Discrete Assemblage as Design and Fabrication Strategy

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CONTEXT: FROM ANALOGUE TO DISCRETE
Architectural experimentation with computational processes in the past two decades, the so called first digital age,[1] has proposed a "morphogenetic" [2] model based on ideas of continuity, growth and organism. Architects such as Greg Lynn, used concepts of Deleuze and D'Arcy Thompson to imagine an organic model for architecture. A digital blob growing, adapting and folding under influence of a field of abstract forces. This idea of architecture corresponded to new ideas of topology, found within 3D modelling software packages. This particular focus on topological continuity resulted in research which privileged surface over volume. However, the growth of this architectural "embryo" had no initial relation to a structure or tectonic system, due to the fact the field of forces it developed in had most often little to no relation to structural force or constructive constraints. Initially, the only tectonic systems that could be relied on were grid based "waffle-cut" or "egg crate" systems. These rectangular grids were usually constructed out of CNC-milled timber or metal sheets to recreate the desired form. Architects were forced to post-rationalize their complex surfaces into discrete, mass-customized elements, which had to be numbered and micro-managed in a labor intensive process of assembly. Most of these projects suffered from intrinsic structural problems, and in effect ended up being a mere panelization held up by a standardized, Cartesian structure. This practice quickly became popular and after a mere two decades is seen in many contemporary buildings today. For example, the *Soho Galaxy,* by Zaha Hadid Architects, follows exactly this approach. Its form is an initially continuous shape that is sliced into horizontal floor plates, then held up by a grid of columns, stiffened with cores. This grid is then wrapped with a metal frame and panelized to achieve a fluid, continuous effect.

Recent research in generative design by offices such as Kokkugia, Biothing and EZCT, have focused on a more bottom-up approach, where the final form is less predetermined and emerges from the interaction of lower level elements. As Mario Carpo describes in his article "Breaking the Curve":

> *The inherent discreteness of nature [...] is then engaged as such, ideally, or in practice as close to its material structure as needed, with all of the apparent randomness and irregularity that will inevitably appear at each scale of resolution.*[3]

