers per jaw, meaning four fingers in total. Their overall height is 200 millimetres, length is 120 millimetres and width is 100 millimetres. Segment a is 110.255 millimetres, segment b 43.863 millimetres and segment c 119.401 millimetres long. The angle between segment a and segment b is 147.197 degrees and between segment b and segment c is 116.550 degrees. The measurements are based on the feasibility tests presented in section A.12.

Non-"sensory control" (see section 8.2.1.3.1): In this case study the cable-driven parallel robot was run using only non-"sensory control". This means that there is no information feedback between the material and the motion path of the robot. Non-"sensory control" is first and foremost a choice of necessity since the interface used in this case study did not allow the integration of sensors. The paths were thus planned with sufficient offset in order to ensure the "end effector" did not collide with the structure or the ground. An image sensor which can be used for the interactive correction of the toolpath would be an appropriate further development of this specific system. However, since the case study works with a clearly defined global geometry and not with an evolving model, any more advanced interactive models are not relevant in this case. The cable-driven parallel robot was run by a G-code interpreter. The G-code was generated in a parametric model and imported into the interpreter.

Globally effective construction systems (see section 8.2.2): In this case study no globally effective construction systems were used. However, during manual construction, shaking and tamping was deployed to further stabilize the structure. This might be turned into an effective machinic construction process.

Boundary construction systems (see section 8.2.3): No boundary construction systems, whether containers or formwork, were applied in this case study. While outer boundaries were constructed both with modular cuboids and developable surfaces in the development stage of the project, the eventual full-scale application did not require any supportive structures.

9.1.1.2.3 Summary of the system categories

With respect to the system categories deployed in case study 1, the vertical angle of repose of highly non-convex particles was the prime focus of the project (see section 9.1.1.2.1). Another key aspect was the application of a cable-driven parallel robot for full-scale in-situ construction (see section 9.1.1.2.1). The secondary system categories are described in section 9.1.1.2.2. They are not crucial for the overall argument of the project, but have a supporting function for its implementation.

9.1.2 Statistics

The statistical tests conducted in combination with case study 1 were done first as a preparation for a serial production process and second in hindsight to understand the load transfer and contacts of the two particle geometries which were eventually produced. Consequently, three separate hypotheses were given, which use the same parametrically defined particle model as a basis for the respective experiments and simulations. In the following sections the hypotheses, methods and results of the statistical series conducted for case study 1 will be presented.

9.1.2.1 Hypotheses

9.1.2.1.1 Hypothesis 1

The first hypothesis states that packing density and consequently production cost per unit volume can be calibrated in a controlled manner if arm amount and arm length are varied based on the parametric particle model.

9.1.2.1.2 Hypothesis 2

The second hypothesis declares that the behaviour under compression changes in a granular material, if arm amount is varied in the individual composing particles.

9.1.2.1.3 Hypothesis 3

If arm amount is varied, the contacts increase with arm amount.

9.1.2.2 Methods

9.1.2.2.1 Methods for hypothesis 1

Hypothesis 1 was investigated with experiments and simulations deploying both analogue and digital means. Initially a parametric particle model was established. It specifies the convex hull

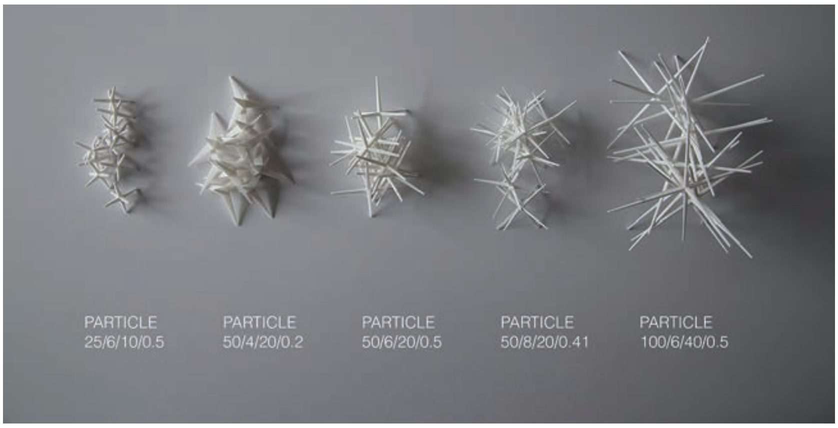

Figure 9.11: Particle types for the statistical series. The five different particle types for the statistical series were produced using selective laser sintering (SLS). Karola Dierichs | ICD, University of Stuttgart | 2014–15

diameter, the amount of arms in a particle, and the axis length and taper of each individual arm. A detailed description of the parametric particle model is given in section 9.1.1.1.1.1.

Based on this, five different sub-geometries of particles were articulated and 3D printed using selective laser sintering (SLS) of the plastic polyamide (PA) 2200 in series of one thousand pieces each. The five particle geometries consist of one base particle and four variations thereof. The base particle is the type 50/6/20/0.5. Two of the particles vary the arm amount, namely the tetrapod 50/4/20/0.2 and the octapod 50/8/20/0.41. Another two of the particles vary the arm length, namely type 25/6/10/0.5 and 100/6/40/0.5 (see figure 9.11). The six-armed particles form one group and were chosen to investigate how a change of arm length affects packing density while the arm amount stays the same. Another group is formed by the six-armed base particle together with the four-armed and eight-armed particles. This allows exploration of how a change of arm amount relates to packing density while the arm length stays the same.

For each different particle geometry, an acrylic cylinder measuring 190 millimetres in diameter and 200 millimetres in height, and thus with a volume of 5670574.8 cubic millimetres, was filled from a height of 350 millimetres. Excess material was taken off using a lid. Each probe was weighed and divided by the average weight of the respective individual particle geometry. In this manner each particle geometry was tested twenty times and the average particle count in the volume was determined through count by weight.

Annotations to the methods: In a future repetition of this specific experiment series probes may need to be vibrated prior to weighing in order to allow an even and repeatable distribution of material between probes. Equally, the long-armed hexapods would need to be tested in a larger container in a larger quantity, since the edge condition between granular material and container with looser packing dominates the entire probe in this case. However, for simple reasons of comparison between particle geometries, the probe size was kept the same throughout. Lastly, the arm taper was set to the relation of the distance between the centre point of the particle geometry and the face centre point of the particle core divided by the largest length of the face edges of the particle core. In a next step it would be advisable for the taper to be adjusted to the demands of the injection moulding process, which requires the arms to have a slope in order to move the particle easily out of the mould.

9.1.2.2.2 Methods for hypothesis 2

Hypothesis 2 was explored using both experiments and simulations deploying both analogue and digital means. The experiments were conducted in collaboration with the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart.

Cylindrical probes of designed granular materials were tested for a deformation of 50 millimetres on a standard compression testing apparatus. For that purpose a cylinder of 200 millimetres height and 190 millimetres inner diameter was filled with two types of designed granular materials: the first consisting of hexapods of the type 50/6/20/0.5, the second of tetrapods of the type 50/4/20/0.2. The particles were not compacted inside the cylinder. The cylinder was removed. The compression piston was equipped with an acrylic plate with 300 millimetres diameter and 10 millimetres thickness. The piston was lowered onto the probe and the test was run until a deformation of 50 millimetres was reached. The tests were repeated 32 times.

9.1.2.2.3 Methods for hypothesis 3

Hypothesis 3 was investigated using simulations based on the discrete element method (DEM). The simulation was set up with a linear contact model. The material values were calibrated according to earlier research conducted on the same particles in the course of this thesis [381; 101]. The particles of type 50/6/20/0.5, a hexapod, and 50/4/20/0.2, a tetrapod, were modelled as clumps, meaning that spheres were bonded to emulate the respective particle geometry [101]. 1000 particles of each type were simulated dropping into a cylinder. Each particle type was simulated twenty times until a specified equilibrium was reached. The diameter of the cylinder was chosen so that the width and height of the simulated particles after simulation were roughly the same. After simulation the amount and distribution of the contacts were recorded.

9.1.2.3 Results

9.1.2.3.1 Results for hypothesis 1

The results of the statistical experiment series are presented in sequence of the packing tests for each selected particle geometry using small series of 3D-printed particles. The parametric particle model, which is explained in detail in section 9.1.1.1.1.1, specifies the convex hull diameter as d_m, the arm amount as a_a, the axis length as a_l and the taper of the arm as a_t. These parameters are used to identify the different particle geometries in the following paragraphs.

Particle 50/6/20/0.5:
Convex hull diameter: d_m = 50 millimetres | Arm amount: a_a = 6 (Steradian = 4π/6) | Axis length: a_l = 20 times particle centre point to face centre point = 25 millimetres | Arm taper: a_t = 1.25 millimetres to 2.5 millimetres = 0.5

Particle 50/6/20/0.5 is set as the norm geometry, which the other four geometries depart from. It has six arms, and is thus a hexapod. Its diameter is 50 millimetres. The average weight of the probe in 20 repetitions is 218.065 grams, the average weight of the particle is 0.46 grams and consequently the average amount of particles is 474.0543478.

Particle 50/4/20/0.2:
Convex hull diameter: d_m = 50 millimetres | Arm amount: a_a = 4 (Steradian = 4π/4) | Axis length: a_l = 20 times particle centre point to face centre point = 25 millimetres | Arm taper: a_t = 1.25 millimetres to 6.12 millimetres = 0.20

Particle 50/4/20/0.2 belongs to the sub-group of geometries which vary arm amount while maintaining the same diameter of the particle. It reduces the arm amount from the norm particle

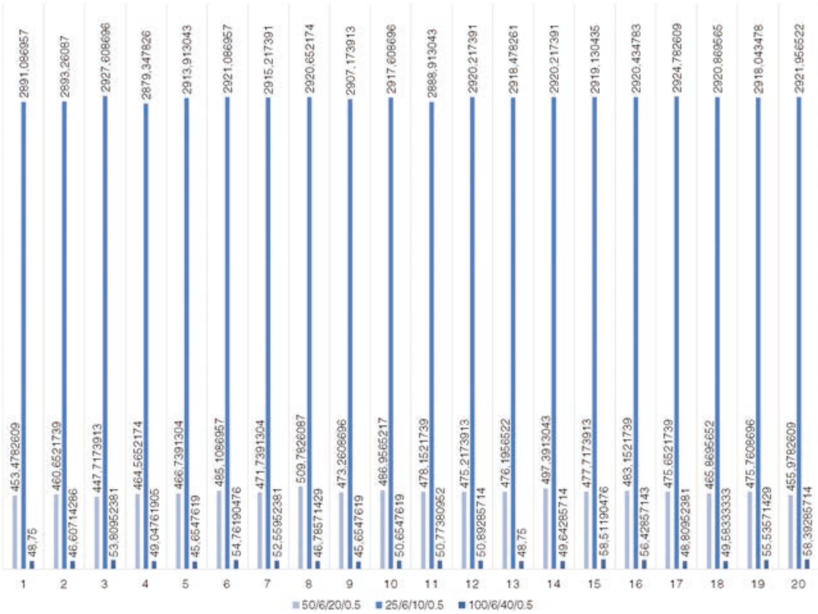

Figure 9.12: Particle count of hexapods with different arm lengths. Karola Dierichs | ICD, University of Stuttgart | 2014–15

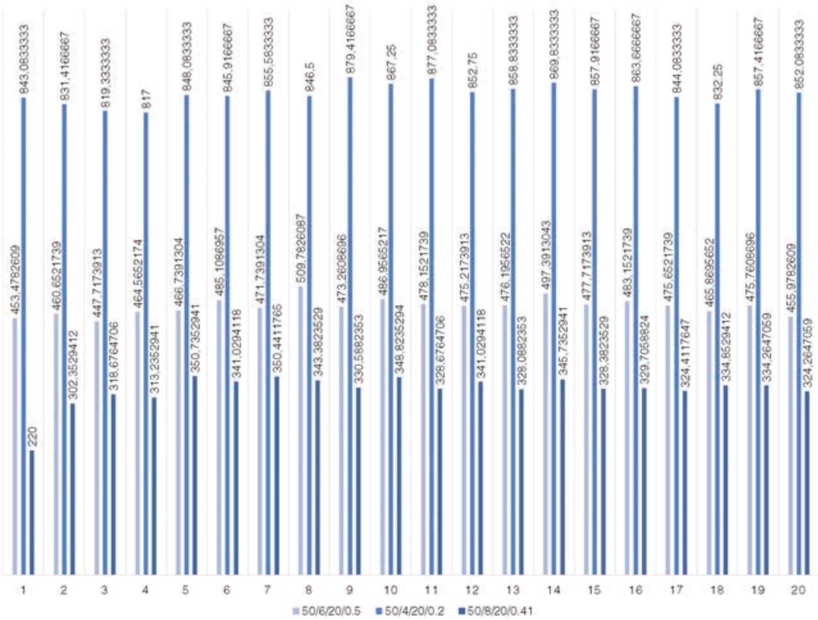

Figure 9.13: Particle count of particles with different arm amount. Karola Dierichs | ICD, University of Stuttgart | 2014–15

by two, which makes it a tetrapod. The average weight of the probe is measured at 510.585 grams in 20 repetitions, the average weight of a particle is 0.6 grams, consequently the average amount of particles per probe is 850.975.

Particle 50/8/20/0.41:
Convex hull diameter: d_m = 50 millimetres | Arm amount: a_a = 8 (Steradian = 4π/8) | Axis length: a_l = 20 times particle centre point to face centre point = 25 millimetres | Arm taper: a_t = 1.25 millimetres to 3.06 millimetres = 0.41

Particle 50/8/20/0.41 is the second geometry in the group which investigates the effect of arm amount at the same particle diameter. It adds two arms in relation to the norm particle, and consequently has eight arm extensions, turning it into an octapod. The average weight of a probe based on 20 repetitions is 111.1575 grams. One particle weighs an average of 0.34 grams, and the average amount of particles in a probe is 326.9338235.

Particle 25/6/10/0.5:
Convex hull diameter: d_m = 25 millimetres | Arm amount: a_a = 6 (Steradian = 4π/6) | Axis length: a_l = 10 times particle centre point to face centre point = 12.5 millimetres | Arm taper: a_t = 1.25 millimetres to 2.5 millimetres = 0.5

Particle 25/6/10/0.5 belongs to the sub-group in which arm amount remains the same and arm length is varied. Departing from the norm particle, it is consequently a hexapod with half the axis length of the norm. The average weight of the probe based on 20 repetitions is 669.99 grams. One particle weighs in average 0.23 grams and the average amount of particles in a probe of this particle geometry is 2913.

Figure 9.14: Packing tests of five particle types. Packing tests were conducted to investigate variations in arm length (top row), and variations in arm amount (bottom row). Both variations in arm length and arm amount depart from the basic particle type 50/6/20/0.5. Karola Dierichs | ICD, University of Stuttgart | 2014

Particle 100/6/40/0.5:

Convex hull diameter: d_m = 100 millimetres | Arm amount: a_a = 6 (Steradian = 4π/6) | Axis length: a_l = 40 times particle centre point to face centre point = 50 millimetres | Arm taper: a_t = 1.25 millimetres to 2.5 millimetres = 0.5

Particle 100/6/40/0.5 is the second particle in the sub-group in which arm length is varied while maintaining arm amount. It is a hexapod with double the axis length of the norm particle. The average weight of probe as per 20 repetitions is 42.9075 grams and one particle weighs 0.84 grams, which results in an average amount of particles of 51.08035714 per probe.

If the particle count and weights are compared with each other again using Particle 50/6/20/0.5 as a basis of comparison, it can be shown that the extension or reduction of arm length has more effect than the addition or subtraction of arms on the packing density of the respective granular material (see figures 9.12 and 9.13). Particle 50/6/20/0.5 is set to be the norm in both particle count and weight. Compared to that, the probe containing particles of the type 100/6/40/0.5 is 0.20 times lighter and has 0.11 times the particles, which is the far end of the spectrum in low packing density. The other end of the spectrum is occupied by the probe consisting of particles 25/6/10/0.5, which has 3.10 times the weight and 6.14 times as many particles per probe. Particle 50/8/20/0.41 shows the second lowest packing density with 0.51 the weight of the norm probe and 0.69 times as many particles. Particle 50/4/20/0.2 is the second densest-packing one, with 1.80 times the amount of parts of the norm particle and 2.34 the weight.

As a result, it can be concluded that with a simple increase or decrease of arm lengths, extremes in packing density can easily be reached while maintaining a particle geometry, such as the hexapod, which can be comparatively easily manufactured, both using the intended injection-moulding process or even semi-finished products such as sheets or wood profiles (see figure 9.14).

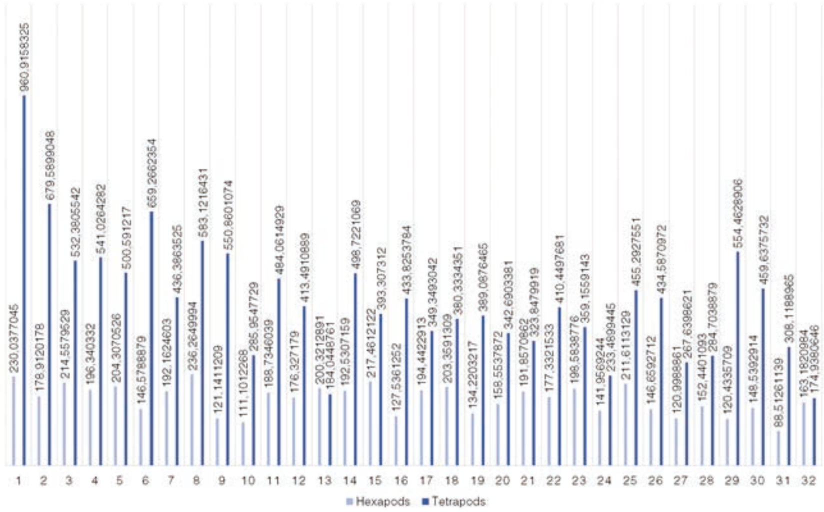

Figure 9.15: Standard force in Newtons (N) for 50 millimetres deformation for hexapods and tetrapods. Karola Dierichs | ICD in collaboration with ITKE, University of Stuttgart | 2014–18

9.1.2.3.2 Results for hypothesis 2

The experiments show that the compressive strength of both designed granular materials increases with increasing loads: the load curves assume roughly the shape of a parabola (see figures 9.15 and 9.16). The probes bounce back after compression and several particles fall out during the compression and during the release process. For the hexapods the maximum load value achieved in a probe at 500 millimetres deformation was 236.27 Newtons, the minimum was 88.51 Newtons and the average was 171.47 Newtons. For the tetrapods the maximum load value achieved in a probe at 500 millimetres deformation was 960.92 Newtons, the minimum was 174.94 Newtons and the average was 433.29 Newtons. The tetrapods are thus circa 2.53 times stronger than the hexapods. It should be stated that the spread between maximum and minimum values is very high. This might be reduced by

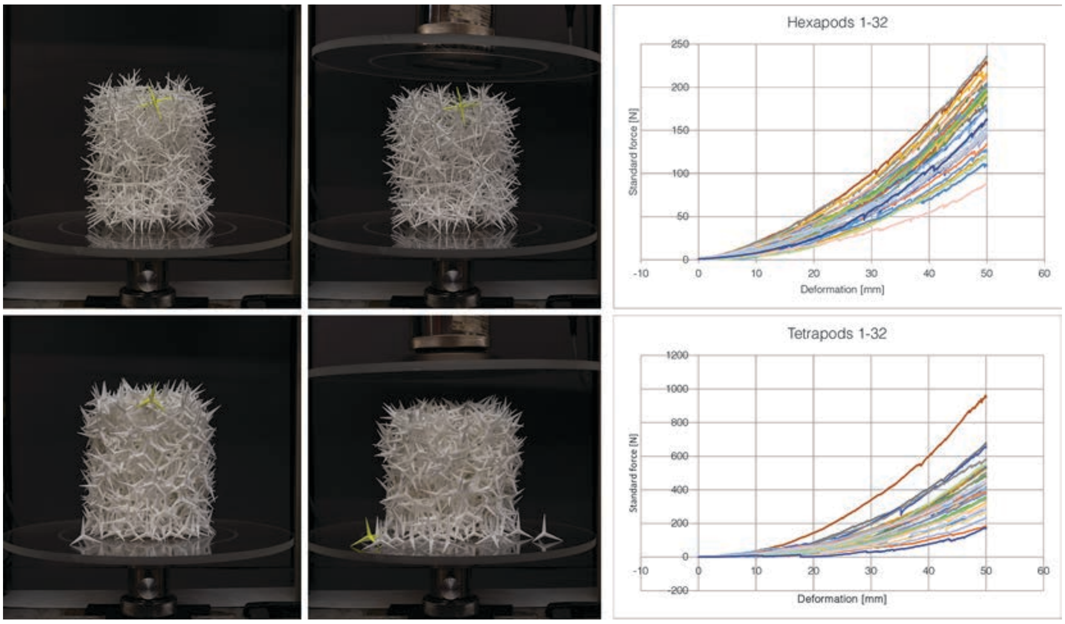

Figure 9.16: Compression tests of hexapods and tetrapods. Compression tests with 32 iterations each for hexapods of the type 50/6/20/0.5 (top row) and for tetrapods of the type 50/4/20/0.2 (bottom row) show that the tetrapods can take higher compressive loads. Karola Dierichs | ICD in collaboration with ITKE, University of Stuttgart | 2014–18

preparing the probes through vibration, yet a higher spread of probable material characteristics than one would expect in other construction materials is immanent in designed granular materials. With respect to an actual application, the minimal statistical values must be departed from in order to allow for a large safety margin.

9.1.2.3.3 Results for hypothesis 3

The hexapods have a minimum number of 3283 contacts, a maximum of 3376 and an average of 3341.45. The tetrapods have a minimum number of 3128 contacts, a maximum of 3239 and an average of 3182.15 (see figures 9.17 and 9.18). The amount of

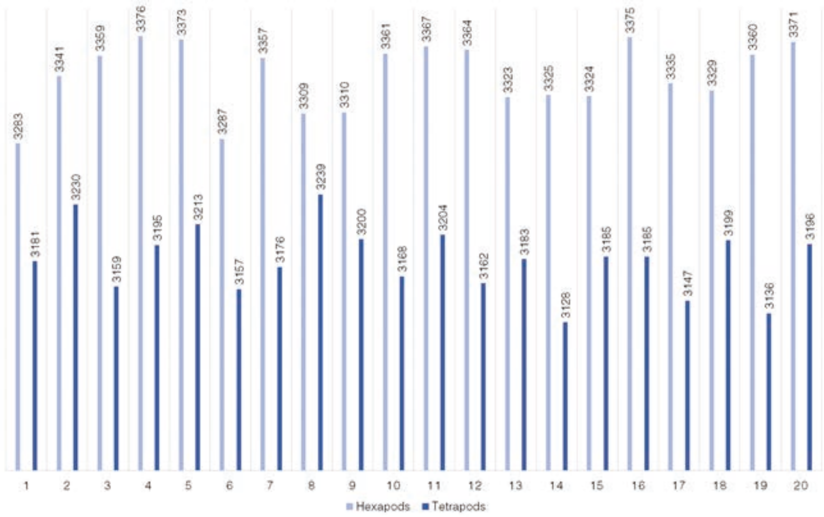

Figure 9.17: Amount of contacts in hexapods and tetrapods. Karola Dierichs with ITASCA Education Partnership (IEP) Research Program | ICD, University of Stuttgart | 2014–18

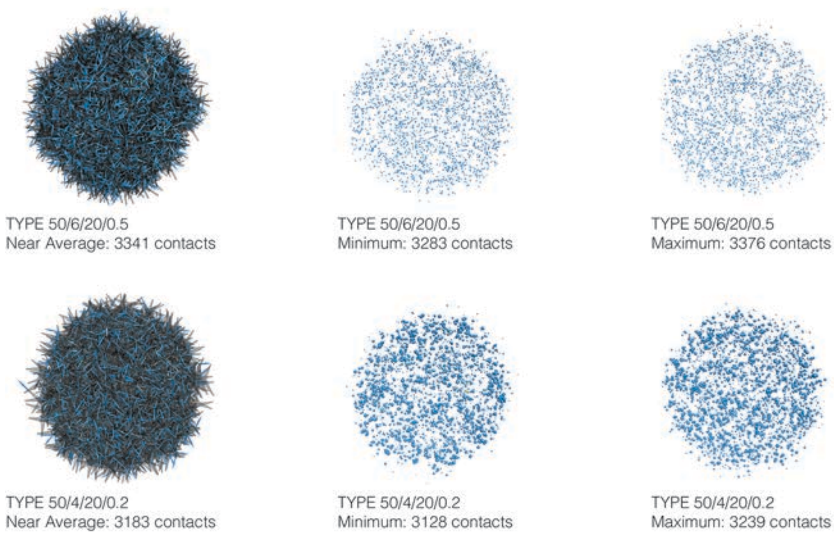

Figure 9.18: Simulation of contacts in hexapods and tetrapods. The contacts for the two particle types 50/6/20/0.5 and 50/4/20/0.2 are analysed using the discrete element method (DEM) in a statistical series. The renderings show views from above of, from left to right, the near average probe, the minimum and the maximum. The tetrapods have been scaled up 1.2 times in this graphic. Karola Dierichs with ITASCA Education Partnership (IEP) Research Program | ICD, University of Stuttgart | 2014–18

contacts is thus only slightly higher for the hexapods. The contacts seem to have different magnitudes and distributions, which could be the subject of relevant further investigations.

9.1.2.3.4 Summary of the results

Hypothesis 1 stated that arm amount and arm length affect the packing density, which has been proven true. An increase in arm length or arm amount reduces the packing density.

Hypothesis 2 stated that a difference in particle geometry changes the compressive strength of the designed granular material. This has been proven true, with the tested tetrapods being about 2.53 times stronger than the tested hexapods.

Hypothesis 3 stated that a difference in arm amount affects the amount of contacts in the granular materials. This has been proven only partially true for the simulated hexapods and tetrapods, the difference being only 159.3 more contacts in 1000 particles on average in the hexapods.

9.1.3 Summary and evaluation of case study 1

Case study 1 encompasses the development and realization of the ICD Aggregate Pavilion 2015 as well as the complementary statistical series in packing density and loading for particles with different geometries.

On the practical level, the contributions of the project included, firstly, the development of a designed granular material and the implementation of its ability to form vertical structures. Secondly, the construction and application of the cable-driven parallel robot can be considered one of the main practical advances of the project. Yet the relatively simple structural and spatial design, using five vertical columns, can be taken further in a future iteration, for example by applying vertical loads and horizontal enclosures, such as platforms, to the vertical structures or making hollow, accessible columns. Equally it would be beneficial to construct the entire structure with a cable-driven parallel robot, which mainly implies higher fixing points for the pulleys.

On the methodological level, the main contribution of case study 1 lies in the introduction of combining qualitative investigations into full-scale building applications with quantitative statistical test series. This might be an especially promising pathway if transdisciplinary work between architecture and granular physics is conducted. The basic principle will be taken on in the next case study. One point of further development would be the direct integration of the statistical results into the robotic construction process.

