Hybrid design workflows of digital crafting and material computation

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ABSTRACT

In this paper, we are presenting a number of research projects, which illustrate a design methodology developed by Research Cluster 6 (RC6) of The Bartlett's Graduate Architectural Design program, positioned on the overlap between the digital (agent-based design strategies and generative form-finding) and analogue computation strategies (material behaviour and crafting techniques). In that context, RC6's agenda argues for a new kind of craft, rooted in a thorough understanding of traditional, hands-on craft combined with expertise in contemporary computational concepts. In this regard, research presented in this paper primarily focuses on merging traditional, low-tech manufacturing processes with advanced technological approaches to design and realise new spatial concepts. Particular interest lies in novel combinations of analogue and digital methods in which hands-on and computer-controlled design and manufacturing operations do not just co-exist but overlap. The two projects presented in this paper, SanDPrint and FaBrick, address these premises through custom developed form-finding and fabrication processes, and test them through 1:1 scale prototypes.

INTRODUCTION

In this paper we discuss the design methodology and research approach carried out by the Bartlett GAD Research Cluster 6 (led by Daniel Widrig, Stefan Bassing and Soomeen Hahm). This is done through the presentation and breakdown of unique workflows, which re-evaluate the role of craft and hands-on production in the digital design domain under the umbrella of the "Crafting Space" agenda.

The research agenda of RC6 argues for a new kind of craft, rooted in a thorough understanding of traditional, hands-on craft combined with an expertise in contemporary computational concepts. The conducted research primarily focuses on merging the traditional, low-tech manufacturing processes with advanced technological approaches to design in order to realise new spatial concepts. In that sense, it is positioned on the overlap between the digital (generative form finding) and analogue computational strategies (material behaviour and crafting techniques). The emphasis here is on exploring the methods for overcoming the discrepancies between the top-down and bottom-up decision making processes, while exploring the benefits of previously mentioned different design inputs - material behaviour, generative agency or human/designers' input.

This was done through a series of individual architectural scenarios / research projects, which address these premises through custom developed form-finding and materialisation processes. These ideas as well as the resulting research and educational projects will be demonstrated in the paper. All of the proposals - prototypical structures, architectural objects and products - are built and tested in a 1:1 scale.

RESEARCH CONTEXT

With the advent of new digital design and manufacturing technologies, designers are working at a pace and resolution unimaginable just a few years ago. Digital systems allow designers to accumulate, structure and utilise massive quantities of information to parametrically shape products and the built environment. Likewise, the corresponding fabrication technologies, such as 3D printing or robotics, synthesise these projects in an increasing scale and resolution, employing rapidly expanding ranges of "digital materials". While these software and hardware systems facilitate rapid design and production, tactile interaction with form and matter throughout the design and fabrication process is increasingly scarce.

Following the application of such systems, new sets of questions, constraints and concerns emerge. While we are now able to rapidly materialise almost any form, we are struggling with issues such as high cost of parts, limited material choice and large-scale applicability. In addition, fully automated fabrication systems often force designers into rather linear production pipelines with little room to manoeuvre or improvise. Since machining is expensive and time consuming, the actual process of making is often delayed to the very end of the design phase, usually delivering highly predictable, pre-simulated results. In such workflows notions of spontaneity, artistic intuition and noise are usually undesirable.

In this context RC6 seeks to explore hybridised design and fabrication models, in which tactile interaction with materials and form initiates and drives all research efforts. We embrace messiness as opportunity, and failure as part of the invaluable learning process. We are particularly interested in novel combinations of analogue and digital methods in which hands-on and computer controlled design and manufacturing operations do not just co-exist but overlap. With the research in such customised, semi-automated processes RC6 engages in the evolution of a new, crafted aesthetic, one that reflects a shift from an architecture predominantly interested in representation and tools towards an architecture that brings new notions of craftsmanship, intuition, and a post-digital design sensibility.