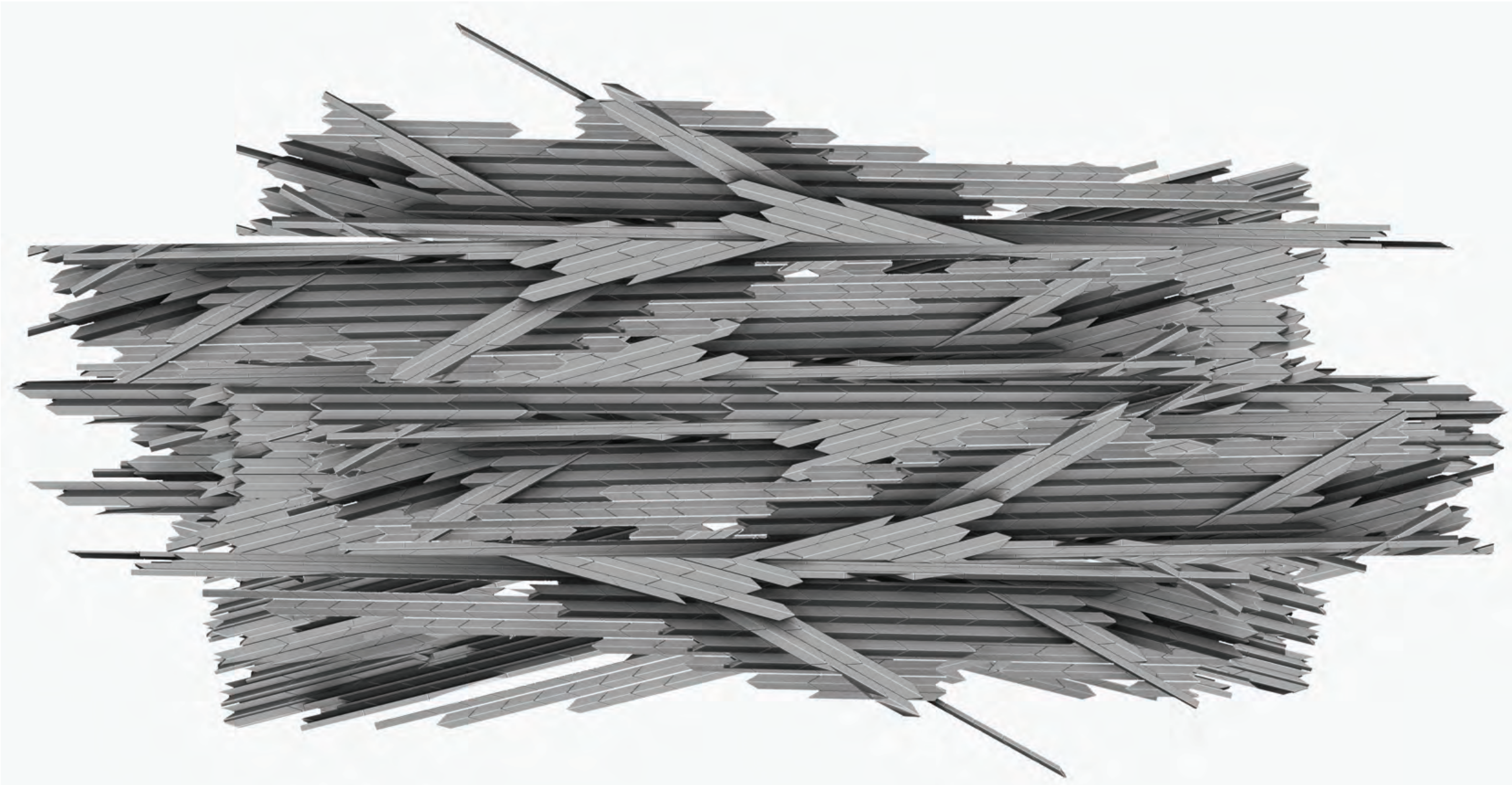


Figure 1: Blokhut drawing.

However, just as in the first digital age, this second digital age of "big data" is in intrinsic trouble with tectonics and materialization. To materialize the second digital age's explorations, old techniques are required: CNC milling molds, 3D printing, and mass-customization of building components. Just as the continuous-organic approach, the generative paradigm has an inherent limited economy of means. It requires complicated, time-intensive manufacturing and micro-managing of thousands of elements during assemblage, and it often ignores structural and constructive parameters. Although the work takes into account large amounts of data, it is still developing algorithms which require continuous fabrication. Most of the algorithms underlying the "big data" work, such as recursive subdivision, fractal growth, cell-division, agents or reaction-diffusion are driven by observations into natural systems, effectively found-objects, which are then appropriated to become architectural. The algorithms used often don't take into account any constraints relating to materialization, structure or constructability. This results in a big gap between design and fabrication. To solve this gap, increasingly complicated and expensive processes are required, such as extreme computing power, robotic vision, expensive sensors, and extensive human labor. This tools are used as problem-solvers to patch up the gaps between design and fabrication, rather than as powerful computing devices which could streamline a fabrication process.

Digitally intelligent architecture will always remain in trouble with tectonics if it does not align its algorithmic logic with the logic of materiel organization or fabrication. So what does it actually mean for buildings or material organizations to be discrete and digital? Can material be organized in the same way as data?

Current rapid-prototyping machines are fundamentally continuous or analog processes. Although many fabrication machines are digitally controlled, these machines continuously cut or add material to make parts. Can machines additively assemble multiple materials to make functional structures rather than simply cutting or extruding material into representational objects? [4] *(Ward, 2010).*

In other words, analog fabrication is based on continuously aggregating material with an infinite connection scheme. Whereas digital or discrete fabrication is based on assembling parts, which the geometry provides metrics and constraints, limiting the connection scheme to a precise digit: yes or no.[5] 3D printing, just as CNC milling, is fundamentally a continuous fabrication process, which may leave us with an interesting form at the end, but fundamentally produces objects which are completely analog. A 3D printed vase, which may have been generated with a complex algorithm, is still going to be analogue once printed. Whether you 3D print a Mickey Mouse, a Corinthian column or a digitally generated sculpture, there is no difference in the final product beyond the form. The organization of material is in all cases the same: it is a continuous extrusion of material, sintered or stuck together with a binder, and it has no relation to the underlying computational process. This is different with discrete fabrication. The part computed digitally is also the part assembled physically. The organization of physical parts is the same as the organization of the digital data.