On the conceptual level, case study 1 can be discussed under the aspects that granular materials can be designed, reconfigured and recycled. With respect to the design of the granular material, case study 1 deploys a single granular material which is designed to have increased stability if compared to most naturally occurring, non-designed ones. Therefore, it allows a departure from a sloped angle of repose and allows the formation of structures with a 90-degree angle of repose. With respect to the reconfiguration of the granular material, case study 1 works with one state only: the columns did not change state once they had been poured in place. With respect to the recycling of the granular material, case study 1 is the initiating project of a series. The designed granular material is therefore new and not yet recycled from a previous installation.

9.2 Case study 2
ICD Aggregate Pavilion 2018

Project credits — *Authors:* Karola Dierichs, Achim Menges | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Research Assistants:* Christian Arias, Bahar Al Bahar, Elaine Bonavia, Federico Forestiero, Pedro Giachini, Shir Katz, Alexandre Mballa-Ekobena, Leyla Yunis, Jacob Zindroski | *Cable Robotics:* Ondřej Kyjánek, Martin Loučka | *Manufacturing:* Wilhelm Weber GmbH & Co. KG | *Funding:* GETTYLAB, ITASCA INTERNATIONAL Inc.

The main aim of the ICD Aggregate Pavilion 2018 was to explore the formation of spatial enclosures using designed granular materials (see figure 9.19). The project was realized over a period of circa nine months. It was situated inside an industrial hall, which had been converted into a single production space by attaching the cable-driven parallel robot to its walls.

Spatial enclosures are common to all granular materials due to an effect called clogging (see section 8.2.3.2.2). In case study 2 this phenomenon is enhanced through the use of two types of designed granular particles: a highly non-convex type, which interlocks, and a convex one, which has the ability to flow. With respect to the construction system, the cable-driven parallel robot constructed in the course of case study 1 was developed further: an interface is written, which allows the robot to be controlled through a parametric modelling software environment. Additionally, the "rated load" of the robot was increased and visual "sensory control" integrated in the system.

On the practical level of design, case study 2 introduces a designed granular system for the formation of spatial enclosures,

Figure 9.19: ICD Aggregate Pavilion 2018. In the ICD Aggregate Pavilion 2018 a designed granular material consisting of hexapods forms a full-scale double vault. Karola Dierichs | ICD, University of Stuttgart | 2018

which in terms of architectural design is an advancement from the basic vertical structures shown in case study 1. It is also the first full-scale structure, in the context of this thesis, which has been fully constructed by a robot. The storage boxes of the granular material were deployed as an "end effector" on the flange of the cable-driven parallel robot and were consequently deposited as a boundary container along the edges of the structure. In this manner the storage, production and containing boundary system also were never discarded but were instead entirely reused.

On the methodological level, case study 2 also uses statistical experiments and simulations as a complement to the case study.

On the conceptual level of design, case study 2 works on all three aspects of relevance for designed granular materials in architecture, which have been laid out in chapter 2.

9.2.1 Application

9.2.1.1 Integrated project

The ICD Aggregate Pavilion 2018 was developed in two phases. Phase 1 encompassed the investigation of construction techniques for arches, vaults and domes made from highly non-convex designed particles (see section 9.2.1.1.1). In phase 2 a full-scale vault structure made from highly non-convex particles was realized (see section 9.2.1.1.2). The following sections give an overview of the specific aspects developed in each of the two phases.

9.2.1.1.1 Project development

For the ICD Aggregate Pavilion 2018 the focus was placed mainly on the development of construction principles for arches, vaults and domes. Another key focus was the integration of new hardware and software features into the cable-driven parallel robot developed in case study 1. These two strands also involved planning the storage system of the particles. These development stages of case study 2 will be presented in the following sections.

9.2.1.1.1.1 Particle geometries

Two different particle geometries are combined in case study 2. The first one is the non-convex particle type 300/6/40/0.5, which has a convex hull diameter of 300 millimetres, an arm amount of six, an axis length of 150 millimetres and an arm taper of 0.5. This type has already been deployed for case study 1 (see section 9.1.1.2.1). These particles were originally assumed to have a packing density of circa 450 particles per cubic metre (see section 9.1.1.2.2). In practice, packing densities of up to circa 600 particles per cubic metre were observed. Most importantly for this project, they have the ability to interlock strongly, which allows them to form arches, vaults and domes.

The second particle geometry is a sphere, meaning that it is a convex particle. It has a diameter of circa 260 millimetres and a packing density of circa 65 particles per cubic metre. For this case study specifically, inflatables were used, which have the added value of a low transportation volume in comparison to the deployed volume. Yet the most relevant aspect of this particle type is its capacity to flow, which makes it an easily removable formwork for the arches, vaults and domes formed by the first particle type.

9.2.1.1.1.2 Storage

Both the non-convex and the convex particles are stored in Euroboxes. The non-convex particle type 300/6/40/0.5, which is a hexapod, is stored in Euroboxes measuring 420 by 600 by 800 millimetres. One box contains about 90 particles. The packing ratio is thus relatively small, but on the other hand the boxes still have a size which can be handled manually without cranes.

Spheres are stored in their deflated state, amounting to 500 particles in a flat Eurobox of 210 by 400 by 600 millimetres.

9.2.1.1.1.3 Arches

The structural type of an arch was chosen as an initial testing ground of construction principles which later allow for the formation of spatial enclosures in the form of vaults or domes.

Initial arch prototypes were constructed in 2013 as part of the seminar "Informed Matter – Aggregate Structure" conducted at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Two formwork principles were chosen: one with stacked boxes, one with balloons as a removable formwork.

The formwork made from cardboard boxes was 660 millimetres wide at the bottom and circa 545 millimetres wide at the top, with a height of 360 plus circa 360 millimetres. The formwork boxes were stacked on top of each other. Consequently, a container of boxes was formed around them leaving a gap. The hollow space between the container and formwork boxes was filled with circa 11250 ten-armed highly non-convex particles, hereafter referred to as decapods, with a convex hull diameter of circa 115 millimetres. The inner formwork boxes were removed by releasing a supporting bottom plate from underneath. The containing boxes were removed. Circa 450 particles flowed out upon removal of the bottom plate. An arch remained standing; its height could be increased by subtracting non-loadbearing particles.

The formwork made from balloons measured 660 millimetres in width on the bottom and circa 300 millimetres on the top. It was circa 700 millimetres high. The balloons were stacked and held in place by a thin foil. Cardboard boxes were stacked around as a container. The void spaces were filled with circa 8550 decapods with a convex hull diameter of circa 115 millimetres. A bottom plate was removed from underneath the balloons so that they could flow out of the structure. The containing boxes were likewise removed. Circa 225 particles flowed out after removal of the bottom plate. An arch remained standing and could further be increased in height by subtracting particles which were not load-bearing.

A second series of arch prototypes was conducted between 2014 and 2015 investigating different principles for formwork as well as different dimensions of the arch. In total ten different tests were carried out, which are presented in the following paragraphs. All prototypes use the same particle type, which is a decapod with a convex hull diameter of circa 115 millimetres (see figure 9.20).

Arch 1 deployed the basic principle of using particles of the same type as a formwork. In this construction process a bottom plate is removed from underneath the structure so that a funnel is formed (see section 8.2.3.2.2). The outer width of the prototype was 3850 millimetres, the height 1740 millimetres and the depth 1500 millimetres. The outflow hole was covered by two bottom plates measuring 1000 millimetres width and 1500 millimetres depth. A container made of cardboard boxes – the storage boxes of the particles – was placed around the cast. The side supports of the arch were cut at an angle in order to allow load transfer from the structure vertical to the supporting plane. The supporting planes were clad in textured foam to increase friction. Circa 43650 particles were poured into the container. After the containing boxes had been removed, the bottom plates were released at the same time from underneath. The prototype collapsed. A video analysis shows that the textured foam on the supports might have induced shear in the arch, which may have contributed to the failure.

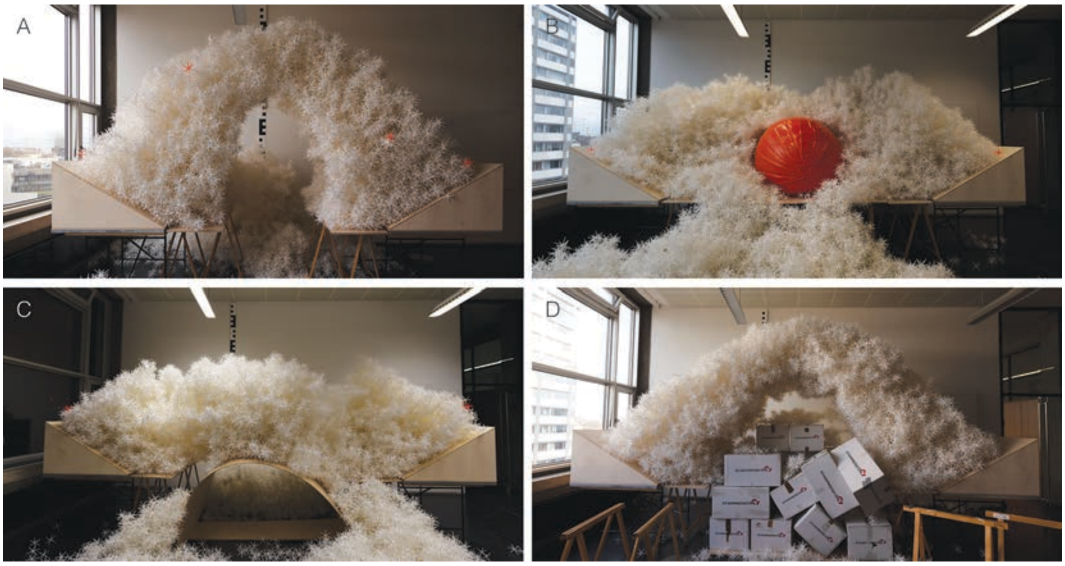

Figure 9.20: Arch prototypes. Arch 4 (A), arch 5 (B), arch 6 (C) and arch 7 (D) of the prototype series are shown directly after the release of the inner formwork. Karola Dierichs | ICD, University of Stuttgart | 2014

Arch 2 also deployed the principle of using particles of the same type as a formwork, where a bottom lid is removed from underneath a container of particles (see section 8.2.3.2.2). The outer width of the prototype was 3800 millimetres, the height 1680 millimetres and the depth 1500 millimetres. The width of the outflow hole was circa 2000 millimetres with two bottom plates measuring 1000 millimetres width and 1500 millimetres depth. The container was made from cardboard storage boxes. The same angled and foam-clad side supports as in arch 1 were used. Circa 50000 particles were poured in. The bottom plates were removed simultaneously from underneath the prototype after the containers had been removed. This prototype collapsed as well. A second video analysis shows that the textured foam on the supports might again have induced shear in the arch, which may have partly caused the failure.

Arch 3 was also based on the principle of using particles of the same type as a formwork (see section 8.2.3.2.2). The prototype measured 3830 millimetres in width, 1800 millimetres in height and 1500 millimetres in depth on the outside. In this case three bottom plates were used on the outflow hole: a middle plate measuring 1000 millimetres in width and 1500 millimetres in depth and two side plates with 500 millimetres in width and 1500 millimetres in depth. The container was again made from the storage boxes. The same supports with a tilted plane as in arches 1 and 2 were used, still covered in textured foam. An amount of circa 50000 particles were poured into the container. After pouring, the containing boxes were removed. In this case, the bottom plates were removed successively: first, the central bottom plate was lowered, about 1800 particles fell out and an arch remained standing; then, the arch was excavated over the remaining two plates, which were subsequently removed. Altogether circa 12600 particles were subtracted from the structure. The final arch after excavation had interior dimensions of 2000 millimetres in width, 900 millimetres in height and 1500 millimetres in depth.

Arch 4 used a one-piece formwork: a large spherical inflatable (see section 8.2.3.2.3). The prototype measured 3800 millimetres in width, 2110 millimetres in height and 1500 millimetres in depth on the outside. The inflatable had a diameter of 1500 millimetres in its inflated state. Removable bottom plates were placed underneath the inflatable, a middle one measuring 1000 millimetres in width and 1500 millimetres in depth and two side plates each measuring 500 millimetres in width and 1500 millimetres in depth. A container made out of the particles' storage boxes was formed around the inflatable. The same angled planes as in the previous prototypes were used as support, but this time the textured foam was removed. Circa 50000 particles were poured into the container and on top of the inflatable. The cardboard boxes were removed and the inflatable was deflated. An arch remained, which measured circa 910 millimetres in width, 750 millimetres in height and 1500 millimetres in depth. After subtracting particles from the structure, the inner dimensions of the arch were 1000 millimetres width, circa 1940 millimetres height and 1500 millimetres depth. The 1000 millimetre middle bottom plate could be removed. Upon further subtraction of particles from the structures, the prototype collapsed.

Arch 5 again deployed the construction principle of a one-piece formwork, a spherical inflatable as in arch 4 (see section 8.2.3.2.3). The outer dimensions of the prototype were circa 5000 millimetres width, 2200 millimetres height and 1500 millimetres depth. The inflatable had 1500 millimetres diameter after inflation. The container was made in the same manner from storage boxes as in the previous arches. The angled side supports were used without textured foam. All available particles, circa 50000, were used. The outer container was removed and the inflatable was deflated. The prototype collapsed upon deflation of the inflatable.

Arch 6 used a one-piece formwork, in this case a bent plywood sheet (see section 8.2.3.2.3). The prototype had roughly the same outside dimensions as arch 5, that is 5000 millimetres in width, 2200 millimetres in height and 1500 millimetres in depth. The plywood in its bent state measured 2000 millimetres in width, 1030 millimetres in height and 1500 millimetres in depth. The same containing boxes and angled supports without foam as in the previous arches were deployed. All available particles, circa 50000, were poured into the container on top of the bent plywood arch. The containing boxes were removed. The bent plywood arch was lowered from underneath the particles. The prototype collapsed.

Arch 7 used a mixed formwork strategy: the storage boxes were stacked on top of each other so as to emulate the intended arch geometry, then a container of boxes was formed around them. On the one hand this points towards a construction principle which uses a granular material consisting of another particle type with a different geometry as formwork for the remaining particles (see section 8.2.3.2.1). On the other hand it also emulates a one-piece formwork, as the boxes are stacked in a very precise and predefined geometry (see section 8.2.3.2.3). The prototype measured on the outside 4500 millimetres in width, 2300 millimetres in height and 1500 millimetres in depth. The boxes were stacked to form a triangular shape, which measured 2000 millimetres in width at its base, 1440 millimetres in height and 1500 millimetres in depth. The formwork boxes were supported by two middle plates measuring 1000 millimetres in width and 1500 millimetres in depth as well as two side plates measuring 500 by 1500 millimetres. Container and side supports were the same as in the previous arches. No textured foam was used on the supports. Circa 50000 particles were poured into the container and on top of the box formwork. The containing boxes were removed. Then, the inner box formwork was lowered from underneath the structure by removing the two supporting middle plates. An arch remained measuring 2010 millimetres in width, 1300 millimetres in height and 1500 millimetres in depth on the inside. On the outside the prototype dimensions were 4500 millimetres width, 1930 millimetres height and 1500 millimetres depth. After the release of the box formwork, particles were subtracted from the structure and the two side supports of 500 by 1500 millimetres could be removed from underneath the arch. After this excavation process, the inner dimensions of the arch were in width 3060 millimetres in the front and back, in height 1140 millimetres in

Figure 9.21: Arch 7. Arch 7 of the prototype series conducted between 2014 and 2015 deployed a formwork made from modular cuboids. Karola Dierichs | ICD, University of Stuttgart | 2014 [99]

the front and 1190 millimetres in the back, and in depth 1500 millimetres in the front and back. The outer dimensions were in width 4550 millimetres in the front and 4540 millimetres in the back, in height 1830 millimetres in the front and 1870 millimetres in the back and in depth 1500 millimetres in the front and back. Circa 4050 particles fell out on removal of the formwork boxes and circa 11250 particles were subtracted afterwards (see figure 9.21).

Arch 8 used the same construction principle as arch 7 with stacked boxes as an inner formwork, which is an approximation to using different particles as a formwork as well as deploying a one-piece formwork (see sections 8.2.3.2.1 and 8.2.3.2.3). The prototype measured on the outside in width 5050 millimetres, in height circa 2200 millimetres and in depth 1500 millimetres.

The boxes were stacked 1800 millimetres wide, 1440 millimetres high and 1500 millimetres deep. Container, bottom and side supports were the same as in arch 7. Circa 50000 particles were poured in. The outer container boxes were removed and the inner formwork boxes were lowered by removing the two middle plates from underneath. An arch remained standing, which measured on the inside in width 2000 millimetres, in height 1310 millimetres in the front and back and in depth 1500 millimetres. On the outside its dimensions were in width 5050 millimetres, in height 2190 millimetres in the front and 2090 millimetres in the back and in depth 1500 millimetres. During initial particle subtraction the arch collapsed.

Arch 9 used the same formwork principle of stacked boxes as arches 7 and 8, which refers to sections 8.2.3.2.1 and 8.2.3.2.3. The outer dimensions of the arch were 6000 millimetres width, 2470 millimetres height and 1500 millimetres depth. The formwork measured 2700 millimetres in width, 1800 millimetres in height and 1500 millimetres in depth. Container and side supports were the same as in arches 4 to 7. In the bottom, three plates measuring 1000 by 1500 millimetres were used in the middle and two plates measuring 500 by 1500 millimetres were used on the sides. An amount of circa 50000 particles were poured in. The containing boxes were removed and the supporting middle plates were lowered, upon which the prototype collapsed.

Arch 10 deployed the same formwork principle as arches 7 to 9 (see sections 8.2.3.2.1 and 8.2.3.2.3). It tried to repeat the setup and procedure of arch 7. Its outer dimensions were circa 5000 millimetres in width, circa 2215 millimetres in height and 1500 millimetres in depth. The boxes were stacked measuring 1990 to 2000 millimetres in width, circa 1440 millimetres in height and 1500 millimetres in depth. Container as well as bottom and side supports were done in the same manner as in arch 7. All available particles, circa 50000, were used for the prototype. After they had been poured in, the containing boxes were removed. The middle bottom supports were lowered so that the formwork boxes could be released and removed from the structure. The arch remained standing and its interior dimensions were in width 1980 millimetres in the front and 2010 millimetres in the back, in height 1000 millimetres in the front and 1250 millimetres in the back and in depth 1500 millimetres. The outer dimensions of the arch after box release were in width 5000 millimetres in the front and 5030 millimetres in the back, in height 1800 millimetres in the front and 2000 millimetres in the back and in depth 1500 millimetres. Particles were subtracted from the arch. After particle subtraction and removal of the remaining bottom supports, the inner dimensions were in width 3020 millimetres in the front and 3040 millimetres in the back, in height 1190 millimetres in the front and 1440 millimetres in the back and in depth 1500 millimetres. The outer dimensions were in width 5020 millimetres in the front and 5040 millimetres in the back, in height 1910 millimetres in the front and 1990 millimetres in the back and in depth 1500 millimetres. About 563 particles fell out upon box removal and circa 7200 particles were subtracted from the structure afterwards.

9.2.1.1.1.4 Domes

Departing from the investigations into construction principles for arches, as discussed in the preceding section 9.2.1.1.1.3, prototypes for domes were conducted, which turned the arch into a spatial enclosure.

A first series of domes was constructed during the 2013 seminar "Informed Matter-Aggregate Structure" conducted at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, the results of which have also been presented in section 9.2.1.1.1.3 in the context of arches.

Dome 1.1 was based on the principle of using the same particles as formwork, which also constituted the eventual remaining structure (see section 8.2.3.2.2). In order to implement this formwork principle, the elevated base of a container measuring 2500 by 2500 millimetres was constructed. It had an outflow hole of 750 by 750 millimetres. The storage boxes of the particles were stacked around the hole, to make a container with a width and length of 990 by 990 millimetres and a height of 900 millimetres around the covered outflow hole. The particles, decapods, were poured into the container. The bottom lid was removed. A dome formed over the outflow hole. Particles which carried no or very little load could be removed from the dome. Only an estimated 10 per cent of the overall mass of particles that had been poured in were structurally relevant to form the dome.

Dome 1.2 scaled up the previous experiment [101, pp. 5–6]. This means that it also used the principle of the same particles being formwork and structure (see section 8.2.3.2.2). The elevated base measured 3300 by 3300 millimetres with a covered outflow hole of circa 1300 by 1300 millimetres. The storage boxes were stacked around the outflow hole to make a 2280 by 2280 millimetres wide and long container with a height of 1350 millimetres.

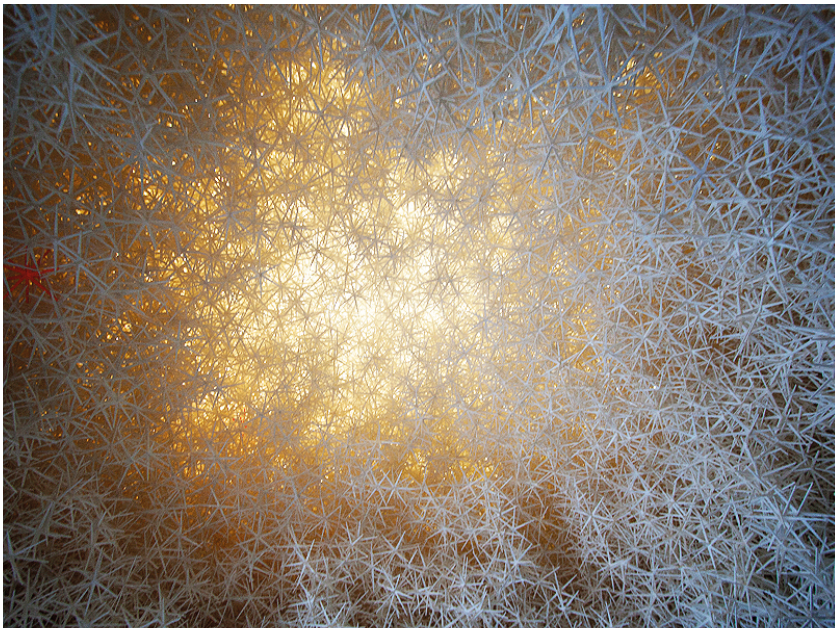

Figure 9.22: Dome 1.2. In dome 1.2 a stable dome formed over an outflow hole at the bottom of an elevated container filled with decapods only. Karola Dierichs | ICD, University of Stuttgart | 2013

Circa 50000 decapods were poured into the container. Upon removal of the bottom lid, circa 1800 particles flowed out and a dome formed over the outflow hole (see figure 9.22). After the formation circa 6300 particles were removed from below the dome, and circa 36000 from the top. Thus, the eventual remaining dome structure had circa 5400 particles. After further removal of 2250 particles the dome collapsed.

Dome 1.3 was conducted at a smaller scale than dome 1.2. It used the same formwork principle as dome 1.1 and dome 1.2, namely the same particles for formwork and structure (see section 8.2.3.2.2). Yet in this test the removal of particles from the final dome was conducted by air-pressure rather than by manual subtraction. This could provide a valuable quantifiable approach for

Figure 9.23: Construction sequence of dome 1.4. The construction sequence of dome 1.4 shows the principle of an elevated tank with an outflow hole at the bottom, which has a removable plate. In this case an inner formwork of boxes was deployed over the outflow hole. Karola Dierichs | ICD, University of Stuttgart | 2013

particle subtraction, since air-pressure can be related to the loads applied to the particles the air-stream is acting on. An elevated base measuring 2500 by 2500 millimetres with an outflow hole of 500 by 500 millimetres was set up. A container made from the particles' storage boxes was formed with dimensions of circa 900 millimetres height and circa 600 by 600 millimetres inner width and length. The particles, decapods, were poured into the container. The bottom lid was removed, and some particles flowed out until a stable dome formed. After that process, the unloaded particles were removed with an air-pressure pump to leave only circa 10 per cent of the material that had originally been poured in.

Dome 1.4 used storage boxes as a formwork in order to make the available volume larger. It was thus a combination of using different types of particles for formwork and structure and of using a one-piece formwork (see sections 8.2.3.2.1 and 8.2.3.2.3). A base platform measuring 4500 by 3500 millimetres was constructed at an elevated height of circa 750 millimetres. The dimensions of the outflow hole were 2500 by 1500 millimetres. The storage boxes were used to form an outer container with 2250 millimetres height and an inner space of 3300 millimetres length and 2580 millimetres width. Storage boxes were also used as an inner formwork: altogether 28 of them were stacked on top of the covered outflow hole to form a wider base and a slimmer top. Circa 50000 decapods were poured into the container on top of the formwork boxes. The base plate was lowered and the formwork boxes were removed from below. Circa 1350 particles flowed out before the structure settled into a dome (see figure 9.23). 4950 particles were manually removed from the inside. Circa 16650 particles were removed with an air-pressure of 9 bars from the outside. An additional rough count of 900 particles was removed by hand from the outside of the dome before the entire structure collapsed.

A second workshop on domes conducted in 2016 with the Integrative Technologies and Architectural Design Research (ITECH) Master Class at the University of Stuttgart investigated construction strategies that can work on a larger scale. The investigations from 2013 all relied on an elevated ground plane with a removable lid, which is a process that cannot easily be scaled up.

Consequently, one of the key aspects was to find construction principles that allow the structure to be built directly from the ground and the formwork to be removed from the sides of the structure.

Dome 2.1 used the principle of a one-piece formwork, which in this case was a spherical inflatable (see section 8.2.3.2.3). An inflatable with 1800 millimetres diameter was placed on the ground, and a smaller inflatable was placed in front of it to form a void for an entry. Circa 10000 particles of type 300/6/40/0.5 were manually placed on top of the inflatables (see section 9.1.1.1.1.2). No outer container was deployed in this process. The two inflatables were deflated: first the smaller one, then the larger one. A dome of 1800 millimetres diameter remained standing. Circa 2000 particles were manually removed until the dome collapsed.

Dome 2.2 also used inflatables as a formwork (see section 8.2.3.2.3). The main inflatable had a diameter of 2500 millimetres, and a smaller inflatable of 1800 millimetres was added to form an entry. No outer container was used. Circa 25000 particles of type 300/6/40/0.5 were manually added in steps of 300 particles on top of the inflatable (see section 9.1.1.1.1.2). First the smaller inflatable and then the larger one was deflated. The structure collapsed on deflation of the larger inflatable.

Dome 2.3 was based on deploying different particle types for formwork and structure (see section 8.2.3.2.1). In this case inflatable spheres with a diameter of circa 240 millimetres were used as a formwork for hexapods of type 300/6/40/0.5. A base container of 2500 by 2500 by 360 millimetres was constructed with storage boxes. The hexapods were manually laid in a ring inside the box container. The inside area of the ring was filled with the spheres. This process was repeated in several layers. The circles were made smaller per layer, so that an enclosed dome was formed. Circa 110 spheres were used in the process. After the dome was closed on top, an access point was formed in the containing ring and an outflow hole was formed in the hexapod layer. The spheres partially flowed out and partially were dug out from inside the dome of hexapods. Spheres which were stuck inside the hexapods could be removed by deflation. The dome remained standing.