FABRICATION AND MATERIAL SYNTHESIS

A number of design and manufacturing disciplines, such as fashion, product and automotive design, are rapidly adapting to previously mentioned new fabrication technologies - particularly additive manufacturing or 3D printing of market-ready products. Noteworthy examples of this include works by fashion designer Iris van Herpen, who utilises rapid prototyping to produce couture pieces, as well as Nervous System - a design studio which works at the intersection of science, art and technology and utilises digital fabrication to create affordable art, jewellery and housewares. In contrast to this, rapid prototyping in an architectural context is still mostly reduced to being a fast and painless way of creating representational models, instead of using its potential for architectural production and to bring a new materiality into the architect's increasingly virtual studio. This is at least partly due to the fact that, until recently, only the larger, commercial practices and institutions could afford this expensive equipment. The reduction in cost of these machines, coupled with the general democratisation of tools (soft- and hardware) will change this. The spread of open source/DIY equipment, shared knowledge and innovation in the bypassing of patents both in terms of machine construction as well as the production of consumables now allows us to economically create complex parts, enabling smaller studios to utilise these systems.

Material research and material computation are often dealing with the post-construction lifecycle of the object. Their translation into computational models is limited to material property simulations within the closed linear system of design and production, missing the tactile interaction between the computer generated form and matter.

Likewise, the application of cutting-edge fabrication techniques such as 3D printing and robotic fabrication is often constrained to predefined modes of production. In such cases, the manufacturing technique is disconnected from the design process and used purely as a means of production of advanced and intricate geometries, without the direct feedback between the two. Examples of such application can be seen in the pioneering 3D printed work of Behrokh Khoshnevis at USC and Enrico Dini of D-Shape.

With the increasing affordability of 3D printers, and recent developments of affordable robotic arms (EVA by Automata Technologies), it is inevitable that such tools will become an integral part of RC6's two-fold approach. However, in spite of advanced material research and robotic fabrication booming recently (Achim Menges at ICD Stuttgart, Gramazio&Kohler at ETH, MIT Mediated Matter group), these avenues of design research are often disconnected. In the robotic fabrication process, machines are often used as end effectors, pre-programmed to deposit (extrude, cut, aggregate) the material as intended by the design, creating 1:1 representation of computer generated form. Robotic fabrication workflows should come from fabrication techniques and inherited properties and latent qualities of used materials, creating a feedback loop between machine and material limitations and properties, and the design, which evolves through received feedback.

GENERATIVE DESIGN TOOLS AND METHODS

With all of us more and more dependent on ready-made fabrication strategies, pre-made scripts and black box ("off the shelf") technology, an unbiased evaluation of our computational design culture is increasingly difficult. Within that context RC6 seeks to re-evaluate the role of craft and hands-on production in the digital design domain. This is done through continuous exploration in hybridised design and fabrication strategies in which digitally-controlled techniques of form-finding and manufacturing naturally blend with existing crafting techniques and low-tech ways of making.

In regard to application of off-the-shelf software packages in architectural practice and academia, Senske (2014) notices the importance of designer's thorough understanding of the used tools, where using off the shelf packages often results in designers using tools without comprehension of the inner working of the tools themselves.

There is no denying that algorithms are becoming an inseparable part in the processes of both the design and production of complex geometrical solutions. However, here the algorithmic approach is often used as optimisation strategy or for geometry rationalisation. Such examples can be seen in the work of Philippe Block and his research group at the ETH Zurich, which is efficiently using topological analysis algorithms in order to simulate and resolve structural issues in the design of shell structures. The project for Qingdao Cultural Centre by ZHA utilises rain-flow analysis algorithms as a means of phenomenological articulation. Here the perceptual identification of functional units and their relations are facilitated by the surface articulation of the structural shells, derived from the algorithm. Examples of custom applications, such as processing libraries do exist within the design community - iGeo by Satoru Sugihara or Plethora by Jose Sanchez, to name a few. However, as elaborate as they are, parts of such libraries are either focusing on a specific design problem, or are not directly built around a specific design workflow.

DESIGN METHODOLOGY - TOOLS, GENERATIVE METHODS & AESTHETICS

Now in its third year, the RC6 - Crafting Space agenda argues for unique workflows, which form a seamless pipeline throughout the entire design process - from the initial concept stage to its fabrication. This comes as a result of a pursuit for new architectural aesthetics, which emerge from innovative way of thinking about material computation and fabrication, while at the same time searching for creative applications of available tool sets in combination with cutting edge technologies and computational powers. The resulting designs are derived from generative systems, which manifest the material behaviours. Manoeuvring between disciplines and techniques, RC6 seeks to occupy in-between territories where traditional and contemporary ways of designing and making blur into one.

