DISCRETE COMPUTATION FOR ADDITIVE MANUFACTURING

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Large-scale discrete fabrication

The research presented in this paper, based on two projects, investigates design methods for discrete computation and fabrication in additive manufacturing. The first project, *CurVoxels* (Hyunchul Kwon, Amreen Kaleel and Xiaolin Li) introduces a discrete design method to generate complex, non-repetitive toolpaths for spatial 3D printing with industrial robots. The second project, *INT* (Claudia Tanskanen, Zoe Hwee Tan, Xiaolin Yi and Qianyi Li) proposes to make this discrete approach physical, suggesting a fabrication method based on robotic discrete assembly. This discrete design and fabrication framework aligns itself with research into so-called digital materials – material organisations that are physically digital (Gershenfeld et al., 2015). The suggested methods aim to establish highly complex and performative architectural forms without compromising on speed and cost. Both projects propose design and fabrication methods that are non-representational and do not require any form of post-rationalisation to be fabricated. The research argues that, compared to 3D printing, robotic discrete fabrication offers more opportunities in terms of speed, multi-materiality and reversibility. The proposed design methods demonstrate how discrete strategies can create complex, adaptive and structurally intelligent forms. Moreover, by moving computation to physical space, discrete fabrication is able to bridge the representational gap between simulation and fabrication. This representational gap is a result of a two-step process usually associated with computational design strategies, where a design is first developed digitally and then passed on to be fabricated.

Analogue and digital fabrication

The projects described in this paper are produced in a research-through-teaching context within The Bartlett Architectural Design Programme (AD) – Research Cluster 4 (RC4). RC4 is a part of BPro, an umbrella of postgraduate programmes in architectural design at The Bartlett School of Architecture, UCL. The research can be situated in the context of robotic manufacturing and the automation of construction processes. The two projects presented are based on the use of industrial robots, but these are assumed as abstract, notional machines. The projects could potentially be more efficiently implemented with other types of custom-made robots, but the research in question here is first and foremost focused on design methods. Both projects should effectively be understood as research into design methods, rather than as research into robotics and manufacturing itself. In terms of fabrication, both projects are additive fabrication processes: *CurVoxels* (Fig. 2) is a 3D printing process, and *INT* (Fig. 3) is an additive assembly workflow.

There have been significant research efforts into robotics and automated construction, especially in the context of additive processes. Gramazio Kohler has developed additive projects such as *The Programmed Wall* (2006), *Complex Timber Structures* (2013) and *Mesh Mould* (2014). However, these attempts to automate construction have had little impact and are caught in a conflict between complexity and speed (Gershenfeld et al., 2015). Neil Gerschenfeld argues the need for digitising not just the design but also the materials (Gershenfeld et al., 2015). In this context, The Centre for Bits and Atoms has developed the notion of digital materials – parts that have a discrete set of relative positions and orientations

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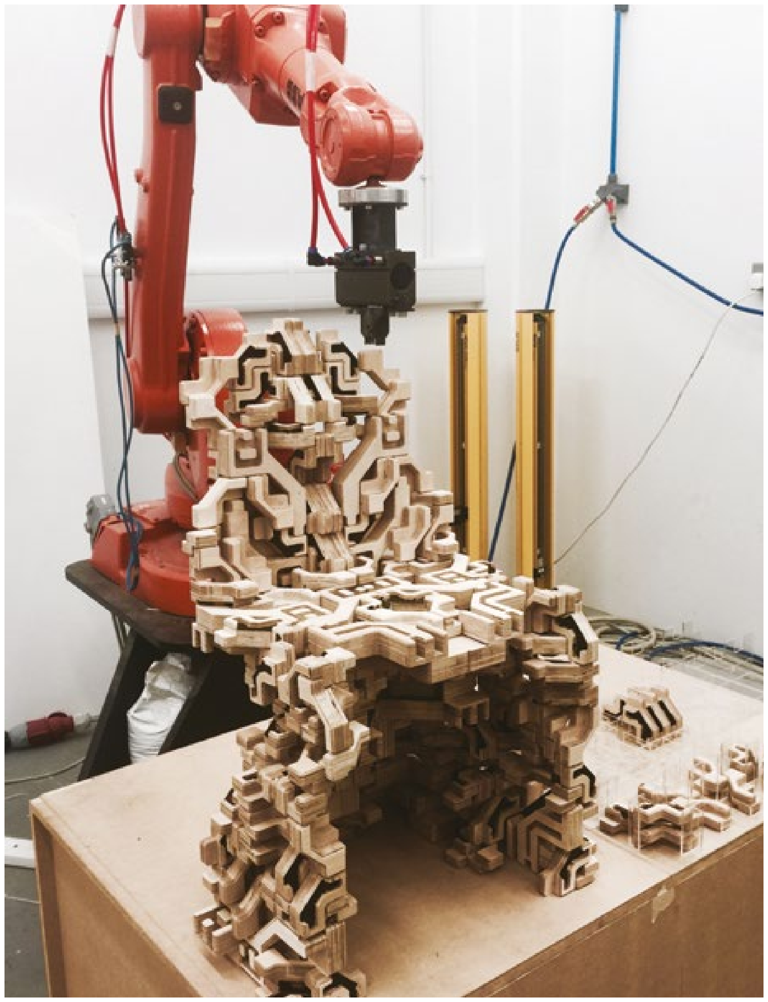

