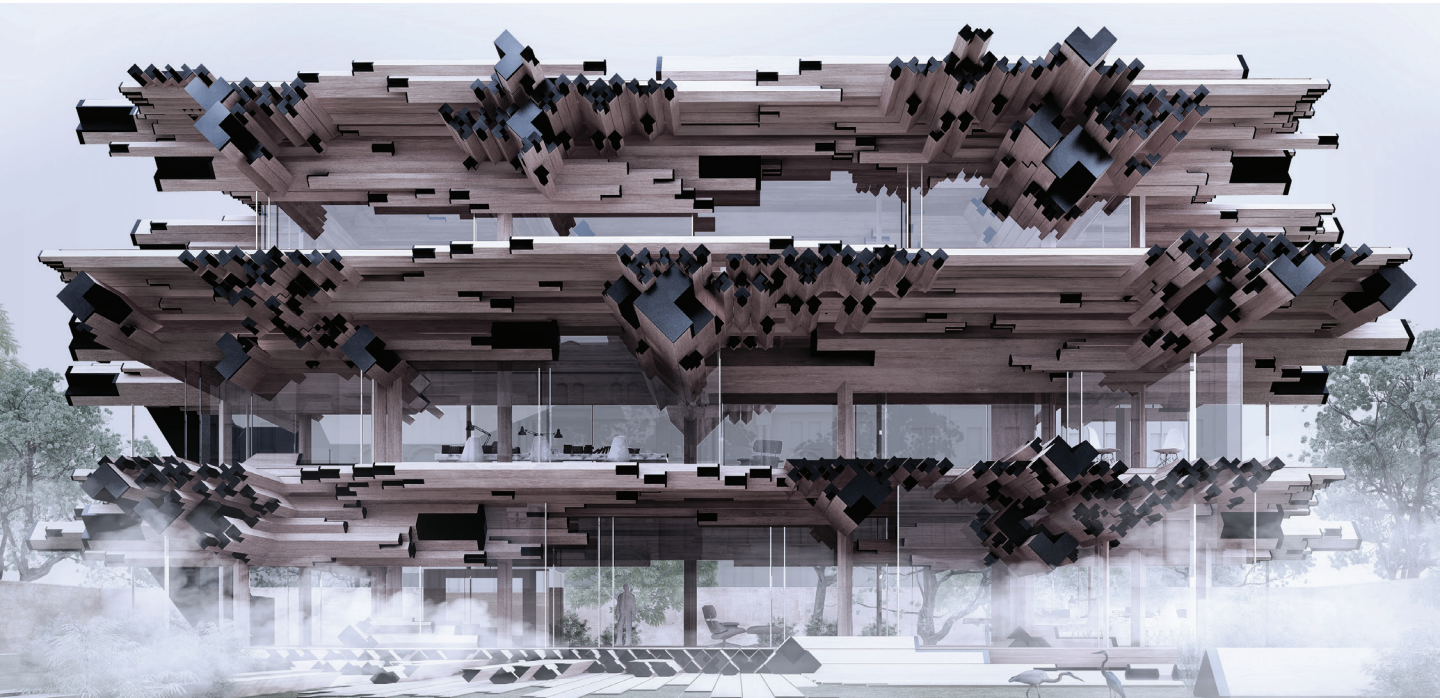# Toward Discrete Architecture: Automation takes Command

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ABSTRACT

This paper describes a framework for discrete computational design and fabrication in the context of automation. Whereas digital design and fabrication are technical notions, automation immediately has societal and political repercussions. Automation relates to industrialization and mechanisation—allowing to historically reconnect the digital while bypassing the post-modern, deconstructivist, or parametric decades. Using a series of built prototypes making use of timber, this paper will describe how the combined technologies of automation and discreteness enable both technical efficiencies and new architectural interest. Both projects are based on timber sheet materials, cut and folded into larger elements that are then assembled into functional structures. Both projects are also fragments of larger housing blocks. Discrete building blocks are presented from a technical perspective as occupying a space in between programmable matter and modular prefabrication. Timber is identified as an ideal material for automated discrete construction. From an architectural perspective, the paper discusses the implications of an architecture based on parts that remain autonomous from the whole.

INTRODUCTION
Post-2008

After dominating the architectural discourse for about a decade, following the 2008 financial crisis, the digital in architecture—or what Mario Carpo refers to as the first digital turn (Carpo 2013)—became associated with troublesome neo-liberal politics and the corresponding lack of social awareness. Architecture schools and important cultural platforms such as the Venice Biennale curbed the digital enthusiasm of the past decade. A number of articles and books such as *The Politics of Parametricism* (Poole and Shvartzberg 2015) and *The Architecture of Neoliberalism* (Spencer 2016) problematised the work of the digital protagonists of the '90s in a social and political context. Confirming what was previously only a suggested, Patrik Schumacher among others, came out as ultra-libertarian free market advocate (Schumacher 2018).