HYBRIDISED WORKFLOWS

With this in mind, the presented design methodology combines top-down and bottom-up approach on one hand, and how manufacturing iterations and techniques feedback the computational models on the other. Here, computational models are not just representational, nor do they consist of material property simulations. In this sense, they are bound to fabrication logic and its constraints. Furthermore, they constantly feed back to the manufacturing process, effectively closing the design-to-manufacturing loop.

Throughout the year, RC6 traditionally works in multiple scales. With a particular focus on physical production, students gradually increase the scale and scope of their work through iterations of prototyping. Later stages of the research are dedicated to the development of a proposal in which material experimentation, applied prototyping, coding and modelling converge into a coherent architectural design proposal.

With regards to this, the proposed design approach is not technique biased. Meaning that we are taking an eclectic, multi-platform, multi-disciplinary approach, with the intention to hack into crafting techniques and corrupt digital workflows. In this sense, the research questions the following:

- Tactile interaction between digital models and physical products
- Black box technology and ready-made fabrication techniques
- The balance between the top-down and bottom-up approach, and the influence this balance has on the aesthetics of the product

In an attempt to achieve this, we are driven by material computation, material performance and its tectonics and the tactile feedback between the digital and physical. We are taking an holistic approach, where we look at the common methods between digital design and manufacturing processes, embedding the generative logic with fabrication constraints, resulting from analogue computation or machine/material limitations.

The analogue computation refers to exploration into material performance, physical manifestations of proposed systems and their tectonic protocols. The design systems are firmly grounded in rigorous research on material behaviour, as well as in its formative and structural properties. From this material uncertainty and unpredictability of hybrid material systems, the true design research can emerge.

DESIGN APPLETS

Custom design applets, programmed in Processing, are developed to support design craft, and not a means for themselves, with the intention of closing the gap between digital simulation and fabrication. The goal was to create scenario specific applets/design engines, establishing the connection between initial inputs, which drive the design and its iterations, and previously mentioned design and fabrication constraints. This approach contrasts project specific scripts (one end of the spectrum) or black-box program packages, which are robust and overly 'open' (other end of spectrum).

As mentioned, the design process for each scenario was two-fold, addressing the fabrication techniques as the means of producing full-scale prototypes, and computational design techniques, which were guiding the design process and establishing generative logic. The computational techniques used in this process are primarily based on the application of multi-agent systems, as a means of achieving heightened control of architectural matter as well as producing novel spatial and formal outputs. Design applets are specifically designed for each of the testing scenarios, in order to respond to and engage with the selected fabrication techniques.

CASE STUDIES

The following chapter introduces student projects developed under the umbrella of the "Crafting Space" agenda. Projects developed within RC6 range from projects derived from a specific material or fabrication system to projects driven with a specific computational technique. While all of the projects address both material computation and application of generative design techniques, we can group the projects into 3 main categories, according to the dominant methodology that drives the process:

- Material behaviours
- Hybrid Material Systems
- Generative computational systems

However, this paper will focus on two projects that are centred around the investigation of material behaviour in conjunction with innovative engineering techniques. The point of departure in these two cases was an exploration into unorthodox material systems, rarely used within the building industry. Projects SanDPrint and FaBrick (which use sand and felt fabric respectively) illustrate the process in which such material system is driving the creation of an innovative construction method.

SANDPRINT

Starting from the interest in casting techniques using recyclable moulds, SanDPrint (Xiyangzi Cao, Shuo Liu and Zeyn Yang) conducted thorough research on a unique mould-making technique which uses rubber tubes and sand. The goal was to create an easily available and low-cost fabrication method, using abundant material in a way that is uncommon in everyday architecture practice, by simulating 3D printing with a low-tech crafting technique. Precedents of similar approach can be found in the works of Victor Castaneda, who developed a series of bowls made from casting plaster over naturally created divots, and Max Lamb, who adapted a primitive form of sand casting, filling the

Figure 1 Fabrication Process // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang

Figure 2 Process of removing the casted piece from the sand mould // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang