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(Gershenfeld et al., 2015). These materials are able to be assembled quickly into complex and structurally efficient forms. These digital materials establish material organisations that are digital rather than analogue. Following Gershenfeld's distinction between analogue and digital materials, most of Gramazio Kohler's robotic fabrication projects are to be considered analogue. Despite the use of discrete elements for assembly, these elements tend to use analogue connections, which are continuously differentiated. Unlike digital materials, every element has a unique connection possibility, increasing the degrees of freedom and possibilities for error. Continuing from Mario Carpo's distinction between continuous and discrete design processes, the notion that structures can be physically digital, rather than analogue, becomes an important driver for the work presented in this paper (Carpo, 2014). However, as a design method, these digital materials present some fundamental problems. In order to be considered digital, the elements necessarily need to be serialised. As a result, the digital materials proposed by The Centre for Bits and Atoms are highly repetitive and homogenous. From an architectural design point of view, these structures are efficient, but not complex in terms of formal possibilities. A possible solution could come from combinatorial design strategies. Jose Sanchez demonstrates how standardised, serially repeated elements can result in differentiated and complex wholes (Sanchez, 2014).

Towards discreteness

In the first instance, this research is driven by the question of how the notion of discreteness can make the automation of construction processes more efficient while also allowing for more complexity and differentiation. It attempts to combine the efficiencies of digital materials with combinatorial design methods. Secondly, as a broader question, the projects presented develop design methods that remove representation, resulting in structures that are digital both in the design process and as a physical product. The research first introduces discreteness as a design process in the *CurVoxels* project, and subsequently as a fabrication process in *INT*. Both projects can be considered additive manufacturing processes.

More specifically, the *CurVoxels* project questions how discrete computational processes can make spatial printing with robots more effective, while also opening up more formal possibilities. It demonstrates how the serialisation of toolpath segments allows for efficient

1. Digital prototypes of vertical elements, using different arrangements of discrete pieces.

2. *Curvoxels* (RC4 2014-15). Half 3D printed chair v3.0. Image: Curvoxels.

3. *INT* (RC4 2015-16). Robotically assembled chair v2.0. Image: Manuel Jiménez García.

4. *Curvoxels* (RC4 2014-15). Robotic extrusion of ABS filament. Image: Curvoxels.

5. *INT* (RC4 2015-16). Human-robot collaboration for the assembly of chair prototype. Image: INT.

error mitigation and prototyping. The project presents a case for combinatorial design as a method to create structures with a differentiated material distribution, and complex formal articulation that bypasses the repetitive and homogenous grids usually associated with spatial printing (Fig. 4).

The second project, *INT*, explores the implications of physical discreteness and discrete assembly as an alternative, non-continuous method of additive manufacturing. The *INT* project questions the benefits of discrete assembly compared to 3D printing. *INT* sets out a framework for discrete fabrication with combinatorial building blocks, investigating both the design of the units and their assembly procedures. The work experiments with human-robot interaction and questions the consequences of moving computation to physical space. The fabrication procedure proposed by *INT* aims to resolve some of the problems associated with continuous additive manufacturing, such as the lack of speed and mono-materiality (Fig. 5).