When fundamentally addressing this issue of discrete or digital fabrication versus analog fabrication, the concept of assemblage and prefabrication comes back into play. For example, Skylar Tibbits researches how discrete elements can self-assemble into an object, which can continuously disassemble, aggregate and change. Jose Sanchez argues for differentiation to emerge from the interplay of resources and social innovation rather than a centralized idea of growing form and differentiation by an omnipresent designer (Sanchez, 2014).[6]

Further back in time, there are several precedents of discrete architecture. Consisting of a limited number of serially repeated timber joints, the traditional Chinese Dou Gong bracketing system can also be understood as a digital material. It is able to produce heterogeneous structures with a multiplicity of scales. In the twentieth century, Frank Lloyd Wright's experiments with the textile blocks engaged with the idea of discreteness. Also, late-modernist structuralism by architects such as Hertzberger, Van Eyck, and Tanghe explored rule-based designs to systematically relate discrete spatial components and programs.

The design method described in this paper is based on the assembly of cheap, standardized, discrete elements into indeterminate, heterogeneous, and differentiated spaces with a high degree of economy. The focus is on a minimum degree of customization for a maximum of differentiation, detail, adaptability and economy. Instead of continuous computational processes which require heavy computational power, these processes are light and can be run in a browser. They don't require expensive equipment and super-specialized knowledge, which remain the monopoly of big institutions or companies. The tools to compute and fabricate are accessible to everyone. They can be run in a browser or from simple applets. Instead of technologically complicated and expensive continuous fabrication, discrete manufacturing is fast, cheap and accessible.

DISCRETE DESIGN

Blokhut: Dutch for Log Cabin. A hut built of whole or split logs.[7]
As a case study of aligning discrete computation and fabrication, the "Blokhut" (2014) was developed. Initially a study for a villa in a Belgian suburb, the design became prototypical for the new approach towards computational

Figure 2: Blokhut atrium study.

Figure 3: Blokhut column study.

design discussed before. The prototype started out with a given: due to a limited budget, a large part of the structure would have to be standardized and made out of cheap elements. The large model of 2x1.5x0.3 m, weights over 150 kg and is built using 4000+ pre-cast plaster components, intersecting and joining around a limited number of customized 3D printed zones. The plaster component is designed as an arrow-shaped brick, with a male and female connection. The arrow-like connection is able to interlock two bricks together in a fixed position. This discrete arrow-shaped building element can be understood as a digital material. *The design possibility, or the way how elements can combine and aggregate is defined by the geometry of the element itself — which leads to a "tool-less" assembly (Cheung 2012).* The Blokhut prototype establishes a differentiated and adaptive architectural system which consists for 90% of serially repeated, discrete, prefabricated concrete elements, and for 10% of unique, customized 3D-printed pieces. The argument shifts from a system where everything is mass customized, with a labor intensive assembly process, to a limited number of super intensive, rule-changing customized zones or glitches and a large number of serially repeated, cheap material. The finished state of the model is undetermined. It can be extended or contracted at any time. The final geometry is messy, redundant and un-simplified. The Blokhut prototype can be constructed without the need for micro-managing thousands of unique, numbered pieces. Instead, the 3D printed components and bricks set out the instructions for assembly. The assembly is "plan-less" and "tool-less", as the geometry of the pieces defines the aggregation.

The material organization does not respect topological continuity. Different strata of elements are self-intersecting, and building elements not only aggregate linearly into surfaces, but can also aggregate three dimensionally into thicker volumes. The organization of building components follows different intensities and patterns in different parts of the structure. For example, towards the ends of the cantilevers only one layer of tiles exists, whereas in the middle parts and towards the central area, double and triple layers are used to deal with higher levels of stress.