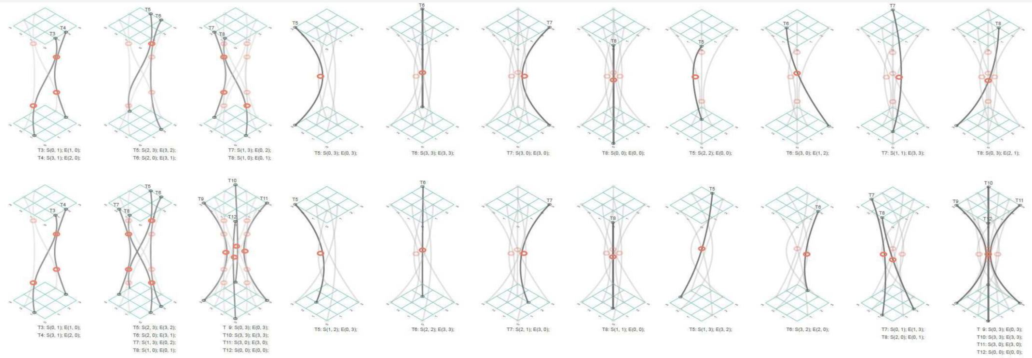
relief carved into the beach sand with molten pewter in order to create furniture pieces.

In the SanDprint fabrication process the mould is formed from wet sand, which is placed around the rubber tubes. Once the tubes are removed, a casting material such as plaster, concrete or metal is poured into the holes. The curvilinear nature of the rubber tubes, in combination with the fine texture which would be formed on the surface after the sand was removed, provided the design of high aesthetic qualities through an easily affordable low-tech fabrication technique (Figure 1 and 2). In addition to this, a removable frame was designed to stabilise and control the direction of the tubes.

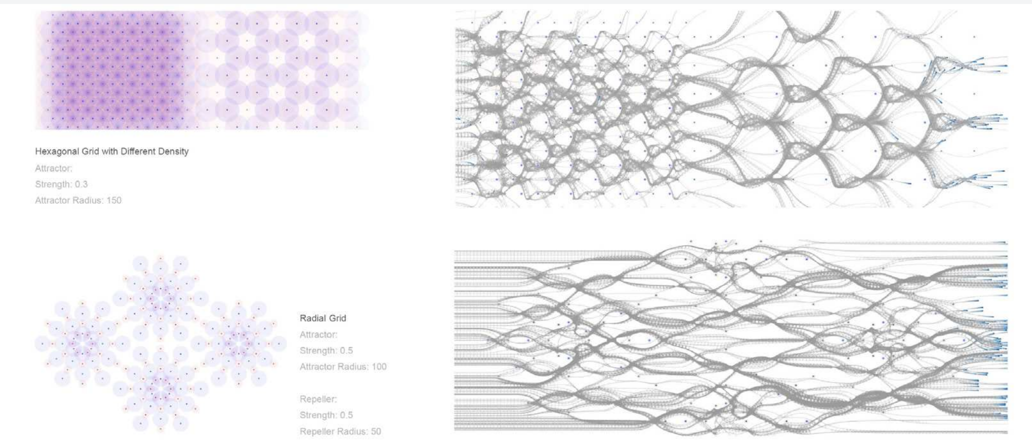
The rubber tubes had constant section, which in combination with rubber material flexibility and low friction allowed them to be extracted from the mould. Furthermore, the type of sand and grain size, as well as their combination with castable materials of different grains established the basic set of design constraints. Sand had to be of a grain small enough to capture the form created by the tubes, whereas the casting material had to be able to flow through the mould without blocking the tunnels. Likewise, the particle size and the drying speed of the sand affected the structural properties of the sand. In regard to the choice of casted material, parameters such as drying time, liquidity and permeability drove the decision towards plaster over resin, cement and a plaster and cement mixture.

Furthermore, the tubes themselves could be bundled only up to a certain point, since if the internal columns were to thick, the mould would internally collapse. In addition to this, specific tube curvature constraints were established. The tube curvature could not be too steep, as it would result in breaking the mould during the extraction process. These constraints – the angle of the branches and the number of branch generations - informed the digital models. Initially, this was translated into a generative process based on the logic of L-systems, which was used to generate the triple branching networked structures, which would later on be translated into tubes for fabrication.

Applying the mentioned constraints derived from the material system, a specific design language of bundled curves was developed. The patterning language was informed by three principal operations of tube cohesion, tube rotation and combination of the two (Figure 3). The digital system would take into consideration parameters such as the maximum number of bundles per column, minimal distance between bridging points, and curvature constraints. Based on the conclusions of initial digital studies, a more elaborate



▲ **Figure 3** Tube patterning operations // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang



▲ **Figure 4** Processing simulation and patterning study // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang

▲ **Figure 5** Full scale SanDPrint column prototype // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang

▲ **Figure 6** Interlocking column detail // GAD RC6 / Team SanDPrint: Xlyanzi Cao, Shuo Liu & Zeyn Yang generative process was established, based on multi-agent systems. Here the agent behaviour was informed with the same constraints and parameters, while the tubes were derived from agent trails (Figure 4).