CurVoxels and INT

CurVoxels is a team of students in RC4 who developed the project *Spacial Curves* (2014-15). The project is a continuation of research into spatial printing, which started with a previous team of students called *Filamentrics* (2013-14). Spatial printing is now a popular method for robotic printing, but first appeared in the *Mesh Mould* project (GHack, Lauer, Gramazio, Kohler, 2014). The printing process is based on a tool head, mounted on a robot arm, extruding hot plastic along a spatial vector. This method saves a lot of time in comparison to layered methods. Preferably, the robot does not stop during the process, but continuously extrudes material. Robotic spatial printing has a number of limiting constraints, the most important being that the robot can never intersect with previously deposited material. There are also structural constraints: material can only be extruded in the air for a limited range – at some point, support structures are needed. Therefore most spatial printing projects make use of a highly repetitive toolpath organisation, based on parallel contours connected with a triangular toolpath. The formal possibilities are limited, and the toolpath organisation is not very complex.

CurVoxels developed a design method which is aimed at controlling the toolpath constraints and developing new freedoms within these constraints. *CurVoxels*' computational approach is based on discretisation: a voxel space is developed, where every voxel contains a toolpath fragment. It was decided to use a Bézier curve as a unit to compose the toolpath. The team then developed a process that cycles through the voxel space in a layered and linear fashion, simulating the trajectory of the robot. Every time a voxel is accessed, the Bézier curve inside the voxel is rotated to connect to the line in the previous voxel. In principle, there are 24 rotations possible but a number of these are not printable, as the extrusion tool would intersect with the curve. The logic of combining separate toolpath fragments is essentially combinatoric: there is a discrete set of options for how curves can connect without losing continuity. The printing process can be prototyped on a few voxels, rather than having to compute and prototype an entire toolpath. The error space is not continuously differentiated, but discrete and limited. After the toolpath is tested for a single curve-voxel in 24 different rotations, it can be used to assemble thousands of toolpath fragments together into one continuous, kilometres-long, printable line. The size of the voxel itself also introduces a structural parameter: if the voxel is smaller, more material is deposited and the structure becomes denser. If it is bigger, the structure is more porous and less strong. This observation was translated into an OcTree subdivision for the voxels, linked to structural data. In areas that carry more load, voxels are subdivided and more material is deposited. The design method was tested on the generic shape of a panton chair. The shape of the chair itself is not questioned and has to be understood as a generic placeholder, similar to the Stanford bunny or the Utah teapot. In total, three chairs were printed. The last chair, which made use of the OcTree subdivision logic, was strong enough to withstand up to 80kg of load.

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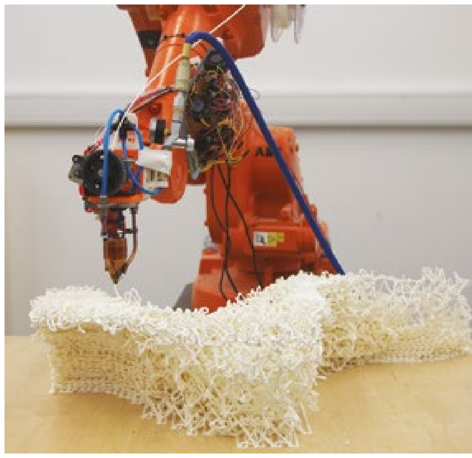