Dome 2.4 was also based on using different particle types for formwork and structure (see section 8.2.3.2.1). It had the same set-up as the preceding dome 2.3, but had a base of 3000 by 3000 by 360 millimetres and used circa 200 spheres. As in the preceding test, in this experiment too the dome remained standing.

Dome 2.5 deployed boxes and spheres for the formwork and hexapods for the structure. It was thus a combination of the principles of a formwork using particles different from the main structure and of a one-piece formwork (see sections 8.2.3.2.1 and 8.2.3.2.3). Inflatable spheres with a diameter of circa 240 millimetres, boxes with the dimensions of 360 by 660 by 450 millimetres and hexapods of type 300/6/40/0.5 were used for the construction. An outer circle of containing boxes measuring 3500 millimetres in diameter by 360 millimetres in height was formed. Twelve boxes were stacked in the centre of this containing ring to have a diameter of 2000 millimetres at the base and a height of 1800 millimetres. The hexapods were laid along the outer containing ring and the gap between hexapods and inner box formwork was filled with spheres. The layers were laid in concentric circles of decreasing diameter to form an enclosed shape. Three boxes were removed from the containing ring and an outflow hole was made in the outer layer of hexapods. Spheres flowed out and the inner formwork boxes could be pulled out. A dome with 2500 millimetres diameter and 1800 millimetres height remained standing.

In summary, the dome prototypes showed that a wide range of construction techniques can be deployed. Overall, strategies that use small units as formwork are more successful than those using a one-piece formwork. Also, principles that deploy another set of particles – the same as or different from the main structure – are very favourable.

9.2.1.1.1.5 Container

Based on the preceding investigations on arches and domes, presented in sections 9.2.1.1.1.3 and 9.2.1.1.1.4, the storage boxes of the particles were used as a container for the entire structure of the ICD Aggregate Pavilion 2018, as described in section 8.2.3.1.1.

The Euroboxes were tied with customized u-shaped clips and corner braces. As a result, the sizing of the pavilion was based on the modules of the Euroboxes. In this specific case the box length of 800 millimetres was used in the x- and y-directions and the box width of 600 millimetres in the z-direction.

9.2.1.1.1.6 Cable-driven parallel robot - Iteration 2

The cable-driven parallel robot which was custom-built during case study 1 was further developed in case study 2. Three main new features were integrated: a custom interface was written, the "rated load" was increased and an observatory camera was installed in the construction area and incorporated into the construction process.

An interface was custom-written for the cable-driven parallel robot. The interface is open, thus allowing the robot to be controlled through a parametric modelling environment. Consequently, the data resulting from the design model can be directly sent from the modelling environment to the robot.

The "rated load" of the robot was increased from its previous 10000 grams to 20000 grams. This was achieved by doubling the cables through adding a winch in each of the four cables.

A camera was installed at the top of the robot's work space, which sent image data through a wireless connection to the robot's control computer. These image data can be used for simple observation and documentation, but also for "sensory control" through image recognition.

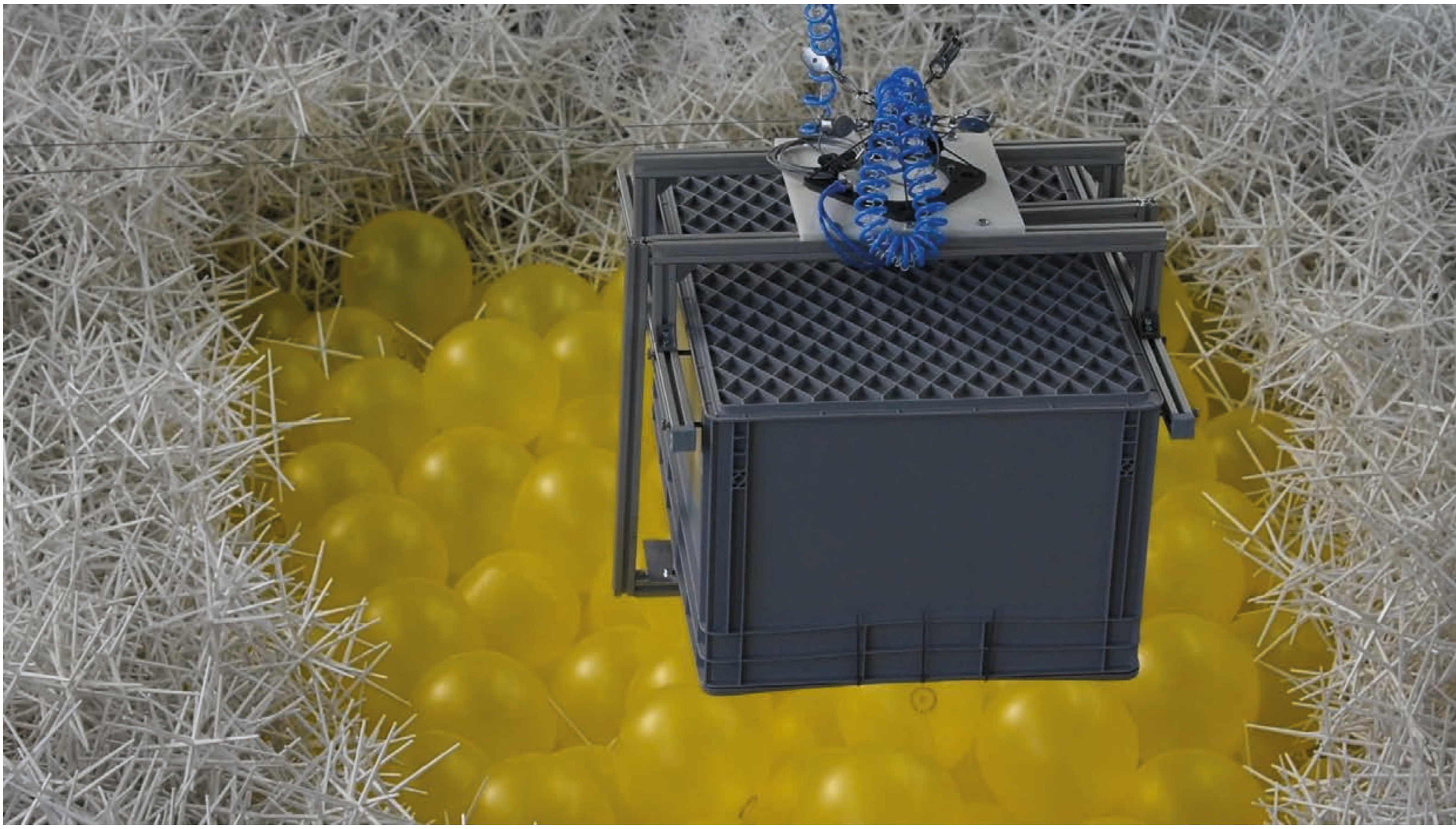

Figure 9.24: Box "end effector". A large storage box containing particles is fitted to the flange on the cable-driven parallel robot. A pneumatic gripper serves to release the particles from the box. Karola Dierichs | ICD, University of Stuttgart | 2018

9.2.1.1.1.7 "End effector"

One key aspect of the construction system is the fact that the particles are dumped directly from their storage boxes, which are in turn used as a container for the entire structure (see sections 9.2.1.1.1.2 and 9.2.1.1.1.5). The storage boxes become the "end effector". Two box sizes can be mounted to a frame that is fitted to the flange of the cable-driven parallel robot: a larger one measuring 420 by 600 by 800 millimetres and a smaller one measuring 320 by 400 by 600 millimetres. The fitting of the boxes was designed such that one frame holds both sizes, which is enabled by the fact that Euroboxes follow a modular metric system. The open and closed state of the boxes is controlled through a parallel pneumatic gripper (see figure 9.24). A range of tests was conducted in order to investigate the spacing of the drop points, the distancing of the "end effector" from the containing boxes as well as the difference in working with the large and the small storage boxes as "end effectors".

Test series 1: The total volume covered by test series 1 is 2400 by 2400 by 600 millimetres. The large box was used as an "end effector". The drop pattern was spaced at 300 by 400 millimetres. Altogether 35 drops were conducted. The boxes were filled entirely, yet the particles were not counted. As a result, the particles fell out slightly beyond the intended construction volume, requiring the containing boxes to be offset. Also, the spacing was so dense that the drops started to stack on top of each other as the robot moved line by line from left to right, leading to a higher mass towards the last deposition points.

Test series 2: Test series 2 aimed to cover a volume of 2500 by 2500 by 600 millimetres. Again, the large box "end effector" was deployed. The drop pattern in this case was spaced twice as widely at 600 by 800 millimetres. In order to test the resolution of the construction system, a cylinder of 200 millimetres diameter was used as a filter for the drop pattern grid: outside the cylinder hexapods were deposited, inside the cylinder, spheres were dropped. Two layers of ten boxes of hexapods and two boxes of spheres were dropped. The boxes of hexapods were filled entirely. The boxes of spheres were filled with ten particles in the first and with eight particles in the subsequent drops, due to clogging issues.

Since the drop grid was spaced more widely, an even distribution of hexapods could be achieved within the volume. The cylinder outline was very coarse, which indicated that curves need to be constructed at the finer resolution of the small box "end effector".

Test series 3: Test series 3 was conducted in the same volume as test series 2, namely 2500 by 2500 by 600 millimetres. Like in the previous tests the large box "end effector" was used. The drop pattern was spaced a little bit more closely at 400 by 600 millimetres. The cylinder of 200 millimetres diameter was again used as a filter between drops with hexapods and drops with spheres. 22 hexapod drops and two sphere drops per layer were conducted. Boxes with hexapods were lightly filled with two small boxes of 320 by 400 by 600 millimetres. Boxes with spheres were filled with eight particles. The hexapod drops were conducted over a string, which was intended to split and disperse the particles. The splitting string did not have the effect of dispersing the hexapods. Only four drops of hexapods altogether were conducted. Nevertheless, they were evenly distributed and the edges between drops were hardly recognizable.

Test series 4: Test series 4 was conducted within the design volume of the overall pavilion. Both large and small boxes were used as "end effectors". The goal was to test the drop pattern spacing for both "end effector" sizes, the particle count of hexapods per each box size as well as the average resultant layer thickness. For the drop pattern spacing two different box overlaps between each subsequent drop were tested: one of 100 and one of 200 millimetres. The particle count was tested at 40 to 50 particles for the large boxes and 20 particles for the small ones. Circa ten drops per box size with varying spacings were conducted.

As a result, the drop pattern for the large boxes was set at an overlap of 200 millimetres on the side of the opening lid and of 300 millimetres on the open sides of the box, resulting in a grid spacing of 400 by 500 millimetres. The layer thickness at a filling rate of 40 to 50 particles was 350 to 450 millimetres. In the later application, the overlap was set to 200 millimetres on all sides of the large box, resulting in a 400 by 600 millimetre base grid, and the particle count of hexapods per large box was reduced to 30. For the small boxes the overlap on the lid side was set to 100 millimetres and the overlap on the open box sides to 200 millimetres, making a drop grid of 300 by 400 millimetres. At 20 particles per small box the layer thickness was 200 to 300 millimetres. In the eventual application, the basic overlap between drop points was set to 200 millimetres on all sides of the small boxes, resulting in a base drop grid of 200 by 400 millimetres. The particle count of hexapods per small box was reduced to 15.

In conclusion, the storage unit of the particles becoming an "end effector" is one key aspect of the project. This allows a relatively fast and precise deposition of the designed granular materials at a construction scale. The non-convex particles of type 300/6/40/0.5 are mainly stored in the larger boxes that measure 420 by 600 by 800 millimetres. Therefore, the logic of using the storage unit as the "end effector" applies strictly speaking only to this box size. However, smaller boxes were required in this specific project: first, these offered a higher resolution of the poured geometry and were used for those areas of the structure where high definition was required; second, the smaller boxes had a lower weight and their use became necessary in the higher layers of the construction process after several load-induced failures using the larger boxes.

Thus, a consistent use of the storage device as the pouring device requires both higher "rated loads" of the constructing robot and potentially a larger scale of the structure for adequate resolution. Alternatively, areas of higher resolution can be constructed with smaller particles, which in turn justify smaller storage units. Ultimately the variables of particle size and packing volume, adequate box size, resulting overall load of the "end effector" and also the construction time depending on resolution of the drop points need to be calibrated for the project both as a whole and with respect to different zones within the structure itself.

9.2.1.1.1.8 Summary of the project development

In the project development phase, several aspects of the ICD Aggregate Pavilion 2018 were investigated separately.

Two particle geometries were introduced: a highly non-convex hexapod and a convex sphere. Euroboxes were chosen as a storage system for these particles. The selected box size was based on the particles' respective packing density and ease of handling. The choice of the two particle types was based on initial investigations of construction systems for arches, vaults and domes. These investigations resulted in the observation that a coupling of convex particles with highly non-convex particles is successful when the convex particles are used as a formwork for the highly non-convex ones.

The storage boxes become the container for these arches, vaults and domes, which also means that the sizing of these structures is based on the modules of the Euroboxes. The cable-driven parallel robot which was custom-built in case study 1 was developed with respect to its control interface, its "rated load" and its potential for "sensory control" through image recognition. The storage boxes are turned into an "end effector" by fitting them to the flange of the cable-driven parallel robot and controlling their open or closed state with a parallel pneumatic gripper.

9.2.1.1.2 Project realization

The ICD Aggregate Pavilion 2018 was realized between autumn 2017 and spring 2018. It was situated in a derelict industrial hall in Stuttgart, Germany, that had been converted into a construction space.

The following sections present the project in its integrated state. Initially the site and the installation of the cable-driven parallel robot on site will be presented. Then, the design model will be introduced. Lastly, the ICD Aggregate Pavilion 2018 is presented with respect to its robotic construction process and the final design.

9.2.1.1.2.1 Site

The construction site of the ICD Aggregate Pavilion 2018 was a former industrial hall. During the course of the project it served as a storage area for the designed granular materials as well as a full-scale in-situ construction setting and exhibition space.

Site constraints and influences were thus limited: access routes around the pavilion were the only parameter that needed to be considered.

In addition, the location of the entrance to the pavilion was chosen in close proximity to the storage area in the hall to allow fast handling of the convex particles during their removal from the structure. The four pulleys were fixed at 4824, 4798, 5215 and 5193 millimetres height directly to the walls and the supporting structure of the hall.

9.2.1.1.2.2 Cable-driven parallel robot on site

The cable-driven parallel robot was directly attached to the walls of the hall, turning the space into a construction plant (see figure 9.25). This was the maximum possible height in this specific

Figure 9.25: Cable-driven parallel robot installation 2. The cable-driven parallel robot was attached to the supporting structure of an industrial hall and equipped with a clustering box "end effector". Karola Dierichs | ICD, University of Stuttgart | 2017

location. Using the maximum height in any construction site to fasten the pulleys is advisable, since forces in the cables increase exponentially the flatter the angles between the cables and the horizontal plane between the pulleys become. This means that an increase in height of the fixing points entails an increased height at which a certain "rated load" can be handled by the robot. The total area in plan covered by the cable-driven parallel robot within the hall was an irregular polygon with edge lengths of 9694 by 11600 by 10038 by 11600 millimetres.

Within that the actual "safeguarded space", as defined in ISO/TC 299 [193, p. 16], of the cable-driven parallel robot was confined by two parameters: in z-direction the flange needed to remain circa 1000 millimetres below the pulleys to allow a safety margin; in x- and y-directions the access routes around the pavilion needed to be considered, leaving a polygon in plan with edge lengths of 5141 by 8397 by 5391 by 8392 millimetres.

A simulation of the forces in the cables shows that the "rated loads" are not distributed homogeneously in space. The "rated load" reaches higher z-values close to the pulleys and lower ones towards the centre of the robot's "working space".

9.2.1.1.2.3 Design model

In principle the design model implemented a goal geometry of a double-vault for the ICD Aggregate Pavilion 2018. During construction "sensory control" was used to adjust the structure in case it deviated from that goal geometry. The design model was developed in a parametric modelling software package. It encompasses the spatial geometry of the pavilion, its translation into deposition points for the clustering "end effectors", the path generation for the robot as well as the image segregation of the individual layers. The data generated in the design model were directly streamed to the cable-driven parallel robot's control interface. In the following paragraphs, the individual aspects of the overall design model will be introduced in detail. Both the considerations of the design and construction of the ICD Aggregate Pavilion 2018 and the translation of these considerations into a parametric model will be explained.

Spatial geometry: The geometry of the ICD Aggregate Pavilion 2018 consists of two intersecting vaults, which are embedded in a rectangular volume of highly non-convex particles. Vaults, which are essentially arrayed arches, were chosen as a structural type since they might allow load transfer along the short span of the structure rather than the long span, thus enabling a space measuring more than 5000 millimetres in length.

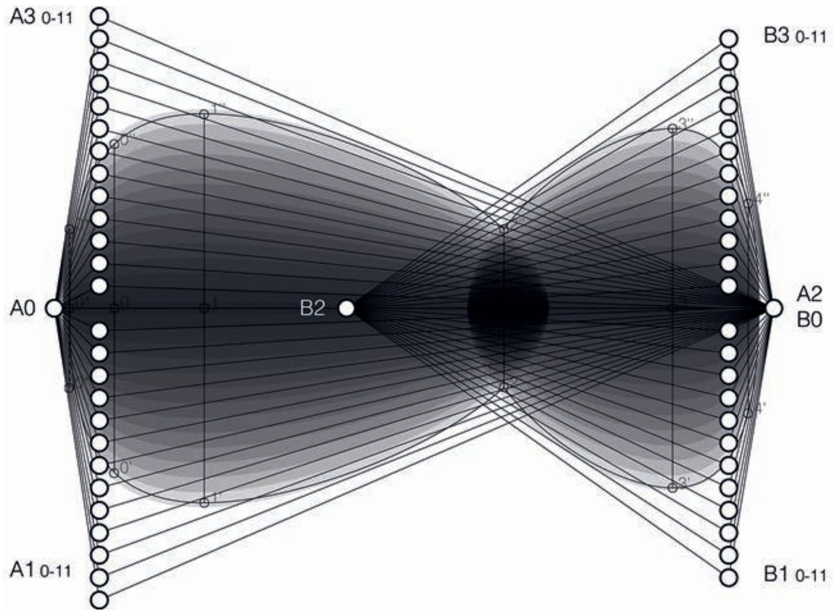

Figure 9.26: Design model of the ICD Aggregate Pavilion 2018. The design model is based on two nonuniform rational B-spline (NURBS) curves, of which the indices 0 and 2 remain fixed and the indices 1 and 3 are moved inwards as the pavilion increases in height. The measurement points 0 to 4 are indicated on the middle axis of the model. Karola Dierichs | ICD, University of Stuttgart | 2018

This assumption would need to be verified by a series of statistical simulations. Two closed planar nonuniform rational B-spline (NURBS) curves were set in a design point grid.

The curve with a larger area in plan was called space A, the smaller space B. Both space A and space B were controlled by four index points numbered 0 to 3 (see figure 9.26). The design grid for the curves was altered from 250 by 200 millimetres to 200 by 200 millimetres after the first layer. This was done in order to align it with the drop pattern. The indices for A1 and A3 as well as B1 and B3 needed adjustment and were set a bit further out than in the first model so that the next layer would have some material to rest on. Initially, the nonuniform rational B-spline (NURBS) curves for space A and space B had fixed point values for points 0, 1 and 3 to allow a defined wall thickness to be set. Point 2 was kept variable to define the intersection between the two spaces. Once the base layout of space A and space B had been defined, points 0 and 2 remained fixed and points 1 and 3 moved inwards as the robot moved up through each of the layers. This way a spatial enclosure was formed which had varying width and a constant length.

Deposition points: The deposition points were based on an intersection of the spatial geometry of the two nonuniform rational B-spline (NURBS) curves and the basic rectangular drop point grid. The deposition points defined the location where a specified filling was emptied from a specified box size. Altogether three different types of fillings were used in the pavilion construction: the main ones deployed were the non-convex particle type 300/6/40/0.5, a hexapod, and the convex spheres, but additionally decapods with a convex hull diameter of circa 115 millimetres were mixed in. These latter ones are an early form of non-convex particles and are not part of the series developed in section 9.1.1.1.1.1. Thus, they do not follow the same parametric logic. The decapods were merely used as a filler on the outside edges of the structure with the added benefit of a higher resolution to show a clean edge. Using the three fillings and two box sizes, four different plot styles were established: a small box with type 300/6/40/0.5, a large box with type 300/6/40/0.5, a large box with decapods gradually mixed with type 300/6/40/0.5 and a large box with spheres. The drop pattern for the small box with type 300/6/40/0.5 was derived from the intersection of the drop grid lines and the spatial geometry curves. It had the highest resolution. The drop patterns for the large box with type 300/6/40/0.5 and that for the large box with the decapods gradually mixed with

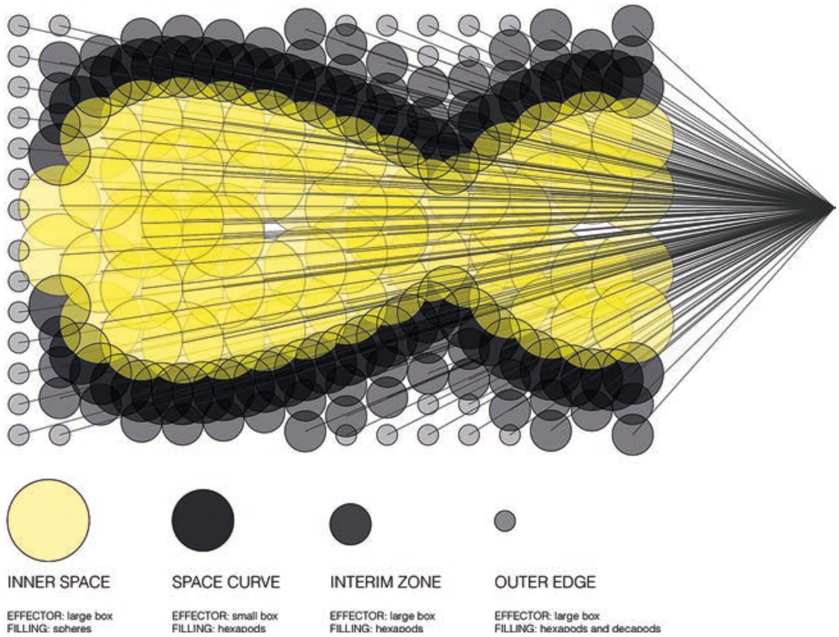

Figure 9.27: Deposition zones of the ICD Aggregate Pavilion 2018. Four deposition zones are defined: the inner space, the space curve, the interim zone and the outer edge. The first two are defined by the curve-geometry, the last two are distinguished using a range filter. Karola Dierichs | ICD, University of Stuttgart | 2018

type 300/6/40/0.5 used a range filter. This range filter mainly negotiated the drop points for the internal nonuniform rational B-spline (NURBS) geometry and for the outside rectangular grid (see figure 9.27).

Robot path generation: The paths were generated from a pickup point, a pickup offset point, a drop offset point and a drop point. Two pickup locations in the x- and y-direction were fixed, and the z-value was increased as the structure grew higher. The path directions were flipped, and both non-flipped and flipped paths were interwoven to allow the robot to travel back and forth.

Image segregation: Image segregation by colour was used to check the design model against the actual physical structure. The spheres were therefore chosen to be yellow, so that they could be filtered out from the white hexapods. A camera was installed on top of the structure, which allowed both still and time-lapse images to be taken (see section 9.2.1.1.1.6). Four basic interaction options of the design model with the physical structure were considered. These four options were evaluated according to two criteria: first, by the stability they could offer to the structure, departing from the paradigm that the more hexapods there are, the more stable the structure is, and the more spheres the less stable; and second, by the control they offer over the spatial geometry.

In option (i), spheres which are lying outside the line of the spatial geometry curves can be removed. This increases stability and control.

In option (ii), spheres instead of hexapods can be added onto spheres which are lying outside the line of the spatial geometry curves. This decreases stability and control.

In option (iii), hexapods which are lying inside the line of the spatial geometry curves can be removed. This decreases stability and increases control.

In option (iv), hexapods instead of spheres can be added onto hexapods which are lying inside the line of the spatial geometry curves. This increases stability and decreases control.

Since this was the first iteration of the construction system and the main goal was to explore a spatial enclosure, option (i) was chosen as it allows an increase in both stability and control and is relatively easy to implement. In the actual construction process, spheres were not removed but pushed back in and away from the spatial boundary curve. This is easier to implement than a removal, especially in the higher layers.

Option (iii), the removal of hexapods which are lying inside the boundary curve, would have further increased geometric control.

However, it was omitted as more hexapods do not endanger stability and hexapods cannot be sucked out or moved around as easily as the spheres.

Options (ii) and (iv), where geometric control is decreased, could be very relevant in future iterations of this construction system, if the exploration of emergent behaviour in the system becomes a design goal.

The image segregation is implemented by filtering out the yellow values of the convex particles from the images. These are checked against the spatial geometry curves. These decisions could also happen within an effective zone, instead of taking just the line of the spatial geometry curves between hexapods and spheres as the control input.

9.2.1.1.2.4 ICD Aggregate Pavilion 2018

The construction process of the ICD Aggregate Pavilion 2018 took place between autumn 2017 and spring 2018. The structure remained for documentation and viewing for a period of five months. In the following paragraphs, the intended project volumes, the robotic production process, the process of container and particle removal as well as the actual resulting spatial dimensions will be presented. An overview of the challenges encountered during the process will be given.

The calculated total inner volume of convex particles was 18.63 cubic metres, and the total outer volume of non-convex particles was 61.32 cubic metres. This means that the estimate for convex particles is circa 1211 with a packing density of 65 spheres per cubic metre and for non-convex particles it is 36792 with a packing density of 600 hexapods per cubic metre (see section 9.2.1.1.1.1). The entire pavilion was constructed with the cable-driven parallel robot. The following paragraphs will give an account of the

Figure 9.28: Construction process of the ICD Aggregate Pavilion 2018. The construction of the ICD Aggregate Pavilion 2018 was conducted over a period of several months between 2017 and 2018. It is in principle a layering process, where different designed granular materials are distributed by a cable-driven parallel robot in horizontal sections. Karola Dierichs | ICD, University of Stuttgart | 2018

construction process layer by layer followed by the total sum of particle counts and deposition points (see figures 9.28 and 9.29).

(i) In layer 0.0 the outer edges of the entire pavilion were marked with the cable-driven parallel robot. The location of the outer container resulted from that.

(ii) In layer 0.1 the marble gravel foundation was laid by driving the gravel bags to their deposition points with the robot and emptying them in that position. A total of 160 gravel bags each containing 15000 grams of marble gravel were deposited.

(iii) In layer 1 the first hexapods and spheres were dropped. The space curve geometry was laid with 186 drops of small boxes containing 15 hexapods each. 22 drops of large boxes containing 30 hexapods each were made in the interim zone. On the outer edge 55 boxes with 1000 grams of decapods were placed and about two large boxes were removed from the top afterwards to form an evenly levelled layer. In the inner space 102 drops of four spheres each were conducted, but the spheres spilled over into the hexapods. The drop pattern of the spheres was adjusted in the following layer to leave a larger offset from the hexapods. The image segregation in layer 1 was conducted using human eye checking of the top-view images and cross checking using the image segregation filter in the design model. In that mode, altogether 31 drops of 4 spheres each were removed in layer 1 in order to pertain to the spatial curve geometry established in the design model. Thus, a total of 71 times four spheres remained in layer 1.