The Blokhut prototype proves that serial repetition of very simple, cheap, prefabricated digital materials is a feasible and accessible method to achieve detailed and adaptable forms. However, the system could have been further optimized if it would introduce an economy of scale. The construction system has no hierarchy of scale in the building elements, there is only one size. A good reference would be a process like Octree optimization, a procedure used in 3D graphics where a space is partitioned with different scales of voxels depended on the resolution required. Translating this to an economic concept; it would make more sense to work with a range of scales in elements. Assembly time could be radically reduced if the core of a model would be made with a few large-scale elements, instead of a few thousand pieces. This economy of scale is an important advantage over classic 3D printing methods, which are not scalable. Moving on from the rather simple and constrained arrow-shaped digital materials used in the Blokhut prototype, elements could be imagined which don't only construct a whole, but are more clearly at the same time part and whole. For example, a digital material which acts at the same time as brick, surface, column and beam would improve structural performance, and establish a more radical diffusion between different hierarchies in the model. Increased capabilities for parts to interlock and support neighboring parts can be developed, introducing patterns of structure in the system. After the initial prototype for the Blokhut, several more test cases were developed. For a museum competition at the Karlsplatz in Vienna, the bricks construct a series of horizontal strata which develop into large column-like elements. Another abstract atrium-like model was developed which shows how an entirely different spatial structure can be achieved with the same method. The same elements were also used as a base unit for a masterplan in Shenyang, China, which is introducing entire buildings as autonomous discrete units within a master plan.

DISCRETE FABRICATION

There has been a lot of speculation in the building industry about 3D printed buildings—including by myself and the SoftKill Collective, when we proposed the Proto-House in 2012, one of the first designs for a fully 3D printed building. The main interest from industry and government lies in the promise of speed and simplified workflow, rather than the formal or aesthetic properties. A 3D printed dwelling, however, will always be constructed slower than a robotically assembled, prefabricated dwelling which makes use of larger components, parts or particles. The potential of rapid assembly and prefabrication in the digital age is illustrated by the Broad Groups project for a 57-story skyscraper. This was assembled in just 19 days in Changsha, China, due to their advanced control over the workflow.[8]

As a continuous method, 3D printing fundamentally suffers from scalability, structural problems such as cantilevers, and more importantly, it has a big problem with multi-materiality.[9] For example, a process which can print at the same time glass and concrete, is hard to imagine, as both materials require different printing techniques. This means that even if a building would be printed out of concrete, one would still have to rely to ideas of assemblage to incorporate insulation, transparency, finishes, etc. On the other hand, it is easy to imagine a prefabricated brick consisting of multiple layers of materials, such as a structural layer, a layer of insulation, waterproofing, finishing and so on. An assembly based process has the potential to differentiate the materiality of parts and particles, introducing transparency, electrical conductivity, channels for air or water flow, all on different recursive scales.

Robotic arms are used in the industry for a number of discrete, repetitive operations. For example, in the car industry, robots spot weld a number of edges, or lift a heavy object from one belt to the other. In architecture, it was Gramazio Kohler who initially explored the first use of robots as serial assemblers, through stacking bricks in the *Programmed Wall* (2006).[10] The *Programmed Wall* is however controversial as the brick as an element is specifically optimized for handling with a human hand. The robot is not used to its full potential as it could easily lift 10 times the weight of the brick, while maintaining the same precision. Gramazio Kohler's assembly process can be understood as a continuous process, as the bricks placed have no fixed geometric position. Pure robotic assemblage