All of the furniture scale prototypes were designed with 1:1 parameters in mind, where the number of agents/trails and distance between them would take into consideration diameter of the tubes that were used in the fabrication process. Following this, larger scale structures were also further tested digitally. The size of the each fabricated object was essentially limited by the size of the supporting frame. In order to efficiently fabricate larger pieces, techniques such as distributed casting, continuous casting, as well as the interlocking of smaller casted components were tested (Figure 5 and Figure 6).

FABRICK

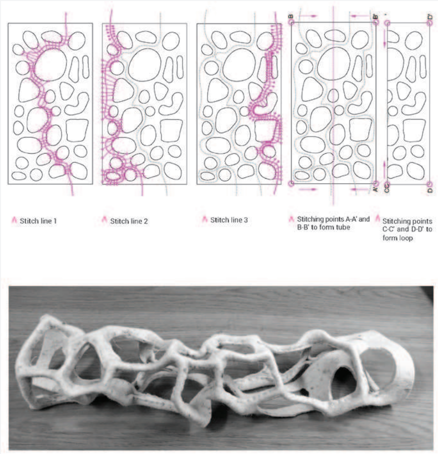
Inspired by the dramatic advances within the field of textile and fashion design, the FaBrick project (I-Ting Tsai, Somdatta Majumdar, Xixi Zhend, Yiru Yun) investigates the correlation between the development of new material craft in the form of couture architecture and the architectural design and fabrication process. With the idea of developing quick and easy methods for designing and fabricating space, this couture architecture project examines the wider implications of textiles in space creation, changing the way that fabric is perceived in architecture. The project links fabric manipulation processes, typically used in the fashion industry, with digital modes of design and fabrication, creating a new typology of fabric architecture.

Traditionally viewed as a flat and two-dimensional material, fabric has mostly been used in architecture as a surface sheet and roofing material, without fully exploring the material's versatility. With this in mind, FaBrick conducted research into a composite material system using felt fabric, and resin, with the fabric as primary structural material, rather than a secondary element to other components in the structural system. The material properties of felt were used to produce 3-dimensional structures from 2-dimensional sheet material by traditional stitching techniques. Softness and malleability of the fabric were used as an advantage in the process of forming complex geometrical shapes.

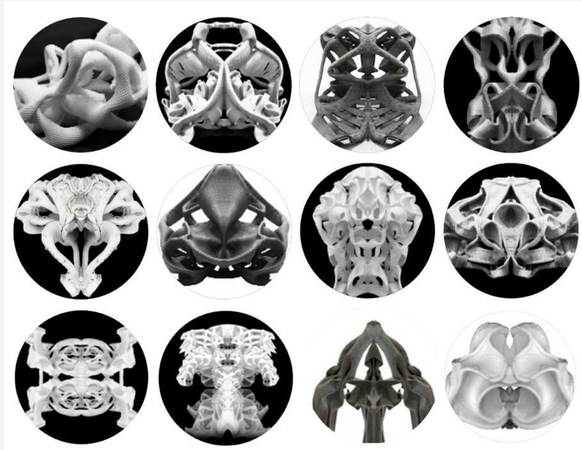
The fabrication process would start by cutting a pattern in the material and stitching the fabric along the cut seams (Figure 7). The shape of each prototype piece was created by cutting out sections from a flat sheet of fabric using a laser cutter. The fabric would then be stitched and folded into one of the three types of formal components (Figure 8):

- Surfaces and creases
- Holes and tubes
- Cut slits

Initially fabric would be moulded into pipe-like structures that could support the weight of the remaining material. After the rest of material is stitched and shaped the hardening material cures to create a completely self-supporting object. Here, different composites (mixtures with wood glue, resin etc.) can be applied to a single piece of material, creating varying levels of rigidity. This logic has been carried further as the main structural principle in the process of production of 1:1 prototypes (Figure 9 and Figure 10). Load-bearing elements would be folded into tubular sections, ensuring stability. The idea here was to create a continuously connected "structural skin", which gradually transitions from linear (tubular) elements, to surfaces and volumetric shapes. These elements would be further combined and reinforced with seams and ridges - transitioning from 2D to 2.5D elements.