(iv) Layer 2 had 126 deposition points with small boxes of 15 hexapods on the space curve. In this case particles were dropped twice in the same location. Large boxes of 30 hexapods were deposited in 70 points in the interim zone. 52 large boxes with a mix of one small box of decapods and 7 hexapods were deposited at the outer edge of the structure. Since the previous layer of spheres was quite high, no spheres were dropped in layer 2 in the inner space. Since no spheres were distributed, surveying through image segregation was not required in this layer.

(v) Layer 3 had 63 deposition points of small boxes with 15 hexapods on the space curve and 70 points with large boxes of 30 hexapods in the interim zone. 58 large boxes containing 50 per cent of a small box of decapods and 15 hexapods were dropped on the outer edge. 50 large boxes with 4 spheres each were deposited in the inside space. 18 spheres were removed based on the image segregation survey.

(vi) In layer 4 a total of 236 small boxes with 15 hexapods were dropped on the space curve. Here again, deposition points were repeated in order to gain sufficient layer height for a level top surface. 100 large boxes of hexapods were dropped in the interim zone. The outer edge was filled with 82 large boxes containing 25 per cent of a small box of decapods and 22 hexapods each. 34 large boxes of 4 spheres were dropped in the inside space. The image segregation rendered 24 survey points of outlying spheres. From this layer on, the survey points were marked with a laser pointer using the cable-driven parallel robot and consequently the spheres were pushed back inside the space curve of hexapods.

(vii) Layer 5 had 123 deposition points of small boxes with 15 hexapods on the space curve. In this layer as well, points were dropped on twice to reach sufficient height. 66 large boxes with 30 hexapods were placed in the interim zone. On the 48th point the motors failed due to high loads. After that the pickup and drop offset heights were lowered. The outer edge was filled with a total of 100 points. 90 of them still contained a fraction of circa 10 per cent of a small box of decapods mixed with 29 hexapods. Ten of them contained 30 hexapods. On the inside space of the structure 24 large boxes containing two spheres only were deposited. Here the sphere count was reduced as the sphere layer was relatively high. In layer 5 the image segregation survey resulted in no outlying spheres.

(viii) In layer 6 load-induced motor failure occurred during the initial deposition of the outer edges of the structure. This meant that after 21 drops of large boxes of 30 hexapods on the outer edge, the whole production was switched to the small box "end effector". Another 155 deposition points of small boxes with 15 hexapods were conducted on the outer edge. The space curve was laid with 61 points. The interim space was filled with 125 drops, where the grid pattern still followed the large boxes, but a small box "end effector" was used. 46 drops of small boxes containing one sphere only were deposited in the inner space. Layer 6 had 26 survey points for outlying spheres.

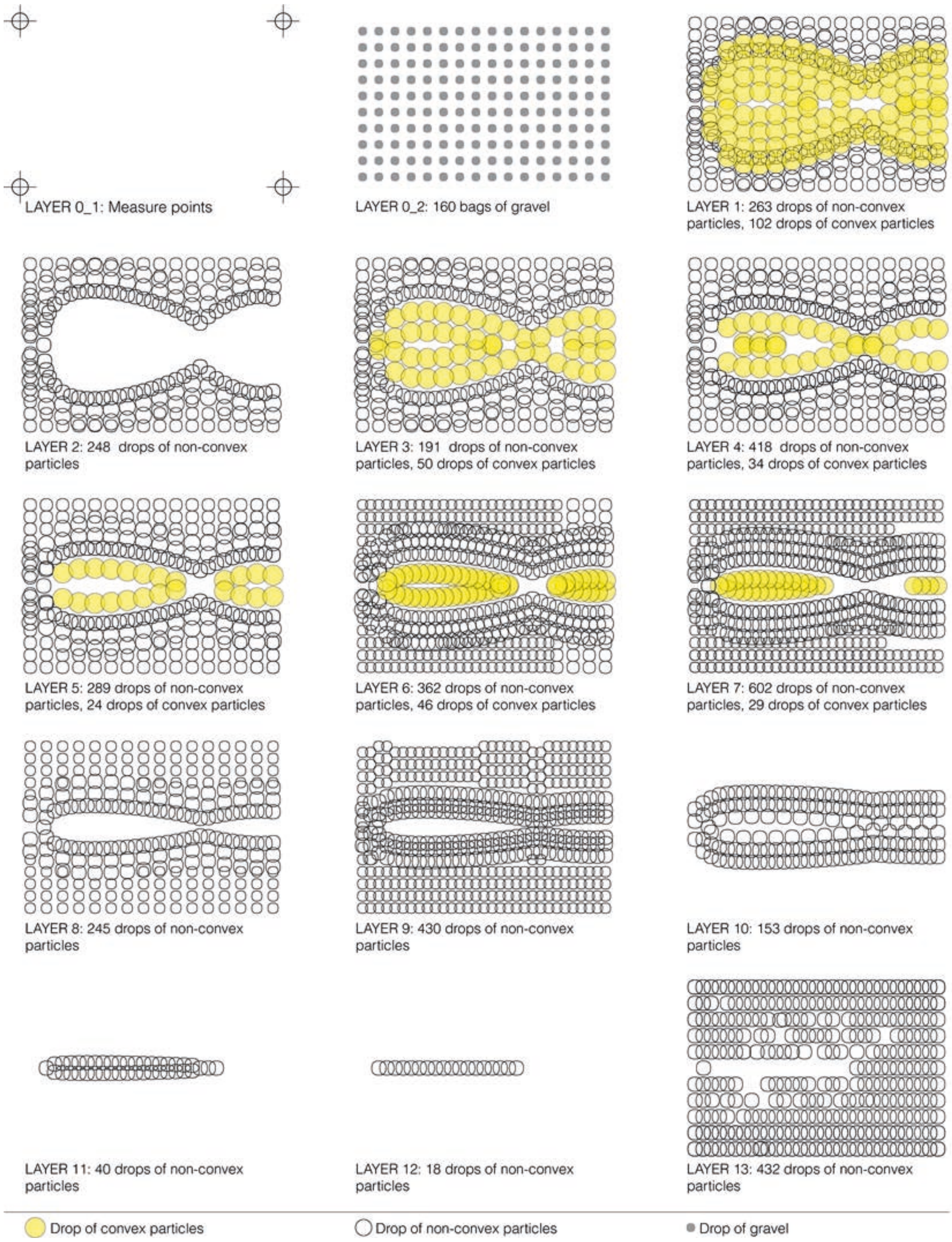

Figure 9.29: Layers of the ICD Aggregate Pavilion 2018. The ICD Aggregate Pavilion 2018 was constructed in 13 layers. The diagram shows the distribution and count of drops of non-convex and convex particles as well as the first two construction steps of measuring the site and laying the gravel foundation. Karola Dierichs | ICD, University of Stuttgart | 2018

(ix) Layer 7 had 118 deposition points of small boxes with 15 hexapods on the space curve. In the interim zone 183 small boxes of hexapods containing 15 particles were dropped. The outer edge of the structure was constructed with 301 drops of small boxes with 15 hexapods each. In the inner space 29 small boxes of one sphere each were deposited. In layer 7 there were 9 survey points of outlying spheres.

(x) In layer 8 the space curve was laid with 59 drops of small boxes with 15 hexapods each. The pattern for the outer edge and the zone filling was flipped by 90 degrees. Using this new pattern, 64 small boxes with 15 hexapods were placed in the interim zone between contour curve and outer edge and 122 on the outer edge. No spheres were deposited in layer 8 in the inner space. This also meant that no surveying through image segregation was required from this layer onward.

(xi) Layer 9 had 59 deposition points with small boxes of 15 particles on the space curve. The interim zone was filled with 125 small boxes of 15 hexapods and on the outer edge 246 were dropped. The drop grid pattern was flipped back to its original orientation. It was set to a dense spacing of 150 by 200 millimetres, yet this denser pattern was intended to be deposited in alternating columns between layers 9 and 10. However, since in layer 10 the edges were high enough, only the columns for layer 9 were dropped. In layer 9 no spheres were deposited in the inner space.

(xii) In layer 10 the space curve was laid with 30 small boxes of 15 hexapods and the interim zone was filled with 123 of them. The outer edge was relatively high already and was left out in this layer. No spheres were dropped in the inner space.

(xiii) In layer 11 only the space curve was laid with 40 small boxes of 15 hexapods. The interim space and outer edge were high enough and left out. In the inner space no spheres were dropped.

(xiv) In layer 12 as well only the space curve was laid with 18 small boxes of 15 hexapods.

(xv) In layer 13 the drop pattern was switched to a basic grid of 400 by 200 millimetres. In order to level the top of the structure, particles were deposited only in locations with lower height than their surroundings. 398 small boxes with 15 hexapods and 34 with ten hexapods were dropped.

In total 160 bags of 15000 grams of gravel, circa 67593 hexapods, circa 49550 decapods and circa 725 spheres were deposited in the structure. A total path length of 22041186.143 millimetres was covered. This means that the production time calculated by path length alone amounts to circa 124.65 hours.

Once the pouring had been completed, the removal of material from inside the structure as well as that of the containing boxes took place in two stages. In the first stage of excavation the middle front row from the outer box container was removed so that the spheres could flow out. In this first step of excavation, circa 625 spheres came out of the structure, and 118 remained stuck inside the non-convex hexapods. Circa 329 hexapods and 18 decapods fell out of the structure during this process. Measurements were taken using the key control points in the middle axis of the design model (see figure 9.25). The measurements of this excavation stage were conducted 20 days after completion. At point 0 the width was circa 1440 millimetres, the height circa 2100 millimetres, at point 1 the width was circa 1995 millimetres and the height circa 1820 millimetres, at point 2 the width was circa 1080 millimetres and the height circa 1390 millimetres, at point 3 the width was circa 1475 millimetres and the height circa 1665 millimetres and at point 4 the width was circa 800 millimetres and the height circa 1740 millimetres. A second stage of excavation encompassed the removal of all spheres from the inside as well as the enlargement of the intersection zone between the two spaces. In this stage of excavation, circa 1183 hexapods and 47 decapods were removed from inside the structure. The aforementioned 118 spheres were extracted from the hexapods, partly through deflation. Immediately after this second excavation process, the containing boxes were removed from the outside. Circa 90 hexapods and one decapod fell out mostly at the corners of the structure. After this second excavation stage measurements were taken 21 days after completion. At point 0 the width was circa 2610 millimetres, the height circa 2100 millimetres, at point 1 the width was circa 2530 millimetres and the height circa 2110 millimetres, at point 2 the width was circa 1080 millimetres and the height circa 1600 millimetres, at point 3 the width was circa 1760 millimetres and the height circa 1750 millimetres and at point 4 the width was circa 800 millimetres and the height circa 1770 millimetres.

In summary, the overall production process can be considered successful, given that it allowed construction in situ and at full scale with good geometric precision and "sensory control" of the production process through image segregation. The main challenge during construction was the relatively low "rated load" of the cable-driven parallel robot, which forced the production to be completed with small boxes from layer 6 onward. This meant that production was roughly twice as slow than using large boxes for the interim zone between contour and edge and for the outside edges. Thus, it would be more efficient to work with even larger containers than the large Euroboxes of 420 by 600 by 800 millimetres in the outer zones of the structure, where high geometric precision is not required. A higher "rated load" would thus allow the "end effector" to be used for different resolutions more strategically.

More hexapods and fewer spheres than initially calculated were required. This might be due to a generally higher packing density caused by self-compaction through increased mass and by the compression of spheres especially in the entrance zone of the pavilion, where the ratio of hexapods to spheres was higher than in the inner space. The expected count of spheres was roughly 1211, the actual count was 725. The estimate for hexapods was circa 36792, the actual count was 67593, and circa 74586 if the volume of decapods is included.

Image segregation was conducted only by visual and manual correction of the curve in layers 1 to 3. From layer 4 onward this process is half-automatized by driving a laser pointer with the robot to the points where spheres need to be pushed in. Inaccuracy has been shown in matching the image-generated data and the physical structure. This might mainly be due to the flattening algorithm and the cropping of the image (see figure 9.30). Furthermore, tuning the red, green and blue (RGB) values and using a blurring effect on the image data might help to correct errors.

The excavation process was conducted manually. If this process were also automatized, for example using erosive processes as described in section 9.2.1.1.1.4, this would allow a more refined, repeatable and quantifiable approach towards the removal of particles. In line with an automatized excavation, it would also be relevant to more clearly distinguish the different excavation phases between the flowing out of spheres, the taking out of spheres, the excavation of unloaded hexapods and the excavation of loaded hexapods. More refined measuring of the excavation process could be conducted using techniques that allow monitoring of deformation, as has been initiated in collaboration with the Institute for Engineering Geodesy in 2014 [113; 315]. The overall goal on the practical level of design was the formation of spatial

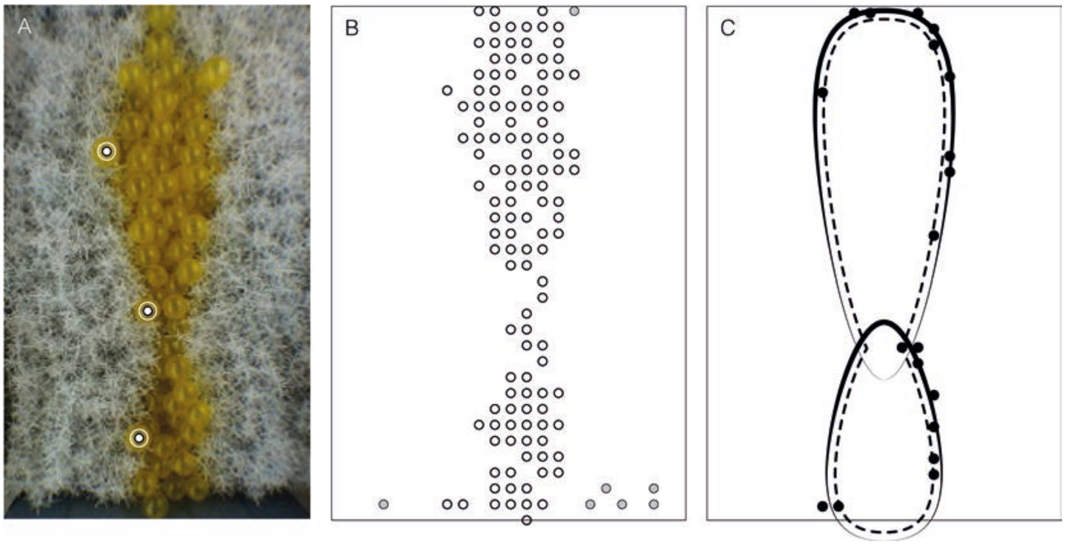

Figure 9.30: Image segregation. The image segregation shown on the example of layer 6 comprises the recording of the image data (A), the filtering of the yellow values (B) and the comparison of these values to the curve geometry and its offset (C). In (A) those spheres are highlighted which have not been recognized by the yellow filter, in (B) those points which are filtered and are not spheres are marked in grey. Karola Dierichs | ICD, University of Stuttgart | 2018

enclosures, which was successfully achieved. The obvious next step would be an increase in scale, which would primarily require a larger "working space" of the production system. The principle of using spheres as the temporary formwork for the permanent structure of hexapods has proven to be successful and appears to be robust enough to increase the spatial dimensions.

9.2.1.1.2.5 Summary of the realized project

Case study 2, the ICD Aggregate Pavilion 2018, is the second of two case studies. The entire project was constructed inside an industrial hall (see section 9.2.1.1.2.1). The cable-driven parallel robot, custom-built for case study 1, was further developed and installed in situ on the walls and the supporting structure of the hall (see section 9.2.1.1.2.2). A design model for a double-vault was developed, that integrated the spatial geometry, the deposition points for the "end effector", the robot path generation and the image segregation for "sensory control" (see section 9.2.1.1.2.3). The ICD Aggregate Pavilion 2018 was entirely constructed using a cable-driven parallel robot. It demonstrates how a human-scale spatial enclosure can be formed by designed granular materials (see section 9.2.1.1.2.4).

9.2.1.2 System categories

Like the ICD Aggregate Pavilion 2015, the ICD Aggregate Pavilion 2018 integrated a range of the categories of the design system, which have been outlined in chapter 8. The following sections will present both the primary and the secondary system categories which are relevant for this specific project. Primary system categories are essential for the overall relevance of the case study. Secondary system categories are deployed within the project yet are not part of its core argument. The primary system categories thus highlight the key aspect of the ICD Aggregate Pavilion 2018, which is the combination of two designed granular materials, one consisting of highly non-convex particles and one consisting of convex ones.

9.2.1.2.1 Primary system categories

The primary system categories which become relevant in case study 2 are convex particle geometries (see section 8.1.1.1.2.1), non-convex particle geometries (see section 8.1.1.1.2.2), industrial robots (see section 8.2.1.1), a clustering "end effector" (see section 8.2.1.2.2) and the use of different types of particles as formwork for the remaining structural particles (see section 8.2.3.2.1). The subsequent paragraphs summarize the most important aspects of these primary system categories.

Convex particle geometry (see section 8.1.1.1.2.1): In case study 2, two particle types are used: a convex and a highly non-convex one. The convex particle geometry of the first type enables the part of the structure that is constructed with these particles to flow easily out of the structure. It acts as a reconfigurable formwork. The convex particle geometry in this case is a sphere with a diameter of circa 260 millimetres. Given that inflatables are used, the packing volume is smaller than the deployed volume (see section 9.2.1.1.1.1).

Non-convex particle geometry (see section 8.1.1.1.2.2): The second particle type is highly non-convex. This geometry allows the particles to interlock and thus form stable vaults and domes. The specific particle mainly used in this case study is a six-armed particle, a hexapod of the type 300/6/40/0.5, which has a convex hull diameter of 300 millimetres, an axis length of 150 millimetres and an arm taper of 0.5. For an in-depth description of the model (see section 9.1.1.1.1.1). A small amount of decapods is mixed in at the edges of the structure to gain additional volume and resolution.

Industrial robots (see section 8.2.1.1): With respect to construction systems, the further development of the cable-driven parallel robot established in case study 1 has again been key to the project's realization. This is due to the fact that the ICD Aggregate Pavilion 2018 could only be installed in situ. Thus, a robotic system with a suitable potential "working space" of circa 13484 by 13484 millimetres in plan and an increased "rated load" of 20000 grams was crucial. "Path" and "position" "accuracy" and "repeatability" were sufficient for the task.

Clustering "end effector" (see section 8.2.1.2.2): The "end effector" in this case study can be classified as a clustering "end effector". In this case it is the storage box of the particles which is mounted to the flange of the cable-driven parallel robot. This "end effector" type is relevant, since it turns the storage system into the construction tool. The precision is high enough for the task at hand. Two box sizes allow for pouring at a higher or lower resolution (see section 9.2.1.1.1.7).

Different types of particles as formwork (see section 8.2.3.2.1): Case study 2 at its core uses designed granular materials consisting of different types of particles, where one is performing as the formwork for the other. Specifically, a designed granular material consisting of convex particles is used as the formwork for one consisting of highly non-convex particles. The advantages are twofold. First, this formwork principle allows a very high geometric flexibility in the distribution of the formwork particles and consequently the resulting spaces. Second, it appears that using granular materials as a formwork is more successful than deploying one-piece formwork systems. This latter observation needs to be verified by comparative statistical experiments and simulations.

9.2.1.2.2 Secondary system categories

The secondary system categories integrated in case study 2 are the dimension of the particles (see section 8.1.1.1.1), non-variable particle geometries (see section 8.1.1.1.3.1), the mechanical properties of the particles' material (see section 8.1.1.2.1), particle mixes (see section 8.1.2), "sensory control" (see section 8.2.1.3.2), globally effective construction systems (see section 8.2.2) and the use of modular cuboids as a boundary system (see section 8.2.3.1.1). The subsequent paragraphs compile the most important aspects of these secondary system categories.

Dimensions of the particles (see section 8.1.1.1.1): The dimensions of the two main particle types – the highly non-convex hexapods and the convex spheres – were chosen to be roughly the same. The two granular materials could thus be layered without slipping into each other. The same non-convex particle type as in case study 1 was used, which has a convex hull diameter of 300 millimetres. Thus, the spheres were chosen to have a diameter of 260 millimetres. Since the latter were bought from industrial stock, the dimensions could not be exactly customized. A set of highly non-convex particles with a smaller convex hull diameter of circa 115 millimetres was used on the outside bottom layers of the structure. Initially these particles were merely used to gain extra volume, but this size grading can be a relevant strategy to further increase stability as outlined below in the paragraph on particle mixes.

Non-variable particle geometry (see section 8.1.1.1.3.1): All particles have a non-variable geometry. Like case study 1, case study 2 also aims at establishing fundamentals, in this case on the use of highly non-convex particles in combination with convex ones to form spatial enclosures. The focus was thus on working with non-variable particle geometries only. The highly non-convex particles were made from recycled polystyrene plastic. This does not vary its behaviour in relation to changes in ambient conditions. The convex particles were made from polyvinyl chloride (PVC) foil.

Mechanical properties of the particle material (see section 8.1.1.2.1): The inflatable spheres were made from polyvinyl chloride (PVC) foil and the hexapods from a recycled polystyrene. For the spheres, the advantages of using inflatables was their low packing density and lightness. Being a thin foil, they were also deformable, which for formwork particles was a viable option. The effects of the deformation on the behaviour of the overall granular material needs to be analysed using simulations. The hexapods were stiff due to their material makeup. This was necessary since they were structural elements.

Particle mixes (see section 8.1.2): The two main particle types – the highly non-convex hexapods and the convex spheres – were not mixed but only layered in this case study. Mixing them would not allow for the spheres to act as a space-defining formwork for the hexapods. Altogether, the highly non-convex particles made up 91.8 per cent of the structure and the spheres made up 8.2 per cent. However, for the decapods, a mixing strategy was deployed in order to form a gradient transition from decapods only in the first layer to hexapods only from the sixth layer. For that purpose, decreasing numbers of decapods were mixed with increasing numbers of hexapods between layers two and five of the structure. In this case study, the strategy of grading two highly non-convex particle types was primarily chosen for visual reasons. However, it can be further explored in terms of its repercussion on other architectural performance criteria, such as stability or light permeability.

"Sensory control" (see section 8.2.1.3.2): Case study 2 used "sensory control". This is a relevant feature of the construction system as it allows the correction of the poured geometry after each layer. The image segregation algorithm colour-filtered the convex spheres which were beyond the geometry of the space curve. The process in this case study was only partially automated. Yet, if an extra "end effector" for the removal or redistribution of spheres were developed, the process would be fully automated.

Globally effective construction systems (see section 8.2.2): Globally effective construction systems were not deployed in this case study. However, the use of vibration in the form of shakers applied to the boundary container might be a highly effective manner of further solidifying the structure.

Modular cuboids (see section 8.2.3.1.1): The storage boxes of the particles were used as a boundary construction system for the ICD Aggregate Pavilion 2018. Although most likely not strictly necessary for stability, the boxes allowed for a straight edge and were used in this first full-scale application as an extra safety measure. The boxes were secured between each other with u-shaped clips. The edges were fixed with braces from the same u-profiles which were customized into corner-pieces.

9.2.1.2.3 Summary of the system categories

The previous sections have introduced the primary and secondary system categories of the designed system established in chapter 8, which were deployed in case study 2.

The primary system categories describe the two key particle geometries, which are convex and highly non-convex particles. Derived from that the system category of using different particle geometries as formwork is a key factor in the project (see section 9.2.1.2.1). The in-situ construction with a cable-driven parallel robot in combination with a clustering "end effector" – the storage box of the particles – are the primary system categories with respect to construction systems (see section 9.2.1.2.1). The secondary system categories are not key factors in the argument of the project, but do support its realization (see section 9.2.1.2.2).

9.2.2 Statistics

The statistical tests conducted for case study 2 aimed to establish first principles on how a designed granular material from convex particles can serve as a formwork for one consisting of highly non-convex particles. The following sections will outline the hypotheses, methods and results of the two statistical series conducted for case study 2.

9.2.2.1 Hypotheses

9.2.2.1.1 Hypothesis 1

If hexapods are poured over a formwork of spheres, the spheres can be removed and the hexapods can form spatial enclosures, such as arches, vaults or domes.

9.2.2.1.2 Hypothesis 2

If particle contacts in spheres and hexapods are compared, the convex spheres have less contacts than the non-convex hexapods.

9.2.2.2 Methods

9.2.2.2.1 Methods for hypothesis 1

The experiment series was based on the construction of arches. The outer dimensions of the arches were 300 millimetres in height, 410 millimetres in width and 130 millimetres in depth. The inner dimensions of the arches were 347 millimetres in width and 234 millimetres in height. They thus had the same proportions at a 1 to 10 scale as the largest span in the ICD Aggregate Pavilion 2018.

The hexapods of type 50/6/20/0.5 introduced in section 9.1.2.2.1 were used as the structural particle type. Altogether circa 1274 hexapods were used with a total weight of 586.1 grams. Spheres with a diameter of circa 40 millimetres were used as the formwork particle type. Other than in the ICD Aggregate

Pavilion these were not deformable. Circa 82 spheres were deployed with a total weight of 183.84 grams. The hexapods were proportionally circa 1.7 times larger than in the ICD Aggregate Pavilion 2018 and the spheres were 1.5 times larger in proportion. Marble gravel was used as a base layer weighing 1418.5 grams.

The experiment series thus had two scale factors: one of the overall arch dimensions and one of the particle size in relation to the size of the structure. The behaviour of the system thus might differ from the full-scale implementation, and a more profound statistical validation would need to be conducted with arches constructed on the one-to-one scale. However, previous experience from experiments conducted during the preparatory phase mainly presented in appendix A shows that granular behaviour is relatively self-similar across scales. Furthermore, it can be assumed that a scaling down of particle size towards size of the structure is more favourable than the inverse, since contact numbers increase, which is the case in these experiments.

The experiments were conducted using a container with the inner dimensions of 300 millimetres height, 410 millimetres width and 130 millimetres depth. The layout pattern for the hexapods and the spheres was marked on the container side walls indicating an arch.

The marble was poured into the container as a base layer. Subsequently the hexapods and the spheres were laid in layers into the container following the markings on the side walls. The container was removed by pulling it up at the top so that the formwork particles could flow out. The spheres which remained in the arch, as well as the hexapods that had dropped out of it, were counted. The experiment was repeated 20 times.

9.2.2.2.2 Methods for hypothesis 2

Hypothesis 2 was verified using simulations based on the discrete element method (DEM). The simulation model was laid out with a linear contact model. The material values were results of previous research conducted on the same hexapod particles [381; 101]. The same material values were assumed for the spheres in order to establish an even basis of comparison.

The particle of type 50/6/20/0.5, a hexapod, was modelled as a clump, meaning that spheres were rigidly connected to emulate the particle geometry [101]. The spheres had a diameter of 50 millimetres and were modelled with a single sphere.