Simultaneous with this polemic, Mario Carpo's 2014 article "Breaking the Curve," revealed some of the inner contradictions of the paradigm of continuity that had emerged from the past two decades of digital research. Carpo outlined that the continuous, spline-based work has little in common with today's computation itself, which is essentially a discrete process (Carpo 2014). A new generation of architects started to criticise the accepted notion of digital production as a form of mass-customisation of curved form, such as EZCT with the Generative Chair and Universal House (Morel 2011). Other architects, such as Jose Sanchez, began to advocate an agenda that has a certain social consciousness, attempting to democratise the process of design while also criticising the starchitect driven model with its doubtful labour practices (Sanchez 2018). Mollie Claypool continues this criticism with a connection to automation and feminism (Claypool 2019).

The notion of the Discrete brought together a new generation of architects and theorists who are interested in the digital but also advocate for a critical and politically aware agenda. The Discrete became a way to kick-start a new architectural project interested in the digital, while taking a distance from the legacy of the parametric and current trends such as the post-digital (Claypool 2019).

Disrupting Construction

The notion of automation is becoming increasingly important in the building industry and the built environment at large. This is timely, as the productivity of the construction industry has essentially not increased since the end of the Second World War (McKinsey 2017). The construction industry is one of the last to be "disrupted," which means that currently a lot of venture capital is channeled in
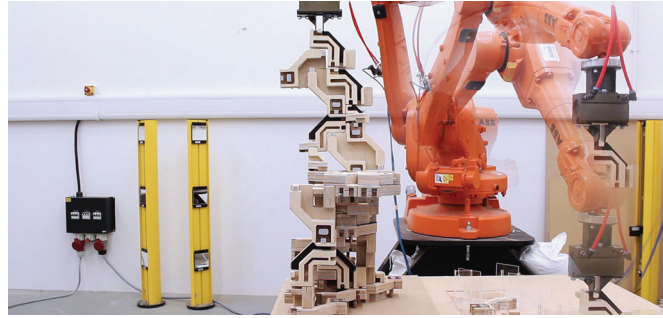

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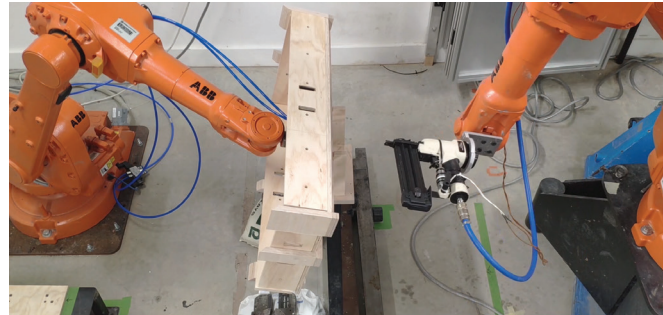
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2 UCL Design Computation Lab, INT: Robotically Assembled Chair using discrete building blocks (2015)

3 UCL Design Computation Lab, ALIS: Fully automated assembly of Building blocks (2019)

4 UCL Design Computation Lab, Ivo Tedbury: Semblr, discrete robotic assembly of tiber building blocks (2016)

5 UCL Design Computation Lab, Pizzabot: assembler and assembled material share the same body (2018)
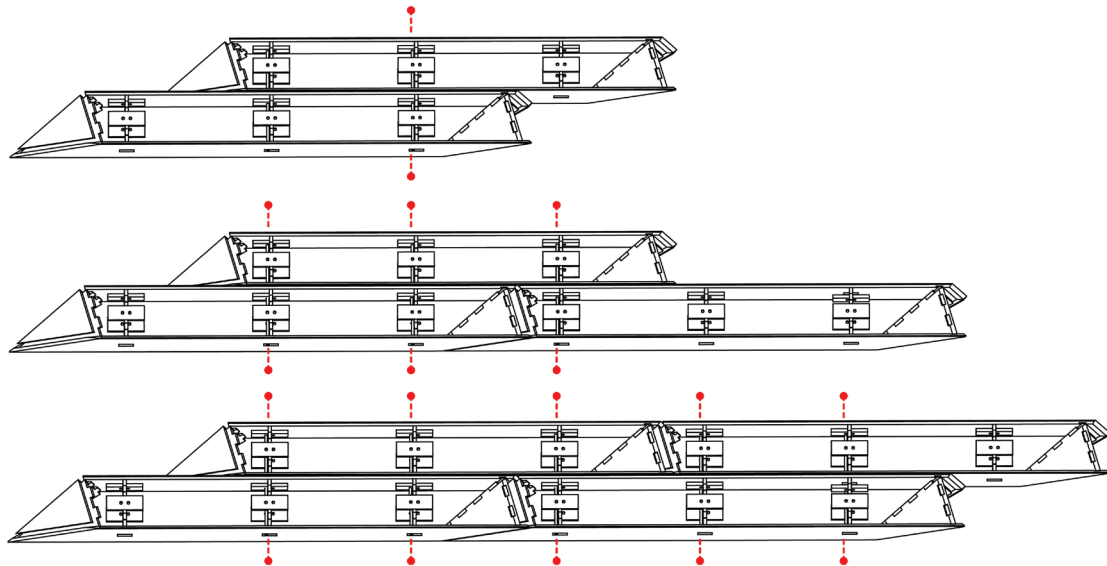
startups promising a future share of the market. Wework has become the biggest office owner in London. AirBnB has already deeply impacted many cities, but is now also seeking to design and build its own housing with project Samara. Katerra has received significant amounts of funding with its promise to overhaul timber construction through vertically integrating the entire production chain. Alphabet's Sidewalk Labs is set to develop Toronto's Eastern Waterfront in return for data.