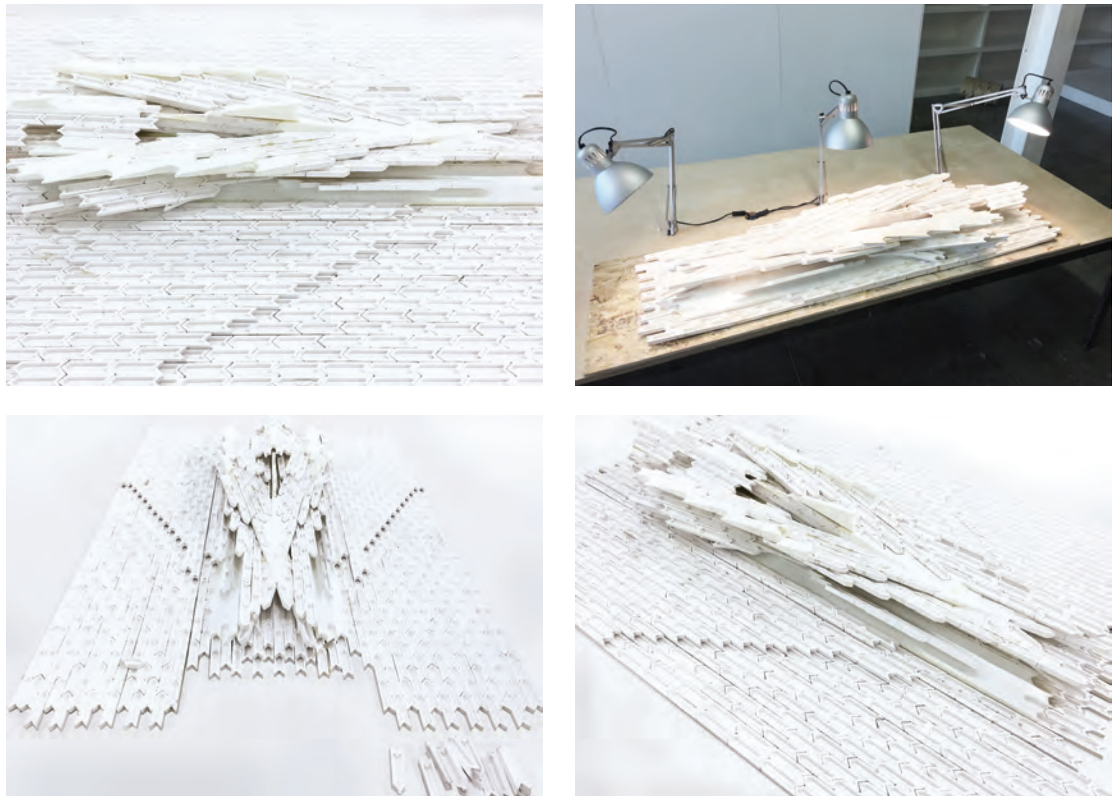


Figure 4: Blokhut chunks.

processes prove to be very difficult, and have probably been pushed furthest projects such as Gramazio Kohler's *Complex Timber Structures* (2012).[11] The main constraints in robotic assembly are so called singularities. These are made up of intersections with material which have been previously deposited, or with the robot itself. A project such as *Complex Timber Structures* has to be carefully planned over a period of several weeks in order to be assembled, as every assembly sequence is different. Complex assembly processes require increasingly advanced technologies to function, such as real-time sensors and robotic vision.

Robotic assembly is only feasible in the context of digital materials and discrete computation, which has a limited set of connectivity problems and as such requires little troubleshooting or problem solving. The components and high degree of serial repetition in the Blokhut makes a robotic assembly process more feasible. The parts are organized in a grid or voxel-like pattern, the connection between elements is repetitive, and the connection problems themselves are always discrete, neighbor-neighbor or part-part problems. The discrete element can be understood as a brick on the scale of a machine rather than a human. With a length of 1.8 m and a weight of 150 kg, it would be not feasible to manually assemble the parts, but an industrial robot would do what it is best at: high precision combined with high payload. Using one or more robots, the Blokhut prototype could be assembled, adapted and disassembled quickly. The proposed methods do not necessarily have to rely on the use of expensive industrial robots. Other types of robots or machines could be used, such as cable robots, or parallel "termite bots,"—small robots which can carry a digital material, and use the already deposited digital material as a geometric guide.[12]

STRANGE MEREOLOGY

What are the implications of a fundamentally discretizing architecture? In the Blokhut project, the basic unit operates at an intermediate scale between brick and spatial module. This intermediate scale effectively increases the resolution of the tectonic articulation, while diffusing and fragmenting fixed architectural types such as columns, slabs, and stairs. In a similar connection to voxelization, the Blokhut introduces a simple piece of architectural matter that is able to diffuse vastly different geometries and different architectural typologies—even those who were previously taboo for the digital age such as the Miesian slab. This shifts the discussion from topological form and spatial definition to purely a discussion about part-to-whole and part-to-part relations. The discussion about the spatial articulation, the actual "whole" constructed out of the parts, becomes in itself secondary to the question of the politics of the part. This allows harvesting from different spatial types which have been developed over time: Miesian slabs, Adolf Loos's Raumplan, Eisenmann's grids, or Gehry's paper bags all become accessible and lose their ideology.