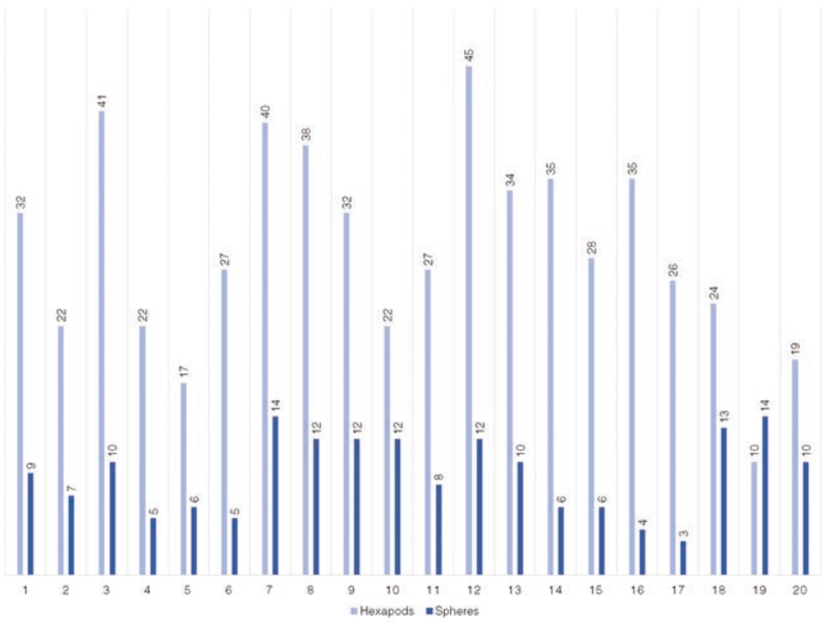

Figure 9.31: Amount of hexapods falling out of the arch and of spheres remaining in it. Karola Dierichs | ICD, University of Stuttgart | 2018

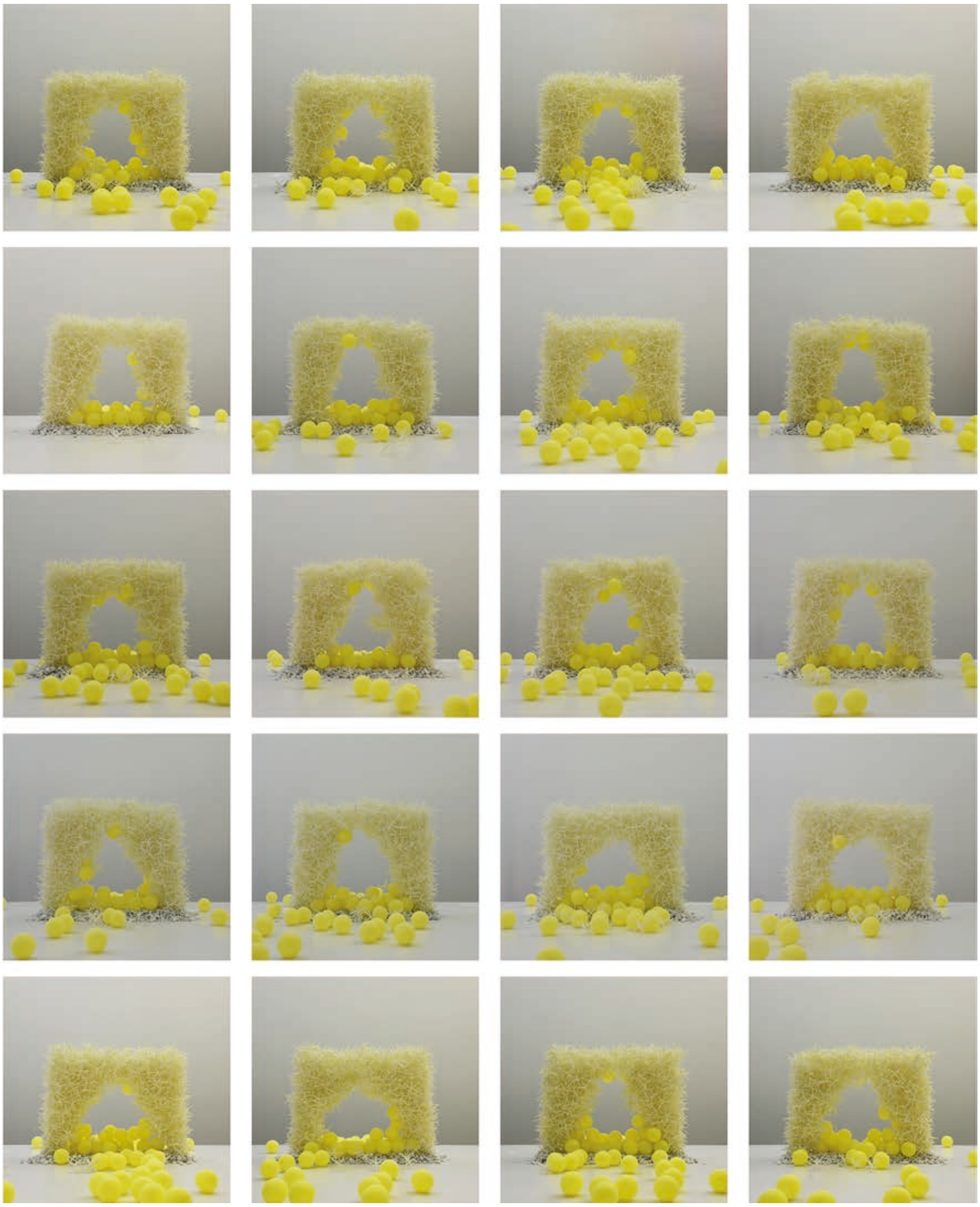

Figure 9.32: Stability tests of arches. Arches corresponding to the widest span of the ICD Aggregate Pavilion 2018 were tested at a 1:10 scale in a repetition of 20. Karola Dierichs | ICD, University of Stuttgart | 2018

1000 particles of each type were simulated falling into a cylinder until a specified state was reached. The diameter of the cylinder was chosen so that width and height of the simulated particles at the end of the simulation were approximately the same. Each particle type was simulated with 20 repetitions and the amount and distribution of the contacts were recorded.

9.2.2.3 Results

9.2.2.3.1 Results for hypothesis 1

All arches remain standing (see figures 9.31 and 9.32). A minimum of three and a maximum of 14 spheres remained in the structure after the formwork removal. On average nine spheres did not flow out. A minimum of ten and a maximum of 45 hexapods fell out of the arch. On average 29 hexapods dropped out.

9.2.2.3.2 Results for hypothesis 2

The hexapods had a minimum number of 3283 contacts, a maximum of 3376 and an average of 3341.45. The spheres had a minimum number of 2125 contacts, a maximum of 2168 and an average of 2149.1. The amount of contacts was thus significantly higher for the hexapods (see figures 9.33 and 9.34).

9.2.2.3.3 Summary of the results

Hypothesis 1 stated that arches can be formed from highly non-convex particles, if convex particles, spheres, are used as a removable formwork. This has been proven true in all 20 iterations.

Hypothesis 2 stated that hexapods have significantly higher contact numbers than spheres. This has been proven true with an average of 1192.35 more contacts in 1000 hexapods than in 1000 spheres. The increase in contacts in the highly non-convex hexapods might be one factor for their increase in stability if compared to spheres.

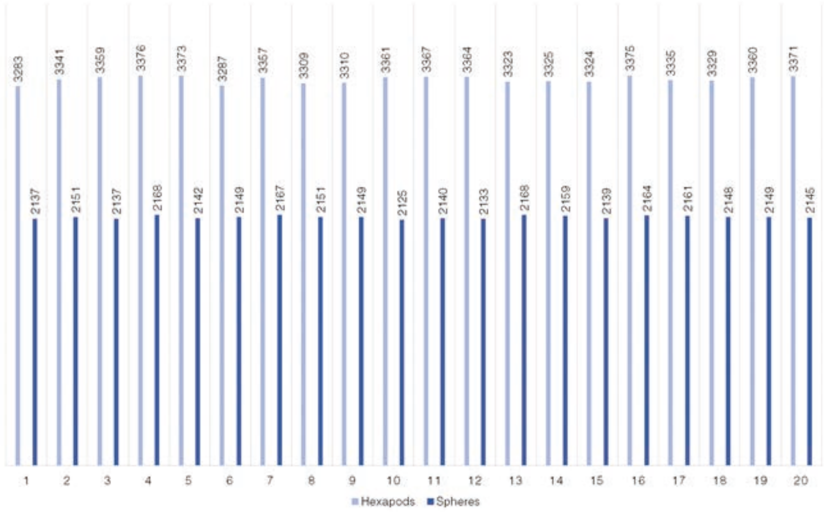

Figure 9.33: Amount of contacts in hexapods and spheres. Karola Dierichs with ITASCA Education Partnership (IEP) Research Program | ICD, University of Stuttgart | 2018

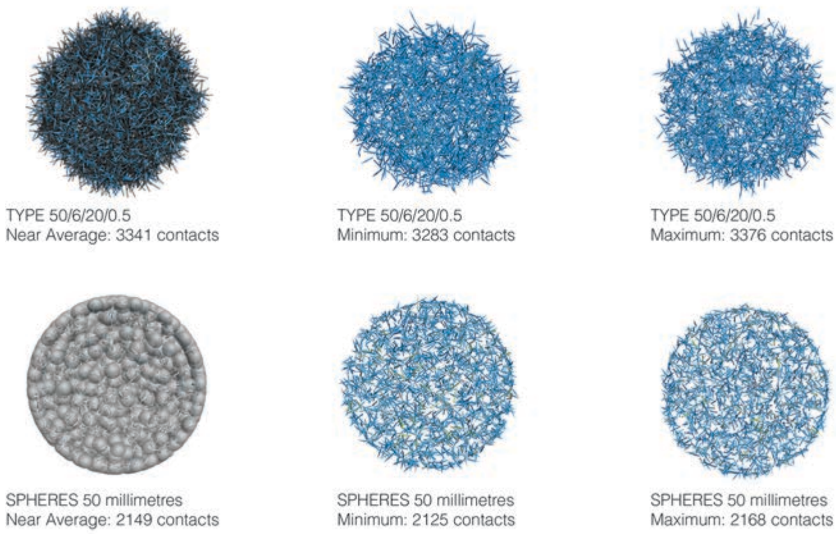

Figure 9.34: Simulation of contacts in hexapods and spheres. The contacts for hexapods of type 50/6/20/0.5 and of spheres with 50 millimetres diameter were analysed using the discrete element method (DEM) in a statistical series. The renderings show views from above of, from left to right, the near average probe, the minimum and the maximum. The spheres have been scaled down 0.49 times in this graphic. Karola Dierichs with ITASCA Education Partnership (IEP) Research Program | ICD, University of Stuttgart | 2018

9.2.3 Summary and evaluation of case study 2

On the one hand, case study 2 comprises the development and the realization of the ICD Aggregate Pavilion 2018. On the other hand, it encompasses a statistical series on arch formation which is based on deploying a designed granular material composed of convex particles as a formwork for a designed granular material consisting of highly non-convex ones.

On the practical level of design, the contributions of case study 2 lie in the full-scale construction of a spatial enclosure from a designed granular material. Furthermore, the structure was made entirely by a robot, in this case a cable-driven parallel robot. Further development on the practical level would need to focus mainly on the construction system. Specifically, a robotic system with higher "rated loads" would help to accelerate the construction process by enabling the use of larger boxes in areas of the structure needing less geometric resolution. In addition, an "end effector" using two grippers would further accelerate production: a pneumatic vacuum gripper could grab the boxes while a pneumatic parallel gripper could release them. The first pneumatic vacuum gripper would most likely be faster than the manual fixing of the box to the "end effector" frame. Another strategy for improving the speed of construction could be a logistical system that strategizes the location of a box in its storage-, deposition- and boundary container-stages, so that robot path lengths are minimized.

On the methodological level, case study 2 continued to combine full-scale applications with statistical series, as introduced in case study 1. Two experimental statistical series – one on arch formation and one on simulations of contacts in hexapods and spheres – were conducted. The integration of simulations into the realization of the project would be a highly valid further development on the methodological level. Key to the simulations would most likely be the modelling of deformation in the pneumatic convex particles. Simulations would also enable the use of "inverse" methods of design for optimization and exploration of the spatial geometry. Another valuable track of investigation would be the integration of models of emergence into the robotic control. Instead of following a predefined path and adjusting the structure to match it through "sensory control", models of emergence would allow working with the non-predefined behaviour of the designed granular materials towards non-predefined spatial results.

On the conceptual level, case study 2 can be evaluated along the same lines as case study 1 with respect to the three aspects of the relevance of granular materials in the context of architectural design (see chapter 2). With respect to the aspect that the behaviour of a granular material can be designed, case study 2 deployed two different granular materials which were designed to have two degrees of stability: one which interlocks and one which flows, if a boundary container is removed. This allows spatial enclosures to be formed, if the two different granular materials are layered in such a way inside a container that the less stable material flows out of the more stable one when the container is removed. The design of the possible degrees of stability of the two granular materials and the distribution of these degrees of stability in the overall structure thus becomes a key aspect in the conception of the resulting architectural space. This is closely related to the aspect that a granular material can be reconfigured. Reconfiguration in case study 2 was induced by removal of the boundary container. All granular materials, designed or not, can undergo this process of reconfiguration, for example by removal of a bottom lid in a container, as has been outlined in section 8.2.3.2.2. Case study 2 in its most basic implication merely enhances this phenomenon through deploying two types of designed granular materials. With respect to the third aspect, namely that granular materials can be recycled, case study 2 demonstrated the recycling of both the particle system itself and the related construction systems. Regarding the particle system, particles from previous projects were fully reused and new ones were added to the existing system, thus demonstrating that the designed granular materials are entirely reusable and potentially infinitely expandable. Regarding the construction system, the storage units of the particles were turned into both "end effector" and boundary containers, thus becoming an integral part of the construction and deconstruction cycles of the particle systems they contained.

9.3 Summary and evaluation of the case studies

The following sections will briefly summarize the research contributions of each of the case studies on the practical, methodological and conceptual levels of design and compare them to each other.

9.3.1 Practical

Case study 1 investigated the formation of vertical structures using a designed granular material consisting of highly non-convex particles. In this case study the cable-driven parallel robot was custom-built and tested in its first iteration.

Case study 2 was a prototype structure for spatial enclosures using designed granular materials consisting of convex and highly non-convex particles in combination. It was also the first structure made entirely with the cable-driven parallel robot, also integrating "sensory control" into the construction process.

Each of the two case studies thus used a different designed granular material with respect to particle systems. With respect to construction systems they both deployed the same cable-driven parallel robot, yet the robot system was developed further from case study 1 to case study 2.

9.3.2 Methodological

Case study 1 introduced the research methodology of relating qualitative investigations into full-scale prototyping with quantitative tests in small-scale statistical series. This methodology was chosen especially with respect to potential future transdisciplinary work, where the full-scale prototyping can be conducted in the realm of architecture and the statistical series in the realm of granular physics. In this sense, case study 1 combined the ICD

Aggregate Pavilion 2015 with a statistical series of experiments and simulations for packing density and compressive strength for different particle geometries.

Case study 2 pursued the same research methodology as case study 1. It paired the ICD Aggregate Pavilion 2018 with a statistical series on arch formation using convex and highly non-convex particle geometries. These experiments were complemented by statistical simulations which compared contact numbers in hexapods and spheres.

Both case studies thus deployed the same research methodology of combining qualitative architectural prototypes with quantitative statistical series, where the latter are laid out based on relevant key aspects of the former.

9.3.3 Conceptual

On the conceptual level of design, both case studies were evaluated with respect to the three aspects of relevance for designed granular materials in architecture which have been outlined in chapter 2: granular materials can be recycled, granular materials can be reconfigured and granular materials can be designed to have specific architecturally relevant behaviours. Since the last aspect is key in the context of this thesis, these three aspects will be presented in inverse order in the following paragraphs.

In this respect case study 1 presents the concept of a single granular material which is designed for increased stability if compared to most naturally occurring, non-designed ones. Case study 2 is based on the concept of two granular materials which are designed to have different degrees of stability.

Whereas case study 1 does not instrumentalize the reconfiguration of the granular material, case study 2 does: the less stable material flows out of the structure, once the boundary container is removed. This means that the entire granular system reconfigures. With respect to recyclability, case study 1 is the first installation of both a specific particle system and its related construction system. It thus neither explores the recycling of the granular material nor the recycling-related aspects of the construction system. In contrast to that, case study 2 entirely reuses the particles deployed in case study 1 and in previous prototypes. In case study 2 new particles are also added to the already-existing ones, therefore demonstrating that the system is not only recyclable, but also infinitely expandable. In addition, the construction system in case study 2 makes use of the storage boxes of the particles. The construction system therefore integrates the fact that the granular material, which the storage boxes contain, goes through cycles of construction and deconstruction.

Case study 2 is thus a progression from case study 1 not only on the practical, but also on the conceptual level. It expands the understanding and implementation of the design, reconfiguration and recycling of granular materials in architecture. All of these three aspects are relatively novel in the realm of architectural design thinking: architectural design is usually based on deploying given materials, yet both case studies use specifically designed materials; architectural design is aimed at one stable state of a structure, yet case study 2 has at least two stable states; architectural design implies the erection of structures which are meant to be in one place until they are destroyed and mostly never reused, yet case study 2 literally recycles the material deployed in case study 1.

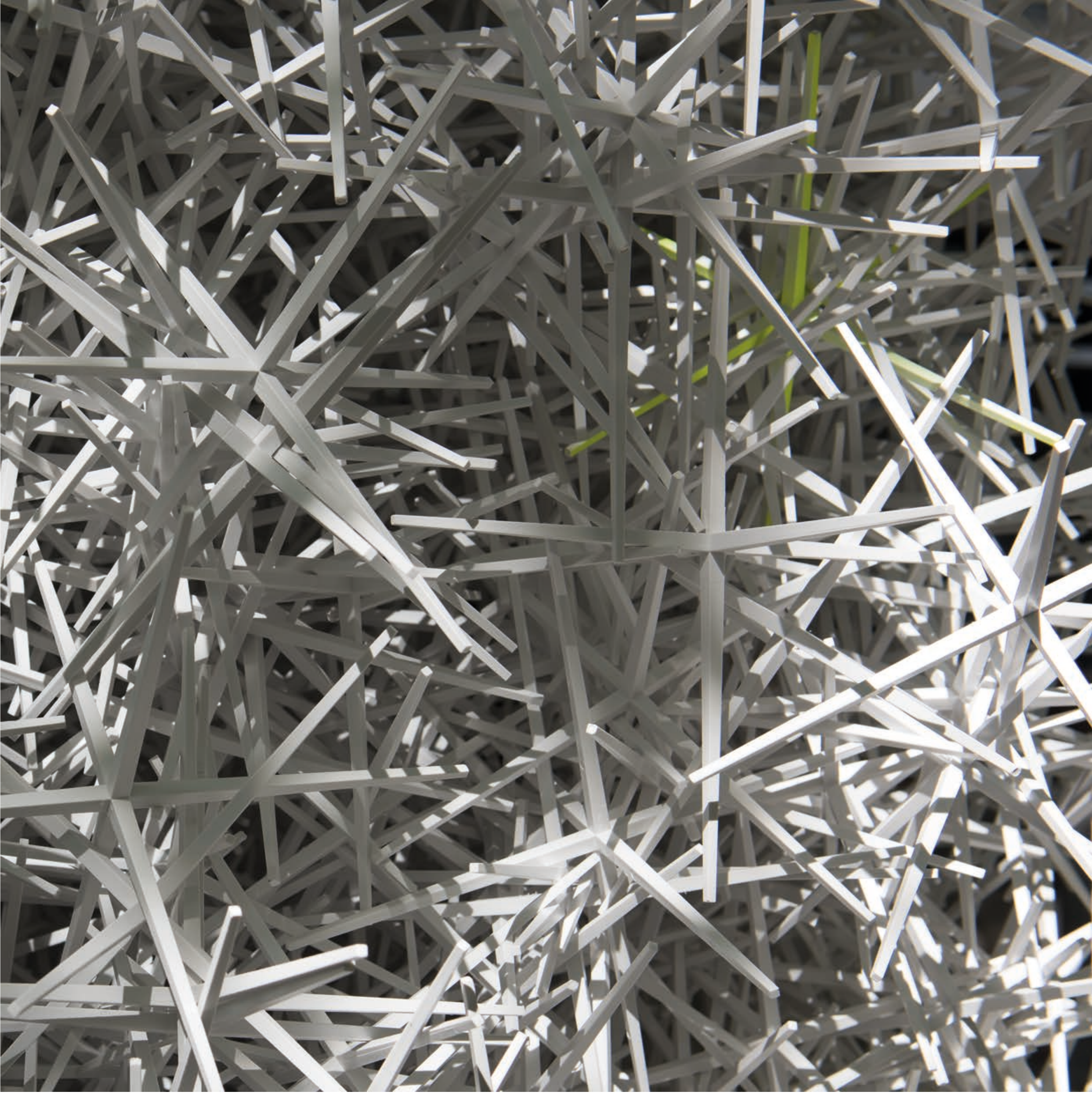

Figure 10.1: Hexapods. Designing the particle geometry in a granular material to achieve specific architecturally relevant behaviours is one of the main contributions of the thesis on a practical level of architectural design. The detail of interlocking hexapods in the ICD Aggregate Pavilion 2015 shows one example of this basic principle. Karola Dierichs | ICD, University of Stuttgart | 2015

10 Summary and conclusion

The following sections will initially give a brief summary of the thesis. Thereafter, and in conclusion, the contributions of the thesis will be discussed. These will be evaluated on a practical, methodological and conceptual level of architectural design research as well as with respect to interfacing with granular physics.

10.1 Summary

Granular architectures made from designed particles have been introduced as a novel architectural "material system" on a practical, methodological and conceptual level of design (see figure 10.1).

The relevance of these designed granular materials in architecture is threefold: first, granular materials can be fully recycled since no binding matrix is used; second, structures made from granular materials are reconfigurable; and third, the behaviour of a granular material can be tuned by defining the individual particle geometry as well as its material makeup, which opens up a new spectrum for architectural design with granular materials (see chapter 2).

The scope of the thesis comprises contributions on a practical, methodological and conceptual level of design as well as a proposed interface with granular physics.

The wider research context of the thesis is the field of "material systems" in architecture and of "designer matter (DM)", which is a transdisciplinary field.

The current state of designed granular materials has been presented for both architecture and granular physics. The thesis contributes to this current state by proposing a comprehensive design system for designed granular materials in architecture and by demonstrating this system with two full-scale architectural structures. The design system also offers an interface between the disciplines of architecture and granular physics.

The research development for this thesis has been presented as laying the foundations for both the design system and the case studies on a practical, methodological and conceptual level.

Both methodological frameworks and actual tools and techniques for experiments and simulations have been introduced (see chapter 7). The actual research methodology applied in this thesis has been based on the development of a design system with feasibility tests and on case studies that integrated selected aspects of this design system (see section 7.3). The methodological frameworks comprise a definition of "forward" and "inverse" methods of design, of analogue and digital processes and of the two terms "experiment" and "simulation" (see section 7.1). Tools and techniques for both experiments and simulations have been outlined. Their actual specification and implementation occurs in the case studies and the design system catalogue respectively (see section

7.2). Tools and techniques for experiments encompass the experimental setup, boundary conditions, particle marking, data capture and processing. For the simulations, the discrete element method (DEM) is the mathematical model which has been mainly applied in this thesis. The research methodology deployed in this thesis combines the development of a design system with feasibility tests. The design system is applied in two full-scale case studies which are complemented by statistical tests (see section 7.3).

Initially the design system has been introduced in chapter 8, which covers both particle systems and construction systems. This design system is complemented by a catalogue of investigations presented in appendix A. This catalogue is established both within the framework of doctoral research and teaching at Bachelor and Master level. It provides relatively rapid feasibility investigations, which can be integrated into larger applied systems as well as investigated within a more scientific framework focusing on quantitative analysis of the tests. Sub-categories for both particle and construction systems have been introduced in the design system (see chapter 8). Altogether nine sub-categories have been developed describing both the individual particle in its geometry and material as well as particle mixes (see section 8.1). For the construction systems, 13 sub-categories have been identified defining locally and globally effective construction systems as well as boundary construction systems (see section 8.2).

Departing from the design system two case studies are conducted, each of which integrates a different set of system parameters (see chapter 9). Each case study is implemented as a full-scale architectural structure which is complemented by a set of key statistical experiments or simulations. The case studies are evaluated with respect to their contributions on a practical, methodological and conceptual design level.

On the practical level, both particle and construction systems are integrated and applied to a full-scale structure in the case studies (see chapter 9). With respect to the particle systems, case study 1 uses highly non-convex particle geometries while case study 2 combines highly non-convex and convex ones. Quantitative verification of relevant sub-aspects of these particle systems is conducted through statistical series. With respect to the construction systems, case study 1 shows the first iteration of a locally effective construction system, the cable-driven parallel robot, which can be installed in situ. Case study 2 develops this robot further with respect to its payload, construction space and control interface. During both case studies a set of boundary construction systems are tested.

On the methodological level, the case studies are based on a combination of full-scale architectural prototypes and related statistical series which investigate key aspects of these prototypes.

On the conceptual level, the two case studies reflect on the three aspects of relevance for designed granular materials in architecture as outlined in chapter 2: granular materials can be recycled, reconfigured and designed. Given that the thesis is situated within the overarching field of "designer matter (DM)", the last aspect, the designing of the behaviour of a granular material, plays a key role in the evaluation of the case studies, whereas the first two aspects pertain to any project working with granular materials, be they designed or not.

Case study 1 deploys a single granular material, which is designed for increased stability forming a 90-degree angle of repose. The pavilion does not deploy reconfiguration and since it is the first iteration of both the particle system and its related construction system, the notion of recycling has not yet been implemented. Case study 2 uses two different granular materials, which are designed for different degrees of stability: one which is less stable and one which is more stable. The less stable material is an inner formwork for the more stable one. On removal of a boundary container the pavilion reconfigures as the less stable granular material flows out of the more stable one, which remains as a space-enclosing structure. Reconfiguration is thus deployed in a productive manner. In case study 2 the particles from case study 1 are re-used and the storage system of these particles is integrated into the construction process. The notion of recycling is thus initiated in this second iteration of the particle system.

10.2 Conclusion

10.2.1 Contributions to architecture

Within the field of architecture, the contributions will be discussed in the following sections on the practical, methodological and conceptual levels of design research. After a brief outline of the specific contributions, the actual achievements as well as the potential improvements will be considered.

10.2.1.1 Practical

The core contribution of the thesis on the practical design level is twofold: a design system for particle and construction systems is established in section 8 and appendix A; and this design system is investigated in two applied case studies in section 9 (see figure 10.1).

The design system is a novel contribution to the field of designed granular materials in architecture and it is potentially even the first comprehensive and validated approach to the topic. Together with its validation through feasibility tests, it can serve as a starting point for a wide range of architectural research in this specific field. The case studies with an increase in scale of the structures and with increasing integration of design system parameters prove the potential application of designed granular materials in architecture.