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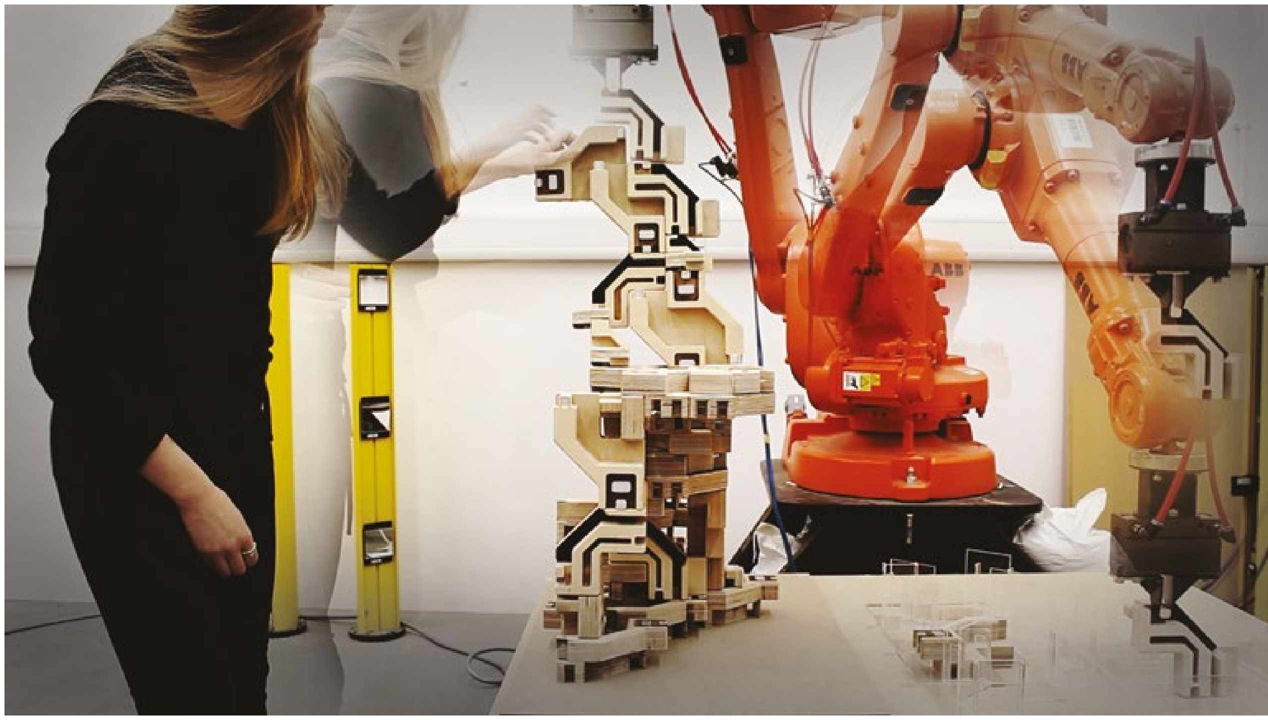
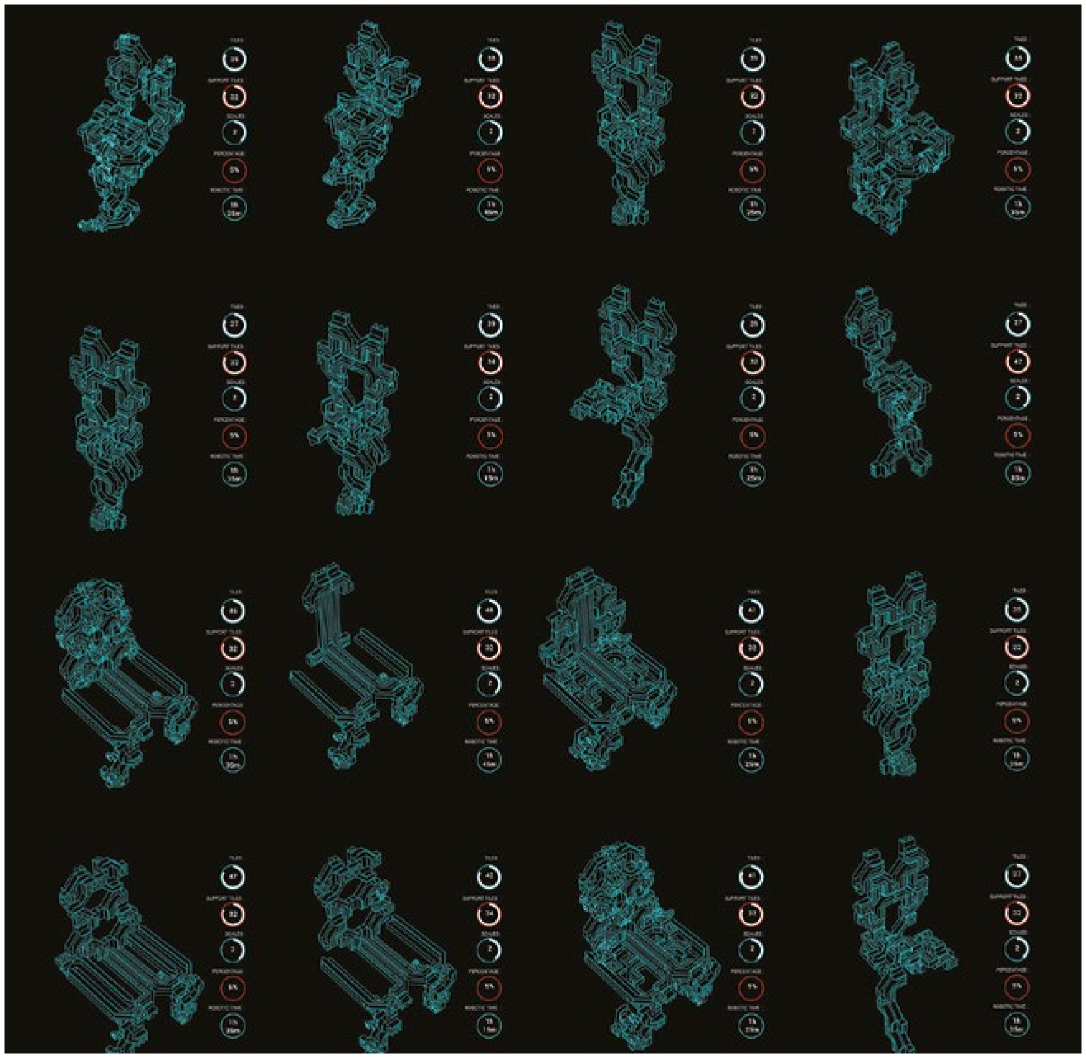