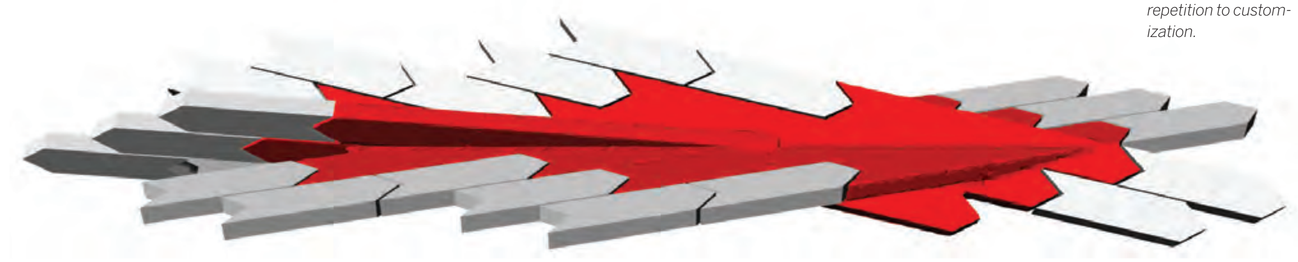
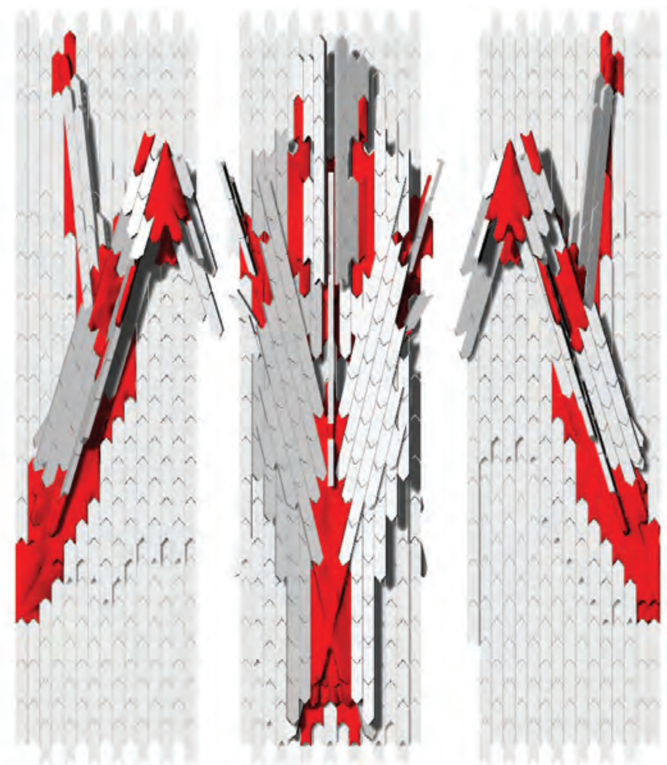


Figure 5: Organizational diagram showing the transition of serial repetition to customization.



This is one of the underlying reasons why the Blokhut project and subsequent experiments articulate themselves as "modernist" slabs. It is a provocation to argue for the importance of the tectonic material organization, the politics of the parts, rather than the spatial manifestation. This is a provocation for the more holistic and morphogenetic approach advocated by the generative designers, which would like to see "true" spatial form emerging from the interaction between the parts. However, it has to be pointed out that a recursive range of scales could be developed in the parts; with the largest scale becoming for example a spatial unit.

To better understand the relationship between part and whole in the particular case of the Blokhut, we can turn to the concept of Strange Mereology developed by Levi Bryant. Wherein mereology is the philosophy of part-to-whole relationships, pioneered by Lesniewski,[13] Bryant develops strange mereology as a situation where *parts aren't parts for the whole, and the whole isn't a whole for the parts*.[14] There is a complex set of part-part relations, and part-whole recursion. In the morphogenetic first digital age, parts are domesticized by the whole and derived from the whole. In the generative or second digital age, the emphasis is often reversed; there are only part-part relations, and the part-whole relation is one of emergence. The whole is not predefined, and expected to arise out of the interaction of lower level parts. The final whole is established at the moment that the designers' criteria, whatever they are, are satisfied. The strange mereology approach aims to overcome both problems: parts are not a product of the whole, and at the same time the whole can't be reduced to the logic in the parts. The Blokhut achieves this partly through the customized glitches, which allows the system to gain form from a maneuver which lies outside of the design agency of the tiles. The introduction of columns as new, independent, autonomous architectural objects is also complicit in establishing "strange" part-to-whole relationship. The columns develop autonomously from the bricks. This introduces an agency in the mereological system which enhances the aggregation logic of the bricks, allowing them to cantilever and proliferate horizontally. At the same time, they reduce their agency and impact the overall whole. The columns effectively establish a sort of ecology of interdependencies within the mereology of the model. Although there is no formal coherence between the column and the bricks, their position allows the bricks to bypass extreme deflection and tension forces appearing at the ends of the large cantilevers. Within the morphogenetic first digital age, the addition of the columns would be considered a taboo. And the argument would be made that the basic elements should take the extreme cantilever into account. However, I would like to argue here that the use of the columns introduces a higher degree of differentiation and heterogeneity in the system, which would otherwise only consist of a single logic, or a single object. The model cannot be reduced to a singular, homogenous logic or