One obvious limitation of this thesis is the potentially selective nature of the design system: relevant aspects of the particle and construction system may have not been included simply because they have not been invented or thought of yet. It can therefore be considered a first version, which needs to be expanded or even reduced in line with the development of the research.

10.2.1.2 Methodological

The methodological contributions will be discussed on the one hand with respect to the methodological framework of "forward" and "inverse" design and on the other with respect to the realm of experiments and simulations using analogue and digital means.

First, the aforementioned design system for both particle and construction systems presented in chapter 8 has been investigated using solely "forward" design methods as described in section 7.1.

The results from the "forward" methods can serve as an input for "inverse" design processes, which in turn can help to optimize the respective design parameters for a specific integrated system application. In that sense the design parameters describe the basic boundary conditions within which the system can be developed and explored.

The fact that only "forward" methods have been used for the design of both particle and construction systems may have already induced a bias. While "inverse" methods frequently claim to develop hitherto unknown forms or principles, "forward" methods are in large part based on a design intuition of what might or might not work. Yet "inverse" methods also need a set of constraints or rule-based inputs which already propel a certain design direction; in a critical stance one might state that "inverse" design in some instances serves to calibrate previously defined design parameters and in that sense does not always allow for radical novelty.

Following this argument it may be revealed that "forward" and "inverse" design are always inextricably linked: a "forward" process always investigates the performance of the system in the next step after deciding on a specific system layout – the cause is quickly followed by the investigation of its effects; and in an "inverse" process a performance-based optimization cannot be initiated without a set of design rules – an effect cannot be considered without stating a cause. The question rather seems to be how these two approaches can be fruitfully combined such that both radical novelty and specific system performance can be achieved.

Second, a range of experimental and simulation methods have been explored as tools and techniques for the investigation of the respective granular material (see sections 7.1 and 7.2).

They are mainly based on already-existing technologies borrowed from granular physics, yet are little explored within the field of architecture and consequently present novel tools for design research. In a next step, new experimental and simulation methods in both the analogue and the digital realm might be developed, especially in collaboration with the field of granular physics (see section 10.2.2).

The applied research methodology of developing a design system with feasibility tests, and of further validating this system through case studies in combination with statistical series, has proven resourceful (see section 7.3). The further validation of this approach also requires close collaboration with the realm of granular physics (see section 10.2.2).

10.2.1.3 Conceptual

Granular architectures present one contribution in the field of "designer matter (DM)", in which the particles are the element on the material mesoscale that are defined by the designer to calibrate the behaviour of the overall granular material on its macroscale.

The concept of "designer matter (DM)" in architecture both in general and specifically in relation to granular materials has been introduced in section 4.3.

On a specific level the two case studies contribute to this conceptual notion of "designer matter (DM)". Case study 1 deploys a single designed granular material that allows for increased stability and thus, in this case, vertical structures. Case study 2 is based on two different designed granular materials: one with an increased stability and one with a decreased stability if compared to most naturally occurring, non-designed granular materials. In this respect the two case studies are explorations of designed degrees of stability.

On a more critical note, it might be stated that the field of "designer matter (DM)" itself is emerging. Since it has not yet been fully defined, it might not serve as a stable conceptual framework. In some respect the new is positioned within the new: that is, designed granular materials are positioned in "designer matter (DM)". Consequently, both the relevance of the specific "material system" of designed granular materials and of the overall field of "designer matter (DM)" within architecture cannot be reliably evaluated at this point in time.

10.2.2 Contributions for granular physics

The research presented in this thesis has a strong relation to the field of granular physics and serves as an instigator of collaborative research. Consequently, the contributions of the research will additionally be evaluated with respect to potential interactions with the field of granular physics. In particular, the design system presented in chapter 8 is considered an interface between architectural design and granular physics.

Both the design parameters for particle systems and those for construction systems have been tested in an architectural context either within the catalogue (see appendix A) or within the case studies (see chapter 9). Yet they can also be considered as inputs for the field of granular physics. Here they can either initiate quantitative analysis and characterization of the respective system or they can be a starting point for "forward" and "inverse" design processes which are conducted collaboratively between the fields of architecture and granular physics.

One of the greatest challenges in the collaboration between architecture and granular physics is the identification of material characteristics and design rules which are relevant to both disciplines. Alongside that, suitable methods of investigation need to be identified. The proposed design system is consequently one-sided at this point in time, since it has been investigated mainly in the field of architecture.

Additionally, both scale and scope of experiments and simulations are frequently crucially different between the two disciplines: whereas in architecture investigations are rapidly and roughly conducted at the large scale, granular physics tends to investigate meticulously on the small scale. Although this observation might seem trivial, in effect it highlights the need for a very careful calibration of the mutual investigations and their interrelation. The model proposed in the case studies of combining full-scale architectural applications with statistical laboratory experiments and simulations is one suggested working format in that direction.

10.2.3 Summary of the conclusion

The contributions of the research have been discussed on a practical, methodological and conceptual design level of architectural design and with respect to their implications for granular physics.

On the practical level, design parameters or rules have been laid out for both particle and construction systems. The possibly selective character of the proposed design system has been pointed out.

On the methodological level, the research has been conducted using "forward" design, integrating tools and technologies from granular physics into the architectural design process. Methodologically "inverse" methods have not been included, yet the results achieved with the "forward" design approach can be looped back into an "inverse" design development. Additionally, it has been pointed out that methods for experiments and simulations have merely been transferred from the field of granular physics into the field of architecture.

On the conceptual level, the thesis is situated within the context of "designer matter (DM)" of which designed granular materials for architecture are one specific research field. It must be stated that the proposed framework of "designer matter (DM)" is rather novel itself and can consequently not yet offer an established reference for the thesis; a more profound evaluation of both the specific and generic fields can only be conducted once both have developed further.

The design system presented in chapter 8 is an interface between architecture and granular physics for quantitative analysis as well as for collaborative design processes. The different working cultures of architecture and granular physics might pose a problem, but they can be integrated if qualitative full-scale prototyping and quantitative laboratory analysis are combined.

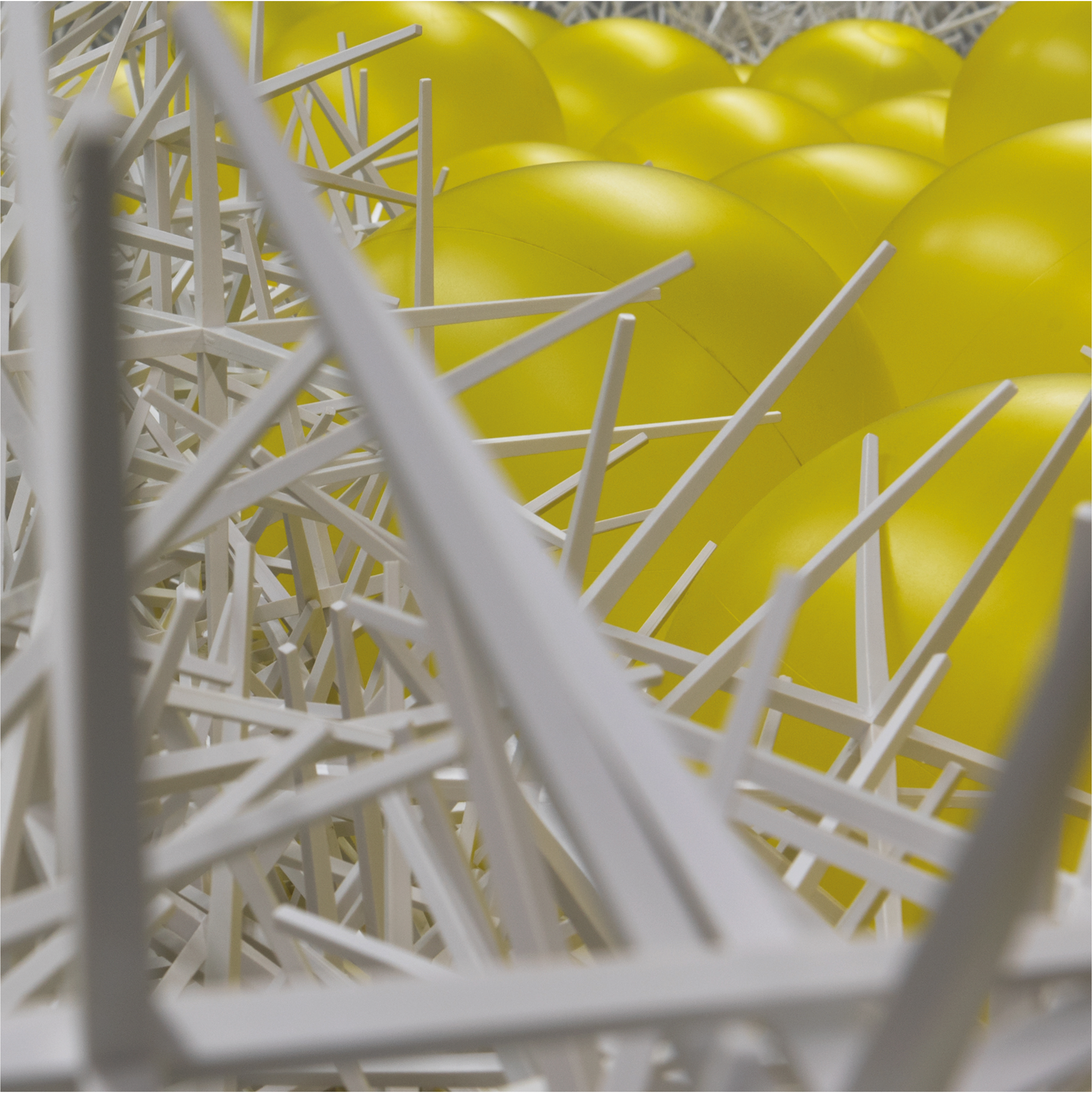

Figure 11.1: Hexapods and spheres. The combination of different designed particle types, in this case hexapods and spheres, for different construction characteristics as well as the integration of the particle system and construction system are highlighted in the ICD Aggregate Pavilion 2018. This prototype thus points the way towards relevant further research especially on a practical level of design. Karola Dierichs | ICD, University of Stuttgart | 2018

11 Further research

Based on the evaluation in chapter 10, further research can be directed towards practical, methodological and conceptual developments in architectural design as well as towards the integration of the two disciplines of architecture and granular physics (see figure 11.1).

11.1 Further research in architecture

11.1.1 Practical

Practical design research might be focused either on the development of the particle system or on suitable construction systems.

Within the realm of particle systems, grading the granular material with different particle geometries is promising, as it might increase loadbearing capacities while keeping the individual particle geometries relatively simple. Calibrating the mechanical properties of the material which the particles are made of can open up another very relevant branch of affecting the behaviour of the overall granular material. Geometrically variable particle types have a lot of potential as well, especially with respect to an actual application where different material characteristics are required during different stages of construction.

Within the area of construction systems, suitable systems for the interactive and continuous formation and reformation of granular architectures seem most relevant. Furthermore, the tendency in construction systems for designed granular materials would be to move towards even more basic construction processes than deployed in case study 2, while making the particle systems more and more refined, so that they perform a large part of the construction process by themselves.

Ultimately, the construction system then becomes a constituent part of the particle system, and the particle system is part and parcel of the construction system.

11.1.2 Methodological

On the methodological level, the integration of "inverse" methods for the development of both particle and construction systems is especially relevant (see section 7.1.1). This can be conducted based on the proposed design system presented in chapter 8. However, more project-specific research questions need to be filtered out in advance.

11.1.3 Conceptual

Within the framework of the research presented here, the conceptual integration of the work into the new field of "designer matter (DM)" is only a very small first step (see section 4.3).

Consequently, the establishment of "designer matter (DM)" as a wider conceptual field for architecture is a highly relevant topic of further research. Here, the identification of relevant subcategories and their pertinence to architecture appear to be an immediate first step. Designed granular materials in particular might be discussed more in depth as one possible form of this newly defined field of "designer matter (DM)".

11.2 Further research with granular physics

The integration of the two fields of architecture and granular physics is key to any further development of the overall research field. The model proposed in the case studies, of using key statistical experiments and simulations in combination with full-scale architectural applications, might be a suitable working mode.

Here, the role of physics would be to offer analytical understanding and predictive modelling of the granular materials. The role of architecture would be to further develop design principles for particle and construction systems, and to increasingly integrate them into design proposals on the full architectural scale.

A
Design system catalogue

Appendix A presents the projects which have directly led to the development of the design system categories introduced in chapter 8. Each design system category is matched by one project. These projects are initial feasibility tests. They served to establish the parametric models of each respective category, but did not make use of them. The projects have been developed both in the context of this thesis and through teaching. The work is credited accordingly in each project section.

A.1 Appendix A – Project 1

Project credits* — *Doctoral candidate: Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Manufacturing:* cirp GmbH | *Year:* 2014

Design system category:
Particle – Geometry – Dimension (see section 8.1.1.1.1)

Project description: The category of the particle geometry defining the dimension has been integrated into the parametric particle model presented in section 9.1.1.1.1.1 and in the related statistical series (see section 9.1.2). In the statistical series, this parameter has been deployed in order to investigate how arm amount affects packing density while the dimensions of the particles remain the same: three different designed granular materials consisting of either tetrapods, hexapods or octapods were compared for their packing density (see figure A.1). While the arm amount varied between four, six and eight, the dimension of the convex hull of the particles was kept the same at 50 millimetres. The results of this series are presented in section 9.1.2. Particle dimensions can be a relevant criterion in the fabrication of a granular material where absolute size of a work-piece is limited but geometry is not, as is the case in most 3D-printing processes.

Design system category parameters: The diameter of all of the three particles is the longest diameter d_m of the convex hull h_c of the set of points p_p describing the respective particle geometry p_g. Keeping the parameter of the particle dimension the same, enabled investigation of the effect of varying the arm amount only.

Figure A.1: Appendix A – Project 1. The dimension of particles is kept the same while varying their arm amount from four to six and eight. Karola Dierichs | ICD, University of Stuttgart | 2014

A.2 Appendix A – Project 2.1

Project credits* — *Doctoral candidate: Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Manufacturing:* cirp GmbH | *Year:* 2015

Design system category:
Particle – Geometry – Geometric types – Convex (see section 8.1.1.1.2.1)

Project description: The series of tests on basic geometric types was conducted in 2015 as a feasibility investigation for the case studies [103, p. 90; 102, pp. 25.4–25.5] (see figure A.2). The study comprises projects 2.1 to 2.3 of this appendix (see sections A.3 to A.4). In order to investigate basic properties of convex particle geometries which might be relevant for architectural design and construction, a cylinder measuring 350 millimetres in height and 190 millimetres on the inside diameter was filled with spheres of 40 millimetres diameter to a height of 200 millimetres. Altogether circa 93 spheres of 2.285 grams each were contained in the cylinder. The cylinder was pulled off from the top and the spheres flowed out.

Design system category parameters: Spheres are convex as their three-dimensional volume V_c contains all of the lines p_l connecting all points p_p which belong to the particle geometry p_g. They were chosen as an example for this specific geometric type since they have the best ability to roll, which is relevant if a construction process requires material to flow out of or into a structure very easily, as has been demonstrated in case study 2 (see section 9.2).

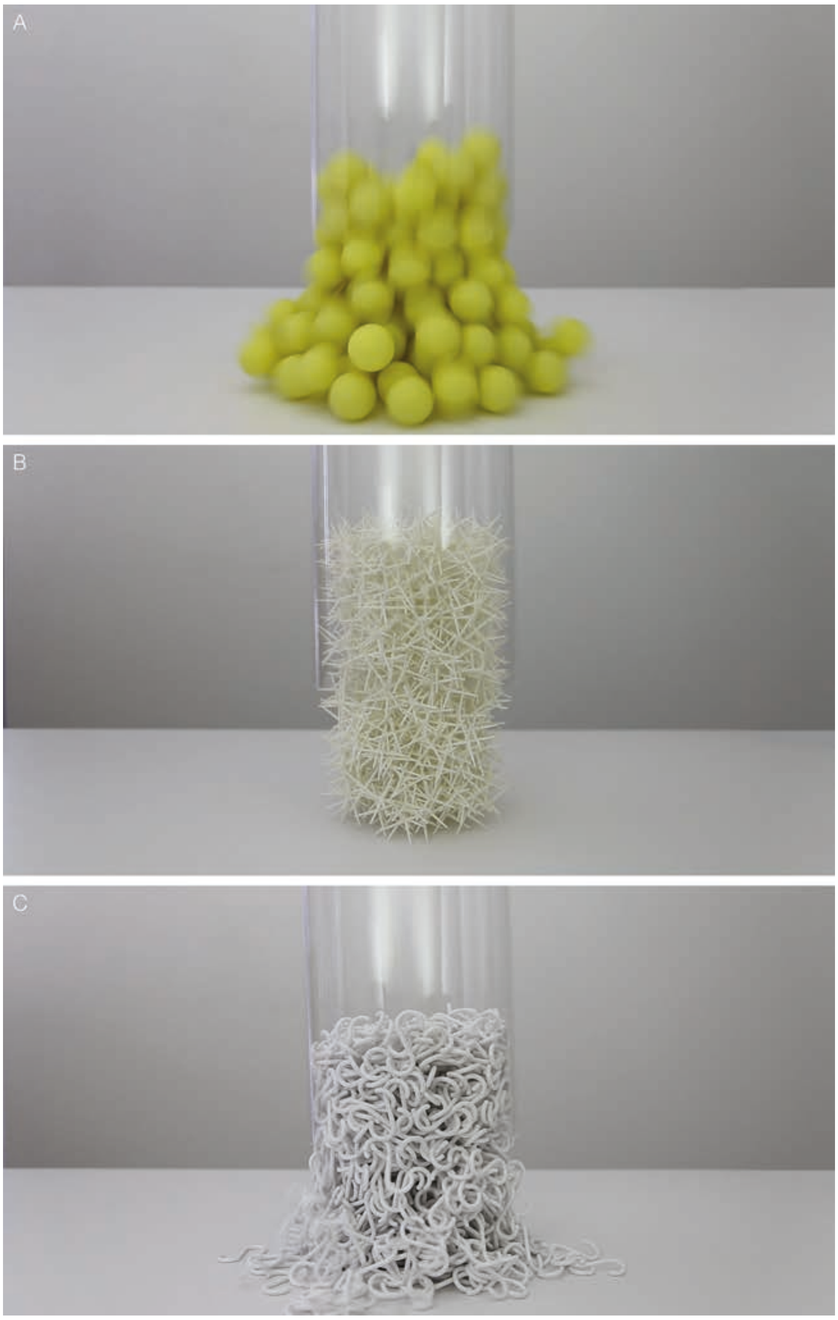

Figure A.2: Appendix A – Project 2.1–2.3. (A) Convex, (B) non-convex and (C) double non-convex particles are explored with respect to their stability. Karola Dierichs | ICD, University of Stuttgart | 2015 [102]

A.3 Appendix A – Project 2.2

Project credits — *Doctoral candidate:* Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2015

Design system category:
Particle – Geometry – Geometric types – Non-convex (see section 8.1.1.1.2.2)

Project description: The same experimental setup as in section A.2 was chosen [103, p. 90; 102, pp. 25.4–25.5] (see figure A.2). This time the cylinder was filled with circa 474 hexapods of the type 50/6/20/0.5 to a height of circa 200 millimetres (see section 9.1.2.3.1). The cylinder was pulled off from the top. The hexapods remained standing. A slight settling appeared to occur, as the cylinder could not be easily slid on again, which indicates that the column had expanded a bit.

Design system category parameters: The particles in this case are non-convex, as their volume V_{nc} does not contain all lines p_l connecting all points p_p belonging to the particle geometry p_g. The specific geometry of a hexapod was chosen to pertain to the parametric particle model introduced in case study 1 (see section 9.1.1.1.1.1). It was investigated as it allows the formation of structures which are relatively stable under self-weight and potentially also under loads, which is an obvious architecturally relevant characteristic for more permanent structures. The stability is due to the interlocking of the particles' arms. This basic particle geometry has been applied in both case studies (see chapter 9).

A.4 Appendix A – Project 2.3

Project credits — *Doctoral candidate:* Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2015

Design system category:
Particle – Geometry – Geometric types – Double non-convex (see section 8.1.1.1.2.3)

Project description: The experimental setup for project 4 was the same as in sections A.2 and A.3 [103, p. 90; 102, pp. 25.4–25.5] (see figure A.2). In this case, the cylinder was filled with s-shaped hooks up to a height of 200 millimetres. The cylinder contained approximately 916 particles of 1.43 grams each. The cylinder was pulled off from the top, the column sagged visibly and some particles fell out. If one particle was grabbed from the top of the cylinder, a cluster of other particles was attached to it and remained hanging.

Design system category parameters: The particles in this test are double non-convex, as their three-dimensional volume V_{dnc} does not contain all lines p_l connecting all points p_p of the particle geometry p_g and in addition this non-convexity is present on two length scales of the particle geometry p_g. Double non-convex particles have the ability to take tensile forces under self-weight and potentially also under external loads. This property is an architecturally highly relevant characteristic as it expands the potential application of designed granular materials to either the formation of hanging structures or to their deployment in loading scenarios, where tensile forces occur. The specific geometry of an s-shaped hook was chosen in this case, as the particles are an existing, industrially produced stock material which could be easily sourced. Like in the test with non-convex particles, this geometric particle type could be parameterized and systematically explored. The two student projects presented in sections A.15 and A.16 are a first approach to this [58; 215].

A.5 Appendix A – Project 3.1

Project credits — *Student:* Alexander Wolkow | *Thesis advisors:* Karola Dierichs, Dylan Wood | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2015–16

Design system category:
Particle systems – Particle – Geometry – Geometric variability – Non-variable (see section 8.1.1.1.3.1)

Project description: The Master's thesis conducted by Alexander Wolkow in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart in 2016 combines two particle types, one with a non-variable and one with a variable geometry [106, pp. 226–228; 103, p. 93; 371] (see figures A.3 and A.4). It is therefore used as a demonstration of the design system category investigated in this section and in section A.6. This section deals with the non-variable particle type. Section A.6 investigates the variable particle type. The non-variable particles measured 5.0 by 5.0 by 200.0 millimetres and were cut from waste wood [106, p. 227; 103, p. 93; 371, pp. 6–7]. Their high aspect ratio allowed for them to interlock [106, p. 227; 371, pp. 80–87]. The dimensions were based on results from granular physics [106, p. 227; 371, pp. 24–25; 125; 351; 40; 282]. These non-variable convex particles are fast to produce and cheap if compared to the variable particles [106, p. 227; 103, p. 93; 371, pp. 4, 8–9]. Yet they can only take compressive and not tensile forces like their variable counterparts in their curled state [106, p. 227; 103, p. 93; 371, pp. 4, 8–9, 26–39]. Two final demonstrations of the designed granular material were conducted: a beam measuring 1070 millimetres in length, 300 millimetres in depth, and 500 millimetres in height, and a square slab measuring 1070 by 1070 by 500 millimetres [106, p. 227; 371, pp. 68–79]. The role of the non-variable particles was to act as a filling material and to take compressive forces in the upper zone of the beam and slab [106, p. 227; 371, pp. 68–79].

Design system category parameters: The geometry of the non-variable particles at time instance 1 $p_g[t_1]$ is the same as their geometry at time instance 2 $p_g[t_2]$. In the zones of a beam or slab where mostly compressive forces occur, it is sufficient to use cheap bulk material which does not need to undergo a geometric alteration in order to change state from a convex to a double non-convex geometry and back.

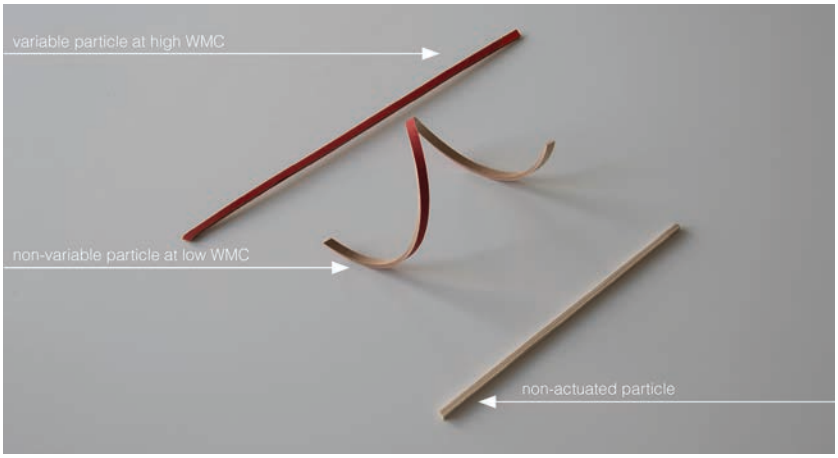

Figure A.3: Appendix A – Project 3.1–3.2. Particles with a non-variable geometry and with a variable one are deployed. The non-variable particles are cut from leftover wood. These particles have a convex geometry, which does not change as a reaction to alterations in moisture content (WMC). The variable particles are made from custom-produced bi-layer wood laminates, which allow the particles' geometry to vary from convex to double non-convex due to changes in wood moisture content (WMC). Alexander Wolkow | ITECH, University of Stuttgart | 2016 [106]

A.6 Appendix A – Project 3.2

Project credits — *Student:* Alexander Wolkow | *Thesis advisors:* Karola Dierichs, Dylan Wood | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2015–16

Design system category:
Particle systems – Particle – Geometry – Geometric variability – Variable (see section 8.1.1.1.3.2)

Project description: In the Master's thesis by Alexander Wolkow undertaken in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart, which was introduced in section A.5, non-variable particles are combined with variable ones [106, pp. 226–228; 103, p. 93; 371] (see figures A.3 and A.4). This section deals with the variable particle type. Section A.5 investigates the non-variable particle type. The variable particles transform from a prolate stick to a helix and back under a change in ambient relative humidity (RH) and consequently in wood moisture content (WMC) [106, pp. 226–227; 371, pp. 30–33, 52–57]. Thus they have two geometric states: a convex and a double non-convex one [106, pp. 226–227; 371, pp. 8–9, 27]. The variable particles were produced by cutting hygroscopically actuated bilayer wood laminate sheets into 10-by-300-millimetre strips at a 30-degree angle with respect to the grain direction of the restrictive maple layer, which induced the twisting behaviour [106, p. 227; 371, pp. 30–33, 52–57]. The role of these variable particles is on the one hand to take tensile forces in their curled, double non-convex state, and on the other to allow the structure to dissolve again, once they change back to their convex state through an alteration in ambient relative humidity (RH) [106, p. 227; 103, p. 93; 371, pp. 4, 8–9, 26–39].

Design system category parameters: The geometry of the particles at time instance 1 $p_g[t_1]$ is a convex stick and at time instance 2 $p_g[t_2]$ it is a double non-convex helix. This enables two types of behaviours of the granular material consisting of them: in their convex state they can be poured and in their double non-convex state they interlock so that they can also take tensile forces. The change in geometry is caused by alterations in ambient relative humidity (RH) and consequently of the wood moisture content (WMC) of the particles.