The next project, *INT*, combines discrete design with discrete fabrication. Similar to *CurVoxels*, a combinatorial unit is developed, but this time as a physical building block that can be aggregated and assembled. This unit is able to combine with itself in different ways and can be robotically assembled. Similar to Neil Gershenfeld's digital materials, the unit is serialised and has a discrete set of connection possibilities. The 'digital' building block, or tile, has a geometry which can be inscribed in a voxel space: one L-shaped unit is comprised of three voxels. The tile is further defined by a series of subtractions so that it can be picked up by a gripper tool in different orientations. It is also marked with multiple reflectors that help a camera system to track the elements in physical space. The project is based on multiple scales of CNC-milled timber blocks. The smallest can be gripped at the outside boundary, and the largest from specifically designed gripping spots. A combinatorial logic was developed to combine tiles into structurally stable forms. Different combinations of blocks are structurally evaluated in terms of surface area. In areas of the design that require more strength, combinations with a larger area of shared surface are privileged. The robot is given a specific boundary and total amount of tiles to fabricate a structure. One tile is placed as a start and then, for every robotic action, the position of the next tile is calculated (Fig. 6). Users can intervene in the process by placing tiles themselves. These are tracked by the camera system and evaluated in respect to the other tiles. The robot can then subsequently add new tiles to complete the structure. In case the new tile would, for example, break the boundary of the design, the robot can remove the tile again. The robot is able to address imperfections in the assembly process – for example, if a tile falls off the structure, it can re-evaluate its position and add a new tile. The design process was tested on two different chairs. The first chair is purely a product of automated decisions, without human intervention. The second chair is an authored product, where the students decided to favour symmetry. The fabrication process is significantly faster than for the 3D printed chair, both of *INT*'s chairs being completed in under 45 minutes (Fig. 7).



6

6. *INT* (RC4 2015-16). Catalogue of emergent objects using custom-made applet developed in processing.

7. *INT* (RC4 2015-16). The Bartlett B-Pro Show 2016, physical prototypes. Image: Manuel Jiménez García.

From continuous to discrete

Both projects question established design methods based on discretisation. They capitalise on the efficiencies emerging from that process, and can be considered less representational.