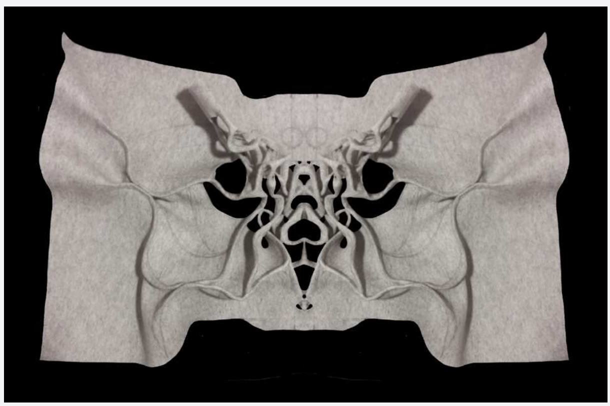


▲ **Figure 7** Cutting pattern // GAD RC6 / Team FaBrick: I-Ting Tsai, Somdatta Majumdar, Xixi Zhend, Yiru Yun



▲ **Figure 8** Catalogue of formal components // GAD RC6 / Team FaBrick: I-Ting Tsai, Somdatta Majumdar, Xixi Zhend, Yiru Yun

▲ **Figure 9** FaBrick chair prototype // GAD RC6 / Team FaBrick: I-Ting Tsai, Somdatta Majumdar, Xixi Zhend, Yiru Yun



▲ **Figure 10** FaBrick surface prototype // GAD RC6 / Team FaBrick: I-Ting Tsai, Somdatta Majumdar, Xixi Zhend, Yiru Yun

Further folding of the tubular and surface elements would result with 3-dimensional arrangements. This allowed for the creation of objects with varying surface and structural properties, depending on the applied formal components, as well as on strategic placement of rigidifying composite material.

The digital workflow itself was set up in order to develop two different aspects of the project in parallel - simulation of stitching and aggregation of smaller objects. Due to the size constraints it has become apparent that in order to scale-up, prototypes could not be made out of a single sheet of felt, but would rather be created as an assemblage of interconnected smaller pieces.

Simulation of high-resolution fabric is computationally very expensive, and reducing the resolution of digital models would result in loss of complexity in comparison with the physical experiments. With this in mind, it became apparent that a hybrid approach of multiple digital strategies (combining generative and explicit modelling) and constant feedback between digital and physical models based on material limitations is of absolute necessity. This directly influenced the digital simulations, which focused on developing the relationship between two-dimensional patterns of felt sheets and three-dimensional geometry, through simulation of folding and stitching behaviours. This relationship between the two-dimensional patterns and the resulting 3D geometry, as well as the design language of travelling seams which would act as the connections between smaller components, presented the basis of the FaBrick digital design repertoire, where different digital techniques were used for simulating different formal components. While surfaces and slits were treated with fabric simulation engine and generative methods were established for creating of tubes and holes, slits and seams were generated through explicit modelling techniques.

CONCLUSION

The presented projects illustrate the importance of closely integrating digital crafting techniques with fabrication protocols, as well as the importance of establishing constant feedback between the two. This can effectively be achieved through the use of custom design applets that take the design methodology as the common denominator for the two ends of creative process. This approach creates a general framework for design research without being overly prescriptive, allowing for the unexpected and novel outcomes to emerge.

While navigating between digital and physical worlds, the approach of crafting agency is able to produce results of high complexity and resolution, while being able to offset the imprecisions in the manufacturing process, unlike the standard linear fabrication processes. This comes as a result of embracing the noise and failure as integral part of the design process, which combines analogue and digital modes of production as inseparable parts of complex design ecology.

CREDITS

The presented projects were developed within Bartlett GAD Research Cluster 6 Crafting Space agenda, during 2013/14 (SanDPrint) and 2014/15 (FaBrick) school years.

- Bartlett GAD RC6 tutors: Daniel Widrig, Stefan Bassing & Soomeen Nahm
- Team SanDPrint: Xiyangzi Cao, Shuo Liu & Zeyn Yang
- Team FaBrick: I-Ting Tsai, Somdatta Majumdar, Xixi Zhend & Yiru Yun

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