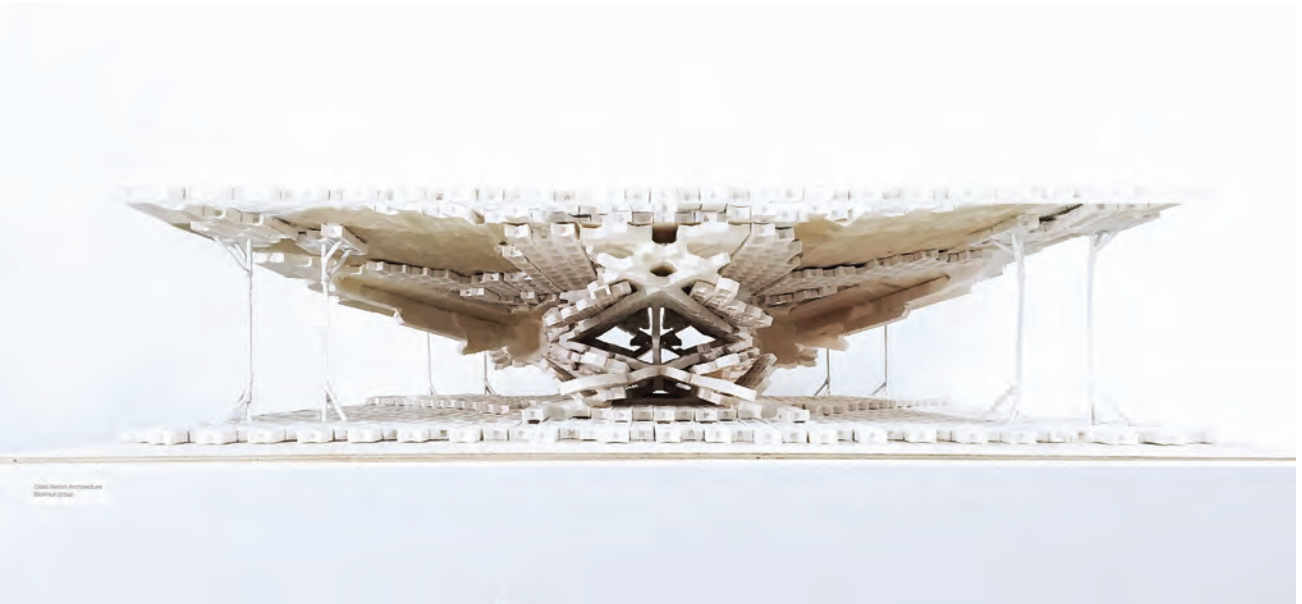


Figure 6: Large-scale physical model of the Blokhut.

whole, but introduces a far less predictable and more agile system with more formal possibilities. For example, the large cantilever and visually uninterrupted facades would have been obstructed if the morphogenetic logic was followed. The strata of aggregated tiles effectively depends on the exact positioning of the columns to be possible. An ecology of interacting, mutually interdependent architectural objects is created, resisting a singular, wholifiying ideology and emphasizing discrete systems which are morphologically autonomous from each other, but functionally related and computed.

LOW-ENTROPY HETEROGENEITY

The gap between simulation and fabrication emerged as a problem coming from the morphogenetic research's failure to align design and fabrication methods. The first digital age designed continuous, fluid forms, which had to be discretized into thousands of analogue bits of material. The morphogenetic-generative work which followed afterwards introduced a more complex and discrete part-to-whole relationship, based on the idea of emergence. However, they relied on the same analogue, continuous fabrication techniques like CNC milling and 3D printing. This focus on continuous fabrication methods deepened the gap between design and materialization. To bridge between simulation and reality, increasingly expensive and complicated technologies are needed. Caught up in a spiral of problem solving with expensive equipment, the second digital age also became inaccessible for many. The part-to-whole relationship or materiel organization of the objects produced, however, is still analogue. In order to make digital objects, to effectively bridge the gap between computation and fabrication, a shift is required towards fundamental discreteness. By aligning discrete computation and discrete fabrication, a new kind of fundamentally digital architecture, which has a complex or "strange" mereology, is uncovered. Through serial repetition of cheap, digital materials, a detailed, adaptive, and complex architecture becomes feasible and accessible.