The narrow focus of the digital in architecture on form and style, has not been able to react to—or understand—this change. Efforts with robotics in architecture are generally still driven by a search for complex form and variability, inherited from the last two decades of continuity and parametrics.

This paper proposes an alternative approach where we move on from the notion of "digital fabrication" to the wider notion of automation. The term automation inevitably connects to a series of deeper political and societal issues, forcing one to take a position. It's a term that relates to some of the biggest challenges we see in society today, alongside the global climate crisis (Claypool, Retsin et al. 2019). Moreover, the notion of automation establishes a historical continuity with modernism, which was grafted on "mechanisation" (Gideon 1948). In doing so, digital experimentation bypasses the "post-something" theorems (PostModernism, Deconstructivism, Parametrics) and again advocates for the digital as having more possibilities than just seeking for variability and difference (which ultimately is a still a mere reaction to modernist homogeneity). As

a historic parallel with the modernists and mechanisation, automation can drive an ambitious architectural project with a radical social, aesthetic, and spatial agenda. Discreteness plays a key technical role in automation, enabling both fast assembly and complexity (Gerschenfeld et al. 2015). Besides these technical concerns, the Discrete has far-reaching architectural ambitions, exploring the myriad implications and consequences of an architecture based on autonomous parts, rather than super-imposing whole.

Prefabrication and Programmable Matter

This work on discrete building blocks and robotics relates to Hod Lipson's Programmable Matter research, MIT's CIAL modular robotics, and the Digital Material Research at the Centre for Bits and Atoms, with projects such as Flexural Materials by Kenneth Cheung, or Bill-E by Benjamin Jennett. The Harvard Wyss Institute's work on the TERMES project is another reference, where a distributed robot assembles serialised building blocks. While these examples are mainly situated in the fields of mechanical engineering, the research agenda and projects in this paper attempt to define large-scale functional architectural parts that share some of the properties of the generally small-scale digital materials or programmable matter building blocks. In scaling up these systems, not all properties need to be kept, while also new constraints are imposed. The principles of programmable and digital materials are combined with existing knowledge of prefabrication, modular construction, and design for manufacturing and assembly (DfMa) in the building construction.
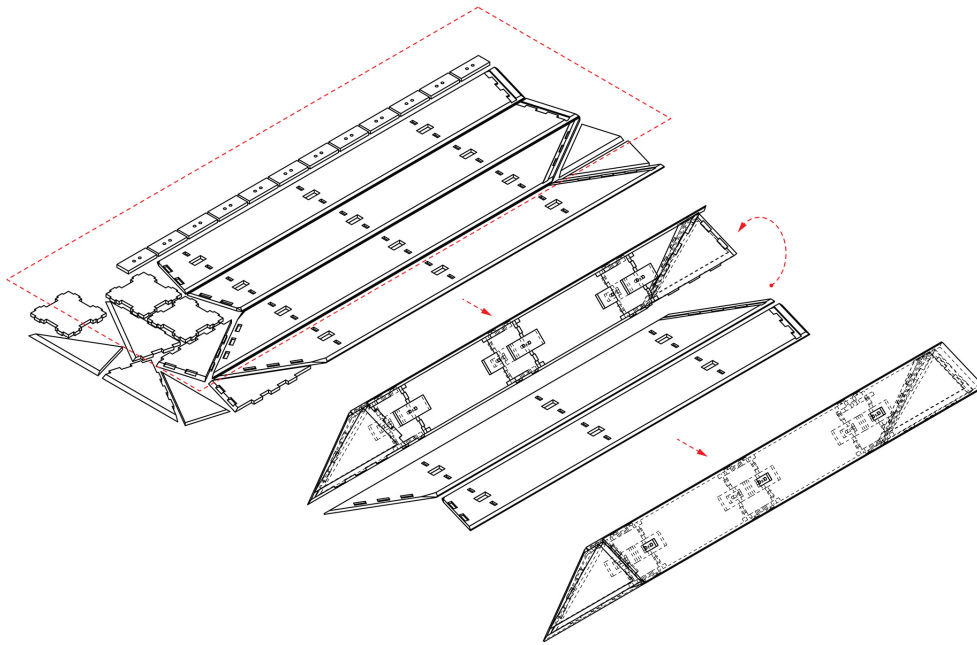
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Digital Discrete