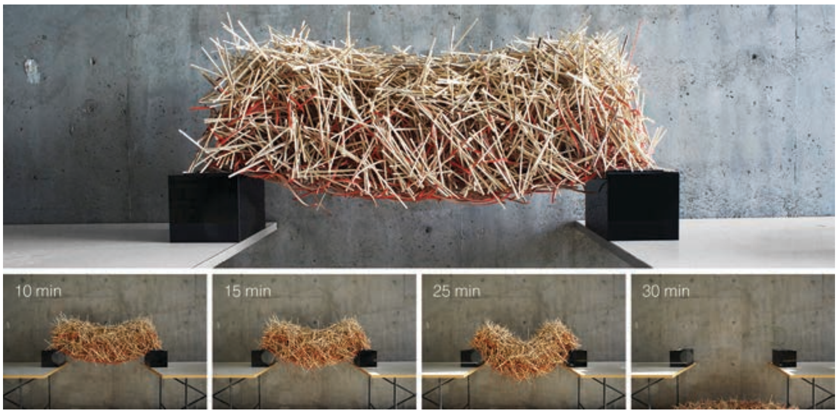

Figure A.4: Appendix A – Project 3.1–3.2. Particles with a non-variable and with a variable geometry are combined to form a beam which is stable under low relative humidity (RH) and dissolves if relative humidity (RH) and thus wood moisture content (WMC) of the particles with variable geometry is increased. Alexander Wolkow | ITECH, University of Stuttgart | 2016 [371]

A.7 Appendix A – Project 4

Project credits — *Doctoral candidate:* Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Manufacturing:* cirp GmbH | *Year:* 2018

Design system category:
Particle systems – Particles – Material – Mechanical properties (see section 8.1.1.2.1)

Project description: Two particle geometries made from two different materials were compared. The first one was made from polyamide (PA) 2200 with selective laser sintering (SLS). It had a friction coefficient of 1.0 (+/- 0.3) [382, p. 06011.2]. The second one was made from a transparent acrylic using injection moulding. It had a friction coefficient of 0.4 (+/- 0.1) [382, p. 06011.2]. Both particles had six arms, and were thus hexapods, but had a diameter of 20 millimetres only. An acrylic cylinder 200 millimetres in height and 190 millimetres in inner diameter was filled with the two different designed granular materials. The filling height was 190 millimetres. The cylinder was pulled off from the top. As a result the designed granular material consisting of the particles made from the polyamide (PA) 2200 formed a 90-degree angle of repose after the removal of the cylinder. The designed granular material consisting of particles made from the acrylic had an angle of repose of circa 37 degrees (see figure A.5). This difference in the angle of repose is most likely due to the different coefficients of friction: the polyamide (PA) 2200 has a high one, the acrylic has a low one.

Design system category parameters: The mechanical property of the material of both particle types p_{mp} is different resulting in two different coefficients of friction. The coefficient of friction affects the mechanical property of the overall granular material m_{mp}, in this case resulting in two different angles of repose.

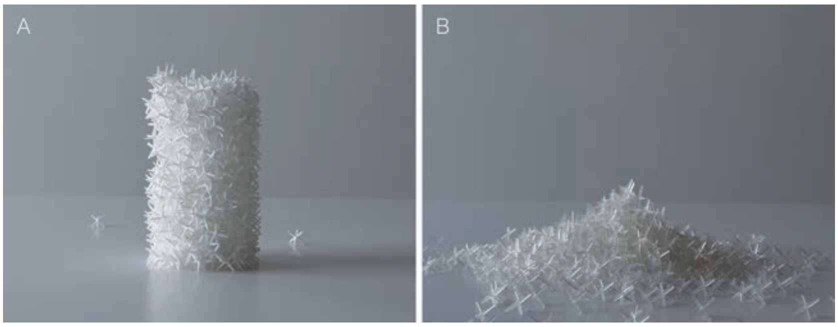

Figure A.5: Appendix A – Project 4. (A) Particles made from polyamide (PA) 2200 form a column on removal of a containing cylinder. (B) Particles with the same geometry but made from acrylic form a sloped mound on removal of a containing cylinder. Karola Dierichs | ICD, University of Stuttgart | 2018

A.8 Appendix A – Project 5

Project credits — *Students:* Sabrina Heldele, Guobin Shen | *Tutors:* Karola Dierichs, Achim Menges | *Project type:* Seminar project | *Course:* "Material Computation: Aggregate Architectures" seminar | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2010

Design system category:
Particle systems – Particles – Material – Optical properties (see section 8.1.1.2.2)

Project description: The seminar "Material Computation: Aggregate Architectures" was taught in the summer term of 2010 at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart [96, pp. 297–299; 93, p. 5; 171; 320]. In the first stage, the students investigated particle geometries that can be made from transparent plastic sheet material [96, pp. 297–299; 171; 320]. In the second stage, the designed granular materials developed in the first stage were tested for their ability to form a half-dome [93, p. 5; 171; 320]. The particles were made from transparent material as this allowed the use of back-light photography in order to observe and compare the internal structure, especially the density, of the respective granular material [93, p. 5; 171; 320] (see figure A.6). In the project by Sabrina Heldele a designed granular material with a looser packing was developed, which consisted of particles made by looping a flat strip [96, p. 298; 171, pp. 8–16]. The resulting granular material packed comparatively loosely and interlocked to form a half-dome [93, p. 5; 171, pp. 17–20]. In the project by Guobin Shen, particles had the basic geometry of a tetrahedron with holes in each face

[96, p. 298; 320, pp. 5–15]. The granular material made from these latter particles packed more densely and the particles did not interlock in as stable a way as the previous ones during dome formation [93, p. 5; 320, pp. 20–33].

Design system category parameters: The optical property of the material of the particles p_{op} in both of the projects is the same, as they are made from identical transparent plastic sheet material. This property is then set into proportion to the optical property of the overall granular material m_{op}. The overall optical property, the light transmittance, is different in both cases due to the difference in particle geometry: the looser-packing particles allow for more light to permeate, the denser-packing allow less light. In this case, the optical properties were used mainly for analysis. Yet they can also be deployed as an architectural means of design. A more systematic mode of investigation could experiment with different degrees of transparency of the particles' material while keeping their geometry the same.

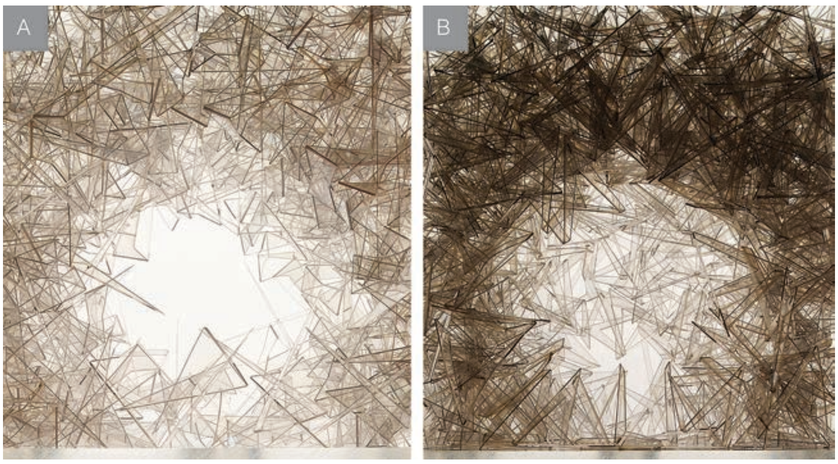

Figure A.6: Appendix A – Project 5. Two designed granular materials have different packing density, which affects the overall optical property of the granular material. (A) Loops pack less densely than (B) tetrahedra with holes. Sabrina Heldele, Guobin Shen | ICD, University of Stuttgart | 2010 [171; 320]

A.9 Appendix A – Project 6

Project credits — *Doctoral candidate:* Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2018

Design system category:
Particle systems – Particle mixes (see section 8.1.2)

Project description: Two types of particles were mixed. One type was the hexapod 50/6/20/0.5. The other type was a sphere with 40 millimetres diameter. These two particle types were mixed at varying percentages in a cylinder measuring 200 millimetres in height and 190 millimetres in inner diameter. The filling height was 190 millimetres. The mixes were assessed by their ability to form a stable column once the cylinder was removed. If 100 per cent hexapods were in the cylinder, they formed a stable column upon its removal, with a 90-degree angle of repose. If 100 per cent spheres were in the cylinder, they flowed out upon its removal. Departing from this observation the mixing ratios tested were 50 to 50 per cent, 60 per cent hexapods to 40 per cent spheres, 70 per cent hexapods to 30 per cent spheres, 80 per cent hexapods to 20 per cent spheres and 90 per cent hexapods to 10 per cent spheres. Up to the 70/30 per cent mix the columns were unstable. The 80/20 mix was stable, yet a few spheres rolled out. The 90/10 mix formed a stable column with a 90-degree angle of repose (see figure A.7). Mixing spheres into hexapods can among others be relevant if inflatables are used as spheres, and can thus reduce packing volume.

Design system category parameters: The particle mixes m_p are defined by the two individual particle types $p_t[1]$ and $p_t[2]$ as well as their mixing ratios in percent.

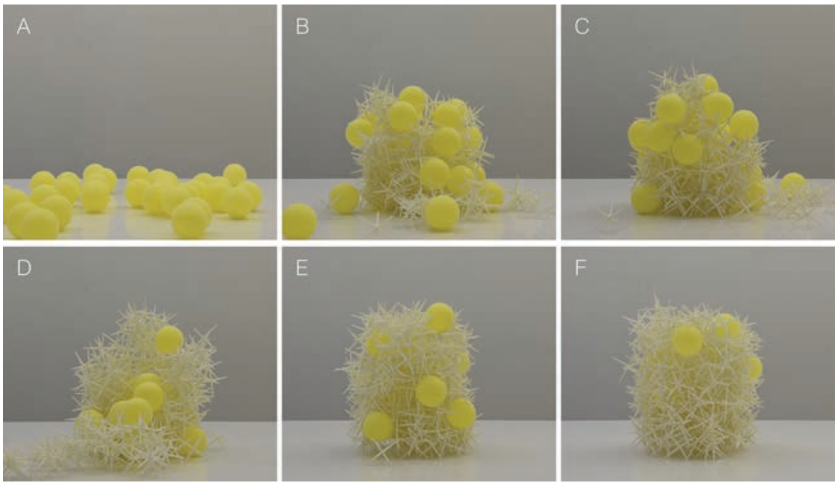

Figure A.7: Appendix A – Project 6. The mixing ratios of spheres to hexapods are (A) 100/0 per cent (B) 50/50 per cent (C) 40/60 per cent (D) 30/70 per cent (E) 20/80 per cent (F) 10/90 per cent. Karola Dierichs | ICD, University of Stuttgart | 2018

A.10 Appendix A – Project 7

Project credits — *Student:* Desislava Angelova | *Thesis advisor:* Karola Dierichs | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2013–14

Design system category:
Construction systems – Locally effective construction systems – Industrial robots (see section 8.2.1.1)

Project description: The Master's thesis by Desislava Angelova conducted in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart investigates the modulation of luminance in a granular structure using a six-axis articulated robot [102, p. 25.11; 89, pp. 11–13; 99, pp. 90–91; 13; 12] (see figure A.8). The robot was equipped with a radial gripper that allowed the adding and subtracting of material from a structure made of highly non-convex ten-armed designed particles, which are referred to as decapods [102, p. 25.11; 89, pp. 11–13; 13, pp. 402–404; 14; 12, pp. 84–101]. Luminance values in a wall made from this designed granular material were measured during material subtraction using a digital camera [102, p. 25.11; 89, pp. 11–13; 99, p. 91; 13, pp. 400–401, 403–404; 12, pp. 22–29, 112–113]. This camera thus acted as a sensor of the six-axis articulated robot [89, pp. 11–12; 13, pp. 400–401, 403; 12, pp. 22–29, 112–113]. The image data were streamed to a parametric model which compared the actual luminance to a target luminance [102, p. 25.11; 89, pp. 11–13; 99, p. 91; 13, pp. 403–405; 12, pp. 102–149]. Based on that difference the next point for the removal of material is calculated and sent back to the robot control system [102, p. 25.11; 89, pp. 11–13; 13, pp. 403–405; 12, pp. 102–149].

Design system category parameters: This application first and foremost shows the relevance of a high "pose accuracy" and "path accuracy" as well as "pose repeatability" and "path repeatability" r_{xp1a}, r_{xp2a}, r_{xp1r}, r_{xp2r} of this specific robot, since the points of removal are precisely defined. The "working space" r_{xw} is key with respect to the size of the structure. Only the "rated" load r_{xrl} of the robot is higher than necessary since the particles taken in one operation are very light.

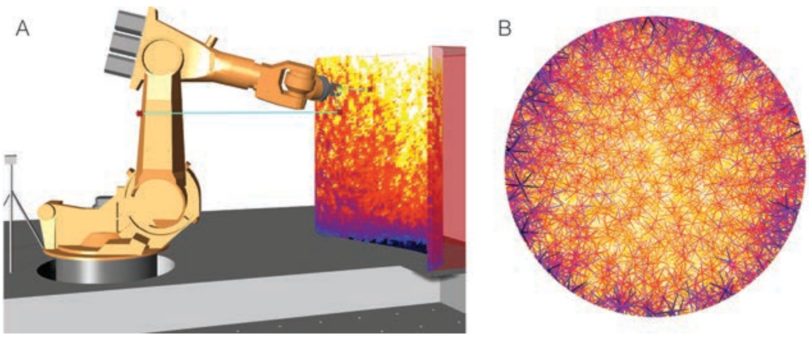

Figure A.8: Appendix A – Project 7. (A) A six-axis articulated robot is equipped with a gripper in order to remove particles from a wall of non-convex particles. (B) This is a process based on luminance values. Desislava Angelova | ITECH, University of Stuttgart | 2014 [12]

A.11 Appendix A – Project 8

Project credits — *Students:* Sven Bauer, Ludwig Ebert, Moritz Finkl, Julian Wengzinek | *Tutors:* Karola Dierichs, Tobias Schwinn, Oliver D. Krieg, Marshall Prado, Achim Menges | *Project type:* Seminar project | *Course:* "Robotic Aggregations" seminar | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2014

Design system category:
Construction systems – Locally effective construction systems – "End effectors" – Singling-out "end effectors" (see section 8.2.1.2.1)

Project description: The project carried out by Sven Bauer, Ludwig Ebert, Moritz Finkl and Julian Wengzinek in the "Robotic Aggregations" seminar at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart investigated an air-driven "end effector" for a six-axis articulated robot [34] (see figure A.9). A magazine was made from a slotted tube [34, pp. 9–11]. It had a release mechanism for the particles on the front of the tube and was connected to an air-blower at the opposite end [34, pp. 9–11]. The particles were lined up and the magazine was filled with them [34, pp. 9–11]. The release mechanism allowed the particles to flow out of the magazine at an even rate, while the air-blower pushed them towards the tip of the magazine [34, pp. 9–11, 13–15].

Design system category parameters: The singling-out "end effector" e_s can be developed into an effective tool for granular construction, especially since it allows the controlled emission of particles in both time and space. It consequently needs to be characterized in terms of particle flow per time unit $f_p[t]$ and particle orientation p_o. One disadvantage is the need to sort the particles in a linear fashion; however, secondary devices might be developed which alleviate this task, such as vibrating boards with slots. Another challenging aspect is the need to refill the magazine, which could also potentially be solved through an external loading device.

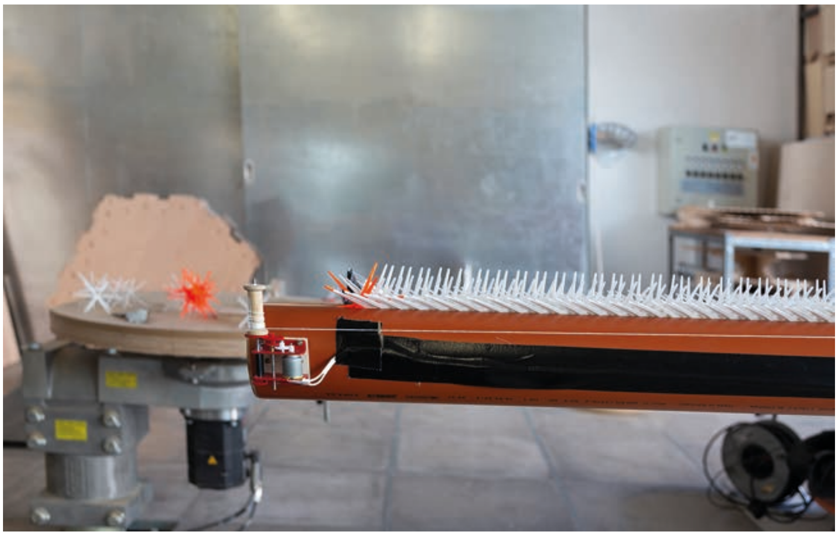

Figure A.9: Appendix A – Project 8. A tube fitted with an air-blower at the back and a slot on the top is equipped with a revolving dispenser to expel non-convex particles one by one. Sven Bauer, Ludwig Ebert, Moritz Finkl, Julian Wengzinek | ICD, University of Stuttgart | 2014 [34]

A.12 Appendix A – Project 9

Project credits — *Students:* Desislava Angelova, Ali Farhan, Yohei Kanzaki, Petar Trassiev | *Tutors:* Karola Dierichs, Tobias Schwinn, Oliver D. Krieg, Marshall Prado, Achim Menges | *Project type:* Seminar project | *Course:* "Robotic Aggregations" seminar | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2014

Design system category:
Construction systems – Locally effective construction systems – "End effectors" – Clustering "end effectors" (see section 8.2.1.2.2)

Project description: The project conducted by Desislava Angelova, Ali Farhan, Yohei Kanzaki and Petar Trassiev in the "Robotic Aggregations" seminar at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart aimed to develop an "end effector" for a six-axis articulated robot for the adding and removing of granular materials consisting of highly non-convex particles [14; 12]. A pneumatic radial gripper was provided; the main task consequently consisted of developing suitable fingers [14, pp. 13–21; 12, pp. 84–91] (see figure A.10). The seminar group initially developed a parametric model for the gripper geometry specifying the lengths of each finger joint as well as the angles between joints [14, pp. 14–17; 12, pp. 88–89]. Eventually two gripper types were developed: one from an acrylic sheet material which grabs small cluster of particles, one from bent metal rods which grabs larger clusters of particles [14, pp. 18–21; 12, pp. 90–91]. Both models had two fingers on each side, thus four in total [14, pp. 18–21; 12, pp. 90–91]. The fingers were used for the construction of a small-scale model of domes made from a designed granular material, which was dropped over inflatable spheres [14, pp. 29–33; 12, pp. 98–101].

Design system category parameters: One of the main aspects of investigation was the calibration of the average particle count per cluster c_p through adjustments to the geometry of the clustering "end effector" e_c. These calibrations are relevant with respect to the task at hand: fingers for smaller clusters allow detailed construction with designed particles, while fingers for larger clusters allow fast and rough processing.

Figure A.10: Appendix A – Project 9. A pneumatic radial gripper is fitted with fingers which allow it to grab clusters of non-convex particles. Desislava Angelova, Ali Farhan, Yohei Kanzaki, Petar Trassiev | ICD, University of Stuttgart | 2014 [12]

A.13 Appendix A – Project 10.1

Project credits — *Students:* Ondřej Kyjánek, Leyla Yunis | *Thesis advisors:* Karola Dierichs, Lauren Vasey | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2014–15

Design system category:
Construction systems – Locally effective construction systems – Control – Non-"sensory control" (see section 8.2.1.3.1)

Project description: The Master's thesis by Ondřej Kyjánek and Leyla Yunis was pursued in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart [103, p. 92; 102, pp. 25.11–25.12; 217]. It investigates non-"sensory" and "sensory controlled" robotic processes of particle assembly, granular material deposition, particle disassembly and granular material removal [103, p. 92; 102, pp. 25.11–25.12; 217] (see figure A.11). The thesis consequently serves as an example for both non-"sensory control" in this section and "sensory control" in section A.14. One particle was assembled from three sticks with a wax-bond, using a custom-made jig on an external axis; altogether three different particle sizes could be produced [217, pp. 62–70, 100–101]. The particle assembly was conducted using non-"sensory control" of a six-axis articulated robot [103, p. 92; 217, pp. 100–101].

Design system category parameters: The robot's "sensory control" r_{sc} is switched off $r_{sc}[f]$ during this assembly of the particle. That is possible since the workpiece coordinates and paths are always the same and exactly measured. On the one hand using non-"sensory control" has the advantage that particles can be produced rapidly. On the other hand, the production and deposition of the particles by one and the same machine enables the piece-by-piece formation of a granular structure, which is relatively hard to achieve, as particles are delivered as a ready-made unsorted mass in most cases.

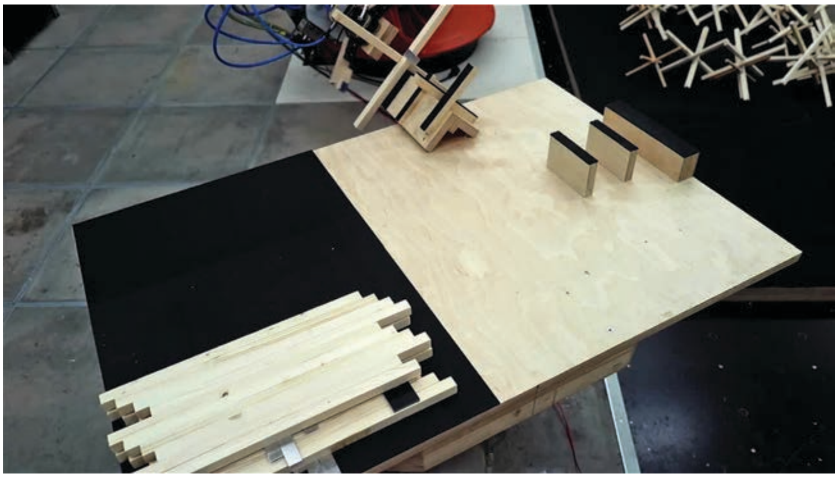

Figure A.11: Appendix A – Project 10.1. A six-axis articulated robot is deployed to produce non-convex particles using non-"sensory" control. Ondřej Kyjánek, Leyla Yunis | ITECH, University of Stuttgart | 2015 [217]

A.14 Appendix A – Project 10.2

Project credits — *Students:* Ondřej Kyjánek, Leyla Yunis | *Thesis advisors:* Karola Dierichs, Lauren Vasey | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2014–15

Design system category:
Construction systems – Locally effective construction systems – Control – "Sensory control" (see section 8.2.1.3.2)

Project description: As introduced in section A.13 the Master's thesis by Ondřej Kyjánek and Leyla Yunis was conducted in the context of the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart [103, p. 92; 102, pp. 25.11–25.12; 217]. The thesis explores both non-"sensory" and "sensory controlled" robotic processes of particle assembly, granular material deposition, particle disassembly and granular material removal [103, p. 92; 102, pp. 25.11–25.12; 217] (see figure A.12). The thesis consequently serves as an example for both non-"sensory control", as presented in the previous section, and for "sensory control", which is shown in this section. Whereas the particle assembly was non-"sensory controlled", the granular material deposition, particle disassembly and granular material removal required "sensory control" of the six-axis articulated robot, since the material behaviour plays a role in the process [103, p. 92; 102, pp. 25.11–25.12; 217]. Several sensors were connected to the robot and its "end effectors" [217, pp. 47–48]. A 3D scanner was used for deposition and removal of granular material in combination with a gripper "end effector" [217, pp. 47–49, 71–75, 78–85, 95–97, 102–109, 115]. A heat camera was deployed in combination with a heat gun for the disassembly of the particles by melting the wax joints [217, pp. 47, 87–93, 110–114].

Design system category parameters: The robot's "sensory control" r_{sc} needs to be switched on $r_{sc}[t]$ in order to integrate the data received from the sensors. "Sensory control" using 3D scanning during the granular material deposition and removal is relevant since the exact location of the material cannot be predefined. For the particle disassembly the heat camera enables the robot to identify the points in the granular material at which the heat gun for melting needs to be aimed.

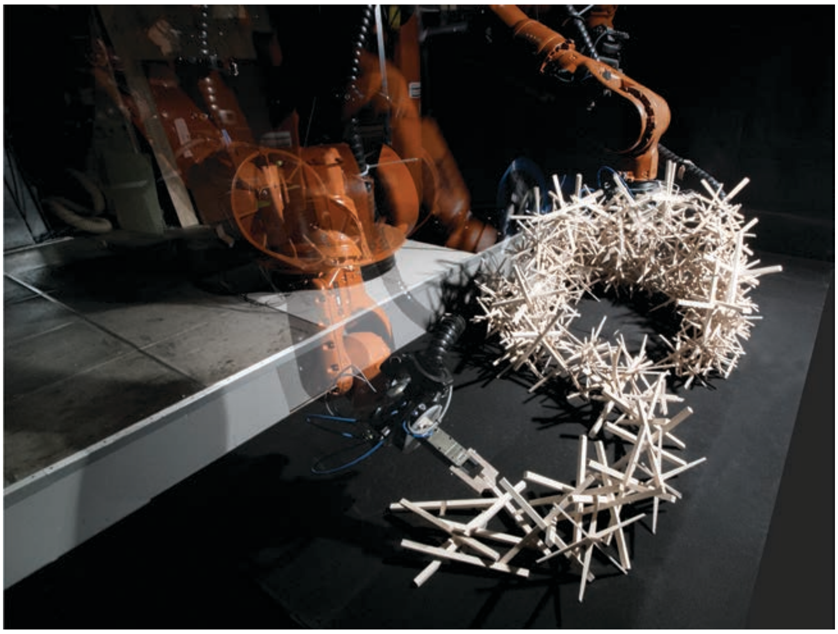

Figure A.12: Appendix A – Project 10.2. After non-"sensory" controlled production of non-convex particles, a six-axis articulated robot deposits them using "sensory" control. Ondřej Kyjánek, Leyla Yunis | ITECH, University of Stuttgart | 2015 [217]

A.15 Appendix A – Project 11

Project credits **—** *Student:* Alexander Kretzschmar | *Tutors:* Karola Dierichs, Achim Menges | *Project type:* Seminar project | *Course:* "Material Computation: Aggregate Architectures" seminar | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2010

Design system category:
Construction systems – Globally effective construction systems – Vibration (see section 8.2.2.1)

Project description: The seminar project by Alexander Kretzschmar was undertaken in the "Material Computation: Aggregate Architectures" seminar in 2010 at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart [102, pp. 25.8–25.9; 215]. It investigated the construction and deconstruction with double non-convex, hook-shaped particles using vibrations [102, pp. 25.8–25.9; 215]. The setup used two loudspeakers, one on top and one on the bottom of the construction space [102, pp. 25.8–25.9; 215, pp. 38–45, 52]. An entangled volume of hook-shaped particles was hung below the top loudspeaker and was vibrated by the speaker [102, pp. 25.8–25.9; 215, pp. 48–49, 53–54, 56–57]. The particle contacts were resolved through the vibrations, and the particles dropped onto a pneumatic formwork, which was placed in a box below them [102, pp. 25.8–25.9; 215, pp. 48–49, 53–54, 58–59]. The second loudspeaker was situated below the pneumatic formwork; it produced vibration and densified the granular material, while the particles dropped onto the inflatable [102, p. 25.9; 215, pp. 48–49, 53–54, 58–59]. Then, the inflatable was deflated and a dome remained [102, pp. 25.8–25.9; 215, pp. 49–50, 54–55, 59]. The bottom loudspeaker was vibrated and the particles disentangled from the structure and dropped into a container underneath [102, pp. 25.8–25.9; 215].