ENDNOTES

1. Mario Carpo, "Breaking the Curve: Big Data and Design," in *ArtForum*, February 2014.

2. Branco Kolarevic, "Digital Morphogenesis and Computational Architectures," in *Proceedings of the 4th Conference of Congreso Iberoamericano de Grafica Digital, SIGRADI 2000 - Construindo (n)o Espaço Digital (Constructing the Digital Space),* Rio de Janeiro, Brazil, September 25–28, 2000, eds. José Ripper Kós, Andréa Pessoa Borde, and Diana Rodriguez Barros, 98–103.

3. Carpo, "Breaking the Curve."

4. J. Ward, "Additive Manufacturing of Digital Materials" (PhD thesis, Massachusetts Institute of Technology, 2010).

5. Kenneth Cheung and Neil Gerschenfeld, *The geometry of the parts being assembled provides the dimensional constraints required to precisely achieve complex forms (Cheung).*

6. J. Sanchez, "Post Capitalist Design: Design in the Age of Access," in *Paradigms in Computing,* eds. David Jason Gerber and Mariana Ibanez (New York: eVolo, 2014).

7. Oxford Dictionaries, accessed October 22, 2015, http://www.oxforddictionaries.com/definition/english/log-cabin.

8. http://www.telegraph.co.uk/news/picturegalleries/worldnews/11485389/Chinese-company-builds-57-storey-skyscraper-in-19-days-in-pictures.html.

9. The Objet printer gradually differentiates stiffness and color within one material.

10. Fabio Gramazio, Matthias Kohler, and Jan Willmann, *The Robotic Touch* (Zurich: Park Books, 2014), 44.

11. Gramazio, Kohler, and Willmann, *Robotic Touch,* 384.

12. Neil Gerschenfeld and Kenneth Cheung (Cheung 2012), as well as Justin Werfel of the Wyss institute at Harvard University (Werfel 2014), propose these types of robots as Voxel Assemblers.

13. Mereology (from the Greek μ, "part") is the theory of parthood relations: of the relations of part to whole and the relations of part to part within a whole. The term was coined in 1927 by Polish philosopher Leniewski. In "Notes to Mereology," accessed October 22, 2015, http://plato.stanford.edu/entries/mereology/notes.html#1.

14. Levi R. Bryant, *The Democracy of Objects* (Ann Arbor: Open Humanities Press, 2011).

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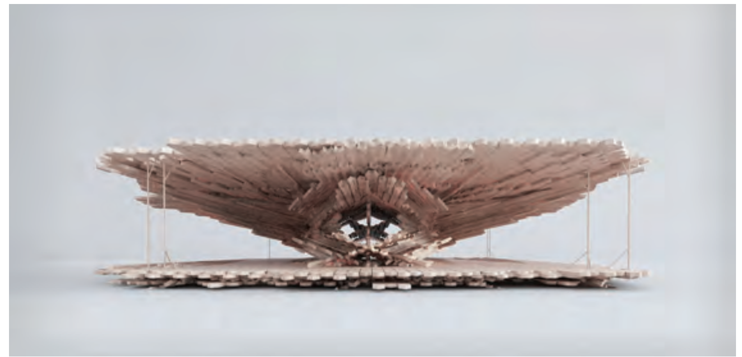

Figure 7: Blokhut renderings.

Gramazio, Fabio, Matthias Kohler, and Jan Willmann. 2014. *The Robotic Touch*. Zurich: Park Books.

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Ward, J. 2010. "Additive Manufacturing of Digital Materials." PhD thesis, Massachusetts Institute of Technology.

Werfel, Justin, Kirstin Petersen, and Radhika Nagpa. 2014. "Designing Collective Behavior in a Termite-Inspired Robot Construction Team." *Science* 343, 754–58.

Figure 8: The elements from the Blokhut applied in the design for a museum at the Karlsplatz in Vienna.