Two built installations explore this framework of automa-
tion and discreteness. The start for these projects is a
series of architectural designs by the author, most notably
the one for the Diamonds House (2015), a commissioned
project for a multi-family home in Belgium (Figure 1). This
project makes use of straight and L-shaped blocks with
three different hierarchies, assembled together to form a
functional structure.

More speculative research-through-teaching—with the
Design Computation Lab in the B-Pro M.Arch AD program
at the Bartlett School of Architecture—focused on the
potential for robotic automation of these discrete building
elements. The project INT (Claudia Tanskanen, Zoe Hwee
Tan, Xiaolin Yin, and Qianyi Li) looked at human-robot
collaboration, where timber elements are assembled
by an industrial robotic arm and tracked with a camera.
(Retsin, Jimenez-Garcia 2017) (Figure 2). While this
project delivered interesting results in terms of interac-
tion, it did not question the material system and tectonic
of the building elements. Semblr, a project developed by
Ivo Tedbury, proposes a distributed robot that assembles
discrete timber building blocks (Figure 4). The building
blocks are used as an environment for the robot to operate
in. Similarly, the project PizzaBot (Mengyu Huang, Dafni
Katrakalidi, Martha Masli, Man Nguyen, Wenji Zhang) made
use of a distributed, discrete robot that has the same
anatomy as the building block itself—a simple square box,
constructed out of timber sheet materials (Figure 5).

METHODS

Discrete Computation

The Tallinn Architecture Biennale (TAB) installation is
the first 1:1 scale, large prototype of the digital-discrete
discourse. It was designed as a case-study, a Domino-
like abstract model of a larger, scalable, and repeatable
construction system for housing. Therefore, the starting
point of the project was the design of a large-scale housing
block (Figure 10), from which the installation was later
extracted (Figure 11).

There are a number of Discrete Design Methods, one
commonly used starts from a voxel-space where every
voxel contains a generic part that can be combined in
different orientations, in respect to its neighbours and/
or data that is embedded in the voxel space itself (Retsin,
Jimenez-Garcia 2017). The parts in the voxel can be
exchanged for other types dependent on the neighbours,
etc. Other methods are graph-based and start from the
part and its inherent connection possibilities. In this case,
specific patterns can be developed beforehand, which can
then be applied and evaluated with either brute force or
more advanced learning principles.

Building Blocks

The design of the building blocks is based on off-standard
sheets of 18mm exterior plywood (3.3 x 1.35m dimensions)
which were locally available. Using a CNC-machine, each
sheet is cut into a series of parts, which can then be assem-
bled into a stiff building block, capable of bearing structural
loads (Figure 6). These building blocks are prefabricated
and then assembled one by one on the site. The geometry

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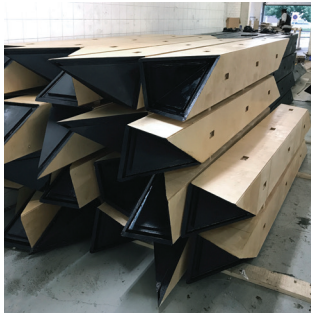
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8   On-site assembly of the TAB installation; the LEGO®-like characteristics
    of the building blocks enabled a fast assembly process with a small team

9   Stack of assembled building blocks; the modular connections are visible
    on the side faces of the elements

10 The installation was extracted from an initial large-scale housing block
    and is in itself not a whole, but a mere abstract fragment

11 View of the finalised installation on site

and dimensions of the part are derived from the dimensions of the sheet and the grid defined by the overarching housing block. The part is defined as box-beam, with the sides of the block carrying the loads while internal frames stiffen out the box. These frames coincide with lateral threaded rods that run across multiple elements and compress the parts together. Every stiffening frame has a position for two rods, so these can cross in two different directions if necessary. The stiffening frames and rods establish modular connectivity across the different parts. Parts can only be connected laterally, and not head to head through the male and female connections. The male-female

connection act merely as a geometric guide and set out the tolerance in the structure.

To establish stiff structures the elements have to be staggered, much like a brick pattern (Figure 7). Depending on the required span and the corresponding amount of force, more elements can be added in the staggered pattern to increase the section. To be able to transfer the loads from horizontal planes to vertical planes, a corner element is developed. The total family of parts, therefore, consists of a straight, 45 degrees, 90 degrees, and 135 