Design system category parameters: The vibrations v which are induced into the granular system act as a means of dissolving and of densifying the granular material. They can be characterized by their frequency v_f and amplitude v_a [25]. These two parameters can be investigated with respect to their specific effect on the dissolution and densification of the granular material.

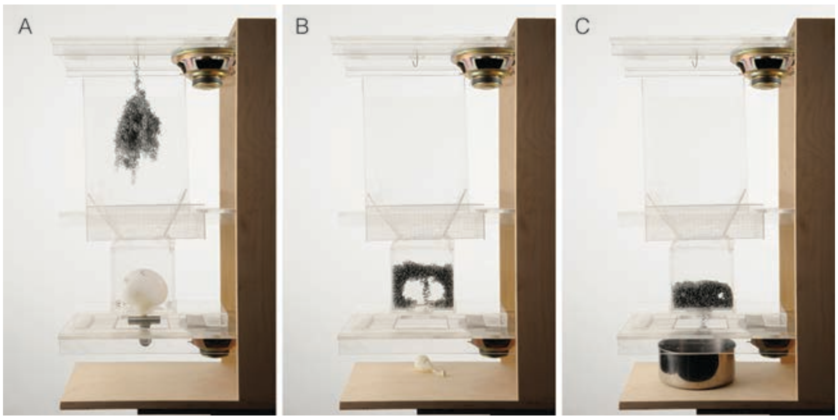

Figure A.13: Appendix A – Project 11. Vibration is used to (A) dissolve, (B) consolidate and (C) dissolve a designed granular material consisting of double non-convex particles. Alexander Kretzschmar | ICD, University of Stuttgart | 2010 [215]

A.16 Appendix A – Project 12

Project credits — *Student:* Benjamin Castro Moore | *Thesis advisor:* Karola Dierichs | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2013–14

Design system category:
Construction systems – Globally effective construction systems – Revolution (see section 8.2.2.2)

Project description: The Master's thesis by Benjamin Castro Moore was undertaken in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart [102, pp. 25.8–25.9; 58]. It explores construction processes with double non-convex, hook-shaped particles [102, pp. 25.8–25.9; 58]. The particles were made from metal rods in two different sizes [58, pp. 25–29]. The basic structural types which were tested were cantilevers and hanging domes [102, p. 25.8; 58, pp. 59–95]. Among others a construction system based on a revolutionary axis was tested [58, pp. 107–108] (see figure A.14). The revolution was induced into a cylindrical container using a motor [58, pp. 107–108]. The particles were sprinkled onto hooks fixed on the central axis of the cylinder [58, pp. 107–108]. They started to form strings, which cantilevered out once the system was rotated [58, pp. 107–108]. Hooks at the edge of the cylindrical container caught the rotating particle strings to form a hanging dome [58, pp. 107–108].

Design system category parameters: The revolution R can be used to define the overall size of the structure by the position of its centre R_c and the length of the revolutionary axis R_a. The entire construction system needs to be calibrated by the number of revolutions per time unit $R_n[t]$ in order to allow the granular material to span from the centre to the edges while the system is rotating. As a construction principle this system is relevant since it reduces operations to one single rotary motion affecting the entire system. As compared to other construction systems, it replaces the need for the construction system to cover the entire "working space".

Figure A.14: Appendix A – Project 12. Double non-convex particles are attached to the revolutionary axis of a cylinder. The cylinder is rotated and the particles fly out, attaching to hooks on the rim of the cylinder. Benjamin Castro Moore | ITECH, University of Stuttgart | 2014 [58]

A.17 Appendix A – Project 13

***Project credits* —** *Student:* Matthias Helmreich | *Thesis advisors:* Karola Dierichs, David Correa | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2014–15

Design system category:
Construction systems – Globally effective construction systems – Humidity or heat (see section 8.2.2.3)

Project description: The Master's thesis by Matthias Helmreich was conducted in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart [106, pp. 225–226; 103, pp. 92–93; 102, pp. 25.9–25.10; 172]. It investigates designed granular materials consisting of particles with a variable geometry [106, pp. 225–226; 103, pp. 92–93; 102, pp. 25.9–25.10; 172] (see figure A.15). Each particle consisted of four elements which were joined in the middle [106, pp. 225–226; 102, p. 25.10; 172, pp. 43–44]. These elements were made from bi-layer wood which undergoes a geometric change from straight to curved when the relative humidity (RH) in the environment is altered [106, pp. 225–226; 103, pp. 92–93; 102, pp. 25.9–25.10; 172, pp. 45–51]. The change from straight to curved can occur either by altering from low to high or in the opposite direction by altering from high to low relative humidity (RH); this can be adjusted via the lamination conditions [106, p. 225; 103, pp. 92–93; 102, p. 25.9; 172, pp. 52–57]. The particles were laid out in various patterns in order to control the behaviour of the overall granular material during entanglement [106, p. 226; 172, pp. 69–103]. Their geometric state was controlled through adjustments of relative humidity (RH) in a confined chamber [106, p. 226; 172, pp. 28–29].

Design system category parameters: The relative humidity *RH* in percent is controlled in an enclosed environment. This is one of the main construction principles. Controlled alterations in humidity lead to entanglement and disentanglement of the particles and consequently to a loose or a solid granular material.

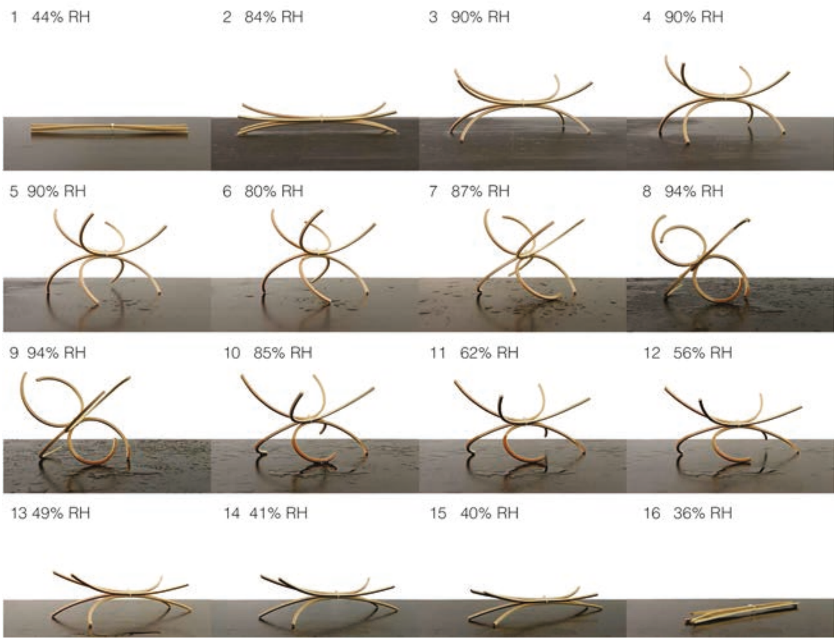

Figure A.15: Appendix A – Project 13. Relative humidity (RH) is used to affect the geometry of a particle which is made from a hygroscopically actuated shape-changing material. Matthias Helmreich | ITECH, University of Stuttgart | 2015 [172]

A.18 Appendix A – Project 14

Project credits **—** *Authors:* Karola Dierichs, Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Research assistants:* Federico Forestiero, Leyla Yunis | *Manufacturing:* Wilhelm Weber GmbH & Co. KG | *Client:* Design Society, Shenzhen, China | *Funding:* ITASCA International Inc. | *Year:* 2017

Design system category:
Construction systems – Boundary construction systems – Containers – Modular cuboids (see section 8.2.3.1.1)

Project description: The project ICD Aggregate Wall 2017 was an exhibition piece for the Design Society China for the opening of their venue in Shenzhen [59]. The ICD Aggregate Wall 2017 explored two aspects of granular materials consisting of highly non-convex particles. On the one hand the vertical angle of repose of these designed granular materials was highlighted. On the other hand, curvature was introduced in the x-, y- and z-directions, which led to a higher structural stability than that attained in a straight wall. The wall was made from circa 6000 tetrapods which had been injection moulded from recycled plastics. It had a length of circa 5000 millimetres and rose to a maximum height of circa 2000 millimetres. Its thinnest part was about 200 millimetres wide. The formwork was made from the packaging boxes (see figure A.16). These were joined with a custom-designed clip-system. Two types of clips were used: standard aluminium u-profiles to join the boxes vertically and custom-designed laser-cut profiles to align the boxes horizontally to achieve the pre-defined curvature.

A static box container was used on the outer curves and faces of the wall, a slip-container was used on the inner curves.

Design system category parameters: The length b_l, width b_w and height b_h of the box is the basic defining factor of a box container system c_b. In this case Euroboxes have been used, which have a standardised, modular system across different sizes. The other basic defining factor is the overall amount of the deployed boxes b_n. Ideally the number of boxes needed as a container corresponds to or is less than the packaging of the entire granular material. The types of custom-made clips are specific to this project and allow the basic box system to become a geometrically controlled container using the packaging material, which is entirely reusable.

Figure A.16: Appendix A – Project 14. Storage boxes of non-convex particles are deployed as a modular container system for a curved wall. Karola Dierichs | ICD, University of Stuttgart | 2017

A.19 Appendix A – Project 15

***Project credits* —** *Authors:* Karola Dierichs, Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Research assistant:* Federico Forestiero | *Manufacturing:* Wilhelm Weber GmbH & Co. KG; Andreas Kulla, Holzwerkstatt für Architekturmodelle und digitalen Modellbau, University of Stuttgart | *Client:* Vitra Design Museum, Weil am Rhein, Germany; MAK – Austrian Museum of Applied Arts / Contemporary Art, Vienna, Austria; Design Museum Gent, Ghent, Belgium | *Year:* 2017

Design system category:
Construction systems – Boundary construction systems – Containers – Developable surfaces (see section 8.2.3.1.2)

Project description: The project ICD Aggregate Column 2017 was developed for the exhibition *Hello, Robot. Design Between Human and Machine* [284]. The ICD Aggregate Column 2017 had a diameter of 600 millimetres and a height of 2000 millimetres. The project is one of the most basic explorations of the potentials of designed granular materials consisting of highly non-convex particles, namely the ability to form a 90-degree angle of repose. The designed granular material in this specific case was composed of tetrapodal particles which had been injection moulded from recycled plastics. The container was designed as a travelling case which had a cylindrical inner cavity made from two layers of bending plywood with a thickness of six millimetres each (see figure A.17). The case was filled from the top. It could be folded open on the vertical side, so that the column emerged as one piece, which could be exhibited without any further construction processes needed.

Design system category parameters: The developable surface container system c_s in this case takes the form of a cylinder. Its radius and height are set and consequently define the length of the unrolled surface s_l as well as its width s_w. The thickness of the surface s_h is chosen so as to allow for the extremely tight bending radius of the surface s_r. The advantage of using a bent container in this case is the fact that the outline of the column is accurately defined and easily repeatable for different installations of the structure.

Figure A.17: Appendix A – Project 15. A box with an inner cylinder, which is made from bent sheet material, serves as a formwork for a column made from non-convex particles. Karola Dierichs | ICD, University of Stuttgart | 2017

A.20 Appendix A – Project 16.1

Project credits* — *Doctoral candidate: Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2018

Design system category:
Construction systems – Boundary construction systems – Formwork – Different type of particles as formwork (see section 8.2.3.2.1)

Project description: Two types of hexapods were combined in order to investigate the use of a designed granular material as a formwork. The particles which were deployed for the structure were hexapods of the type 50/6/20/0.5 with a diameter of 50 millimetres. They were made from polyamide (PA) 2200 produced with selective laser sintering (SLS). The particles which were meant to function as a formwork were hexapods, with a diameter of 20 millimetres. These were made from transparent acrylic and were produced using injection moulding. The test was conducted in a box with inner dimensions of 300 by 300 by 300 millimetres. Below the box was an outflow hole of 120 millimetres diameter, which had a removable lid. The hole was situated at the edge of the container so that a sectioned dome was formed.

As a base test the container was filled with the hexapods of the type 50/6/20/0.5 only. The lid was removed from the outflow hole. Circa eight hexapods fell out, forming a very low cavity of circa 20 millimetres height and circa 70 millimetres width. Then, as a feasibility test of this system category, the container was filled with the acrylic formwork hexapods of 20 millimetres diameter. These were dropped onto the bottom lid to form the geometry of a half-cone using their angle of repose, measuring 100 millimetres in height and 120 millimetres in width. Once the half-cone covered the lid, the container was filled with the structure particles, namely the hexapods of type 50/6/20/0.5. The bottom lid was removed. All of the formwork particles flowed out and a sectioned dome was formed measuring 85 millimetres in height and 120 millimetres in width (see figure A.18).

Design system category parameters: The geometry in which the formwork particles are distributed in p_{fg} defines the interior space. In this case it is a half cone formed by the angle of repose of the acrylic formwork hexapods. The percentage distribution of the formwork particle type p_f and of the structure particle type p_s are measured in percent of the total built volume V_b, which is 87.8 per cent and 12.2 per cent respectively.

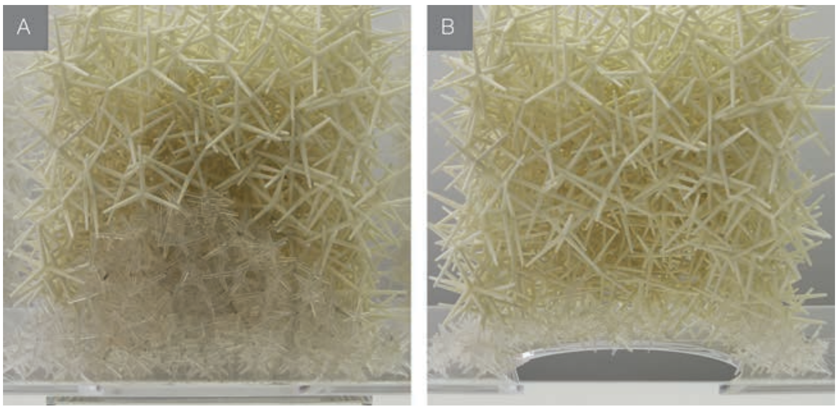

Figure A.18: Appendix A – Project 16.1. (A) Hexapods with a diameter of 20 millimetres are deployed as a formwork for hexapods with a diameter of 50 millimetres. (B) Once the bottom lid is removed, the formwork particles flow out. This is an example of using different types of particles than in the main structure as a formwork. Karola Dierichs | ICD, University of Stuttgart | 2013–18

A.21 Appendix A – Project 16.2

Project credits* — *Doctoral candidate: Karola Dierichs | *Supervisor:* Achim Menges | *Project type:* Doctoral research | *Institution:* Institute for Computational Design and Construction (ICD), University of Stuttgart, Stuttgart | *Year:* 2013

Design system category:
Construction systems – Boundary construction systems – Formwork – Same type of particles as formwork (see section 8.2.3.2.2)

Project description: The tests investigated the formwork principle of using only one particle type, where the opening in a container was deployed to release part of the particles. The particles at the release flowed out, and the remaining particles then formed a spatial enclosure. Hexapods measuring 20 millimetres in diameter were the only particle type used in this test. They were made from a transparent acrylic by injection moulding. As a container a box measuring 200 by 200 by 200 millimetres was deployed, which had circular bottom lids of different diameters. The diameters of the bottom lids were dimensioned as multiples of the particle diameters, namely two particle widths, four particle widths, six particle widths and eight particle widths. The hole sizes were thus 40, 80, 120 and 160 millimetres. The bottom lids intersected with the edge of the container to allow the formation of sectioned domes. Altogether four tests were conducted, one for each size of the bottom lid. In each test the container was filled with the hexapods, after which the bottom lid was removed. For the bottom hole of 40 millimetres diameter a small sectioned dome formed, roughly 15 millimetres in height and 20 millimetres in width. For the bottom hole of 80 millimetres diameter a high sectioned dome formed, roughly 100 millimetres in height and 80 millimetres in width. For the bottom hole of 120 millimetres diameter a high sectioned dome formed, roughly 160 millimetres in height and 120 millimetres in width. The dome half collapsed on one side (see figure A.19). For the bottom hole of 160 millimetres diameter a sectioned dome formed, roughly 190 millimetres in height and 160 millimetres in width.

Design system category parameters: The opening in the container c_o is used to release part of the particles. Defining for the resulting spatial geometry are the length c_{ol} and width c_{ow} of the opening, in this case the different diameters of the circular lids. Measuring the velocity of release of the opening lid r_v would be a valuable next step.

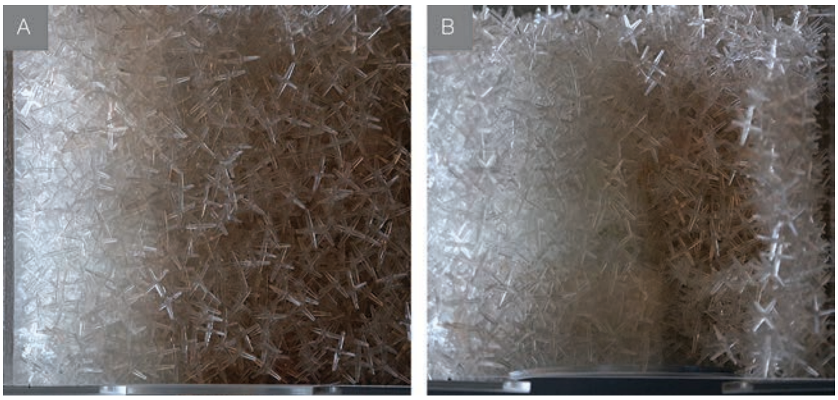

Figure A.19: Appendix A – Project 16.2. (A) A container is filled with the same type of particles. (B) A bottom lid is removed and a small dome forms over the outflow hole. Karola Dierichs | ICD, University of Stuttgart | 2013–18

A.22 Appendix A – Project 17

Project credits — *Student:* Gergana Rusenova | *Thesis advisors:* Karola Dierichs, Ehsan Baharlou | *Thesis supervisor:* Achim Menges | *Second supervisor:* Jan Knippers | *Sponsor:* ITASCA Education Partnership (IEP) Research Program | *Project type:* Master's thesis | *Institution:* Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart, Stuttgart | *Year:* 2014–15

Design system category:
Construction systems – Boundary construction systems – Formwork – One-piece formwork (see section 8.2.3.2.3)

Project description: The Master's thesis by Gergana Rusenova was pursued in the Integrative Technologies and Architectural Design Research (ITECH) programme at the University of Stuttgart [103, p. 92; 306; 305]. It proposes a pneumatic formwork for designed granular materials which was driven based on the evaluation of a discrete element method (DEM) simulation [103, p. 92; 306; 305] (see figure A.20).

A group of four commercially available inflatables were fixed into a ground plane [306, pp. 65–66; 305, pp. 94–103]. When a designed granular material was distributed on top of the inflated inflatables, dome-like spaces were formed once the inflatables were deflated [306, pp. 65–66; 305, pp. 104–111]. The inflatables were inflated and deflated with a valve system which was controlled through a parametric modelling software package [306, p. 66; 305, pp. 94–103]. A discrete element method (DEM) simulation of the entire experimental setup was integrated into the parametric model [103, p. 92; 306, pp. 64–65, 66–69; 305, pp. 43–87, 114–133]. Through this integration the inflation and the deflation of the inflatables could be controlled based on the predictive data of the granular material's behaviour, which were obtained from the discrete element method (DEM) simulation [103, p. 92; 306, pp. 66–69; 305, pp. 114–133].

Design system category parameters: In this project the one-piece formwork f_o is determined by its centre point f_{oc} as well as by the radii of the principal curvatures f_{or1} and f_{or2} of the inflatable [39, p. 117]. In this case it is the pneumatic actuation of the one-piece formwork f_o, which is key to the project, since it allows the interactive and reversible actuation based on the simulations.

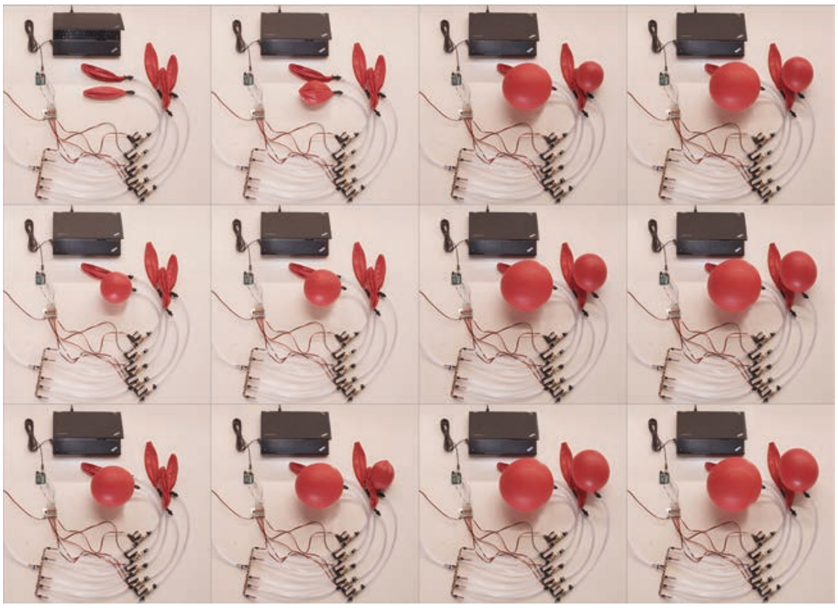

Figure A.20: Appendix A – Project 17. An inflatable formwork for domes made from non-convex particles is controlled by statistical discrete element method (DEM) simulations. Gergana Rusenova | ITECH, University of Stuttgart | 2015 [305]

B
Glossary

The glossary gives a brief definition of technical terms particular to this thesis, which are used in the main text. Only commonplace technical terms are included here; technical terms which are specific to the thesis are defined in the respective sections of its main part.

B.1 Aggregate

An aggregate is defined as matter consisting of high numbers of discrete particles which is added to cement or lime to produce concrete [327; 145]. It is thus a granular material, but more specifically the type of granular material that is used in concrete construction as an additive.

B.2 Angle of repose

The angle of repose is defined as the "maximum angle" which a granular material forms to a horizontal surface, once it has come to rest [7; 146]. Parameters affecting this angle are "particle size and angularity, the degree of interlocking between particles, and pore-water pressure" [7].

B.3 Arch

An arch is the inversion of a hanging chain [39, p. 96]. The basic geometry of an arch is a curve [147]. The arch spans between two supports, which can be either articulated or clamped [39, p. 96; 147].

B.4 Aspect ratio

The aspect ratio is the result of the division of the "longest to the shortest dimension of a shape or object" [18].

B.5 Coordination number

In granular physics the coordination number is understood as the amount of neighbouring particles which any given particle in a granular material has on average [40, p. 1095; 54, p. 181].

The term stems from crystallography, where it describes the amount of surrounding composite or individual elements for any given component element in a "complex or crystal" [221].

B.6 Dome

A dome is a spatial structure which has the geometry of a hemisphere [148]. A dome is generated by rotating an arch around a vertical axis [39, p. 112].

B.7 Granular material

A granular material is defined as matter which consists of large amounts of discrete particles which are larger than a micrometre and between which mainly short-range contact forces are acting [222]. For a more elaborate definition of the term see section 1.1.1.

B.8 Nonuniform rational B-splines (NURBS)

A NURBS curve is "the ratio of two nonuniform B-spline curves" [53]. A B-spline curve is "a polynominal function, defined over a knot sequence, that has local support and is nonnegative" [52].

B.9 Parameter

A parameter is a quantifiable unit of a shape or a material [151]. Its values can be adjusted in order to achieve different resultant shapes or material properties [151].

B.10 Particle

A particle is defined as a "small part or fragment of a material" [152].

B.11 Platonic solid

A Platonic solid is a regular convex polyhedron [67]. This means that all faces have the same count of edges and that the same count of edges meet at every single vertex [67]. Five Platonic solids are known: the tetrahedron, the cube, the octahedron, the dodecahedron and the icosahedron [67].

B.12 Solid angle

The solid angle is "the 3-dimensional analogue of the 2-dimensional concept of angle" [68]. It is described by a cone and measured in the unit of steradian (sr) [68].

B.13 Vault

A vault is a spatial structure, the basic geometry of which is a linear array of arches, which is a barrel vault [153; 39, p. 113]. Other vault types are the cross vault, the rib vault and the fan vault [39, p. 113].

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Biography

Karola Dierichs is a researcher in the field of computational design and construction in architecture. She has has studied at the Technical University of Braunschweig, the Swiss Federal Institute of Technology (ETH) Zurich and the Architectural Association School of Architecture (AA) and graduated from the Emergent Technologies and Design (EmTech) programme at the AA with Distinction in 2009.

During her time at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart she has conducted research on granular architectures, where she has developed designed granular materials as architectural design and construction systems. She has published in her field and lectured both within Europe and the USA. Her research has been recognized with the Holcim Acknowledgement Award Europe 2014 and a materialPREIS 2019 Acknowledgement in the Study and Vision category. Selected works have been included in the travelling exhibition *Hello, Robot.* that started in 2017 at the Vitra Design Museum and the opening exhibition *Minding the Digital* of the Design Society in Shenzhen.

Abstract

The thesis investigates designed granular materials in architecture. Granular materials are both fully recyclable and reconfigurable due to the fact that the individual particles are in no way bound to each other. However, designed granular materials, in addition to being recyclable and reconfigurable, bear the potential for the development of entirely novel material behaviours. These three aspects make them a highly relevant area of design research. In the context of architecture, designed granular materials can be considered as a form of "material systems". In the wider transdisciplinary context they can be seen as a form of "designer matter (DM)".

The current state of research into designed granular materials is presented for both architecture and granular physics, on a conceptual as well as on a project-based level. In this context the thesis aims to establish and validate a first version of a comprehensive design system for exploring designed granular materials in architecture and for interfacing with granular physics.

The core part of the thesis comprises the design system and a related design system catalogue as well as two case studies. The design system formulates the basic categories and parameters for particle and construction systems. The design system catalogue summarizes tests which investigate individual aspects of the overall design system for particle and construction systems. Each of the two case studies explores the integration of a different set of design system categories. They were conducted both through full-scale prototypes and a related set of tests with statistical repetition. The case studies are evaluated with respect to their practical, methodological and conceptual contributions to architectural design research.

The thesis is summarized and further research in the field of designed granular materials in architecture is outlined on the practical, methodological and conceptual level of design. Key to any further development of the overall research field is the integration of the two fields of architecture and granular physics.

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