The *CurVoxels* project enables the efficient generation and evaluation of complex toolpaths. After optimising one toolpath fragment in one voxel, an entire structure can be generated without further problems. This serialised approach reduces the amount of unique problems to solve. Toolpaths with continuous formal differentiation, on the other hand, also have to deal with continuously differentiated problems, which all require unique solutions. The proposed combinatorial method, in combination with the OcTree logic, allows for complex differentiation and adaptability to structural criteria. Through embedding a combinatorial logic, the repetitive character commonly associated with digital materials is avoided. Through always combining the initial toolpath unit into different patterns, complex structures with differentiated formal qualities and structural behaviour can be designed. This introduces a fundamental shift away from the paradigm most usually associated with digital design: from mass customisation and continuous differentiation of parts to discrete, serially repeated elements.

The resulting objects are not a result of a post-rationalisation, where a shape would be first designed and then sliced into layered toolpaths for printing. The design method operates directly on the toolpath itself. However, the project does not manage to bridge the gap between design and fabrication. Essentially, the design first has to be generated and then sent off for fabrication. As a consequence, if there is a problem in the fabrication, the entire object has to be printed again. There are significant logistical constraints to the project: multi-materiality is hard to achieve, and the printing time is slow.

On the other hand, the *INT* project allows for the efficient assembly of objects which could potentially be multi-material, while also maintaining a high degree of complexity and heterogeneity. The research establishes structures that are physically digital. It introduces interesting new questions about the potential interaction of robots and humans in the design process. The project could, however, benefit further from more advanced feedback loops between the simulation and the physical assembly. The use of heavy, compression-based material introduces an added difficulty to the assembly process, presenting a whole range of structural problems. More significantly, the project makes use of joints, but in the end relies on a significant amount of glue in order to be assembled. The use of glue prevents the reassembly and reconfigurability promised by the project. The problem with the joint is one of the main limitations of discrete fabrication: the smaller the elements, the more joints are created. Potential solutions could attempt to make the element itself interlocking, but this would inevitably increase the complexity of the robotic assembly process and again severely limit the formal possibilities.

Discrete fabrication

The design methods developed in the *CurVoxels* and *INT* projects have significant implications for additive manufacturing, the automation of construction and architecture. The proposed discrete design methods establish a series of efficiencies while also enabling complex material organisations. The shift from continuous fabrication to discrete fabrication moreover introduces a series of advantages, such as multi-materiality, structural performance, speed and reversibility. The proposed combinatorial method allows for complex differentiation compared to the repetitive character commonly associated with digital materials. Formal differentiation no longer relies on the mass customisation of thousands of different parts, but can be achieved by the recombination of cheap, serialised units (Fig. 1). The use of cheap, prefabricated building blocks, in combination with increased assembly speed, reduced error space and vast formal possibilities, provides a firm ground for additive manufacturing techniques to scale up. From a design point of view, in moving computation to physical space, discrete fabrication is able to bridge the representational gap between simulation and fabrication. Digital data and physical data are aligned. Computation and fabrication can happen in parallel, and design decisions can be made during the fabrication process. This versatility makes the process more robust and adaptable to demanding scenarios such as onsite fabrication.

The potential for reversibility has implications reaching far beyond automated construction. Architectural building elements that are recombinable could significantly change the lifecycle of buildings. The combinatorial aspects can help to introduce complexity and adaptability in prefabricated building systems, without losing the benefits of seriality and standardisation.

References

Dillenburger, B., Hansmeyer, M., 2014, 'Printing Architecture: Castles Made of Sand' in *Fabricate 2014*, Zurich, ETH, p.92–97.

Carpo, M., 2014, 'Breaking the Curve. Big Data and Digital Design' in *Artforum* 52, 6, p.168–173.

Hack, N., Lauer, W., Gramazio, F., Kohler, M., 2014, 'Mesh-Mould' In *AD 229, 84, Made by Robots: Challenging Architecture at a Larger Scale*, p.44-53.

Ward, J., 2010, 'Additive Assembly of Digital Materials', PhD thesis, Massachusetts Institute of Technology.

Gershenfeld, N., Carney, M., Jenett, B., Calisch, S. and Wilson, S., 2015, 'Macrofabrication with Digital Materials: Robotic Assembly' in *Architectural Design*, 85(5), p.122–127, doi: 10.1002/ad.1964.

Sanchez, J., 2014, 'Polyomino – Reconsidering Serial Repetition in Combinatorics' in *ACADIA 14: Design Agency*, 23–25 October 2014, Los Angeles, ACADIA/Riverside Architectural Press, p.91–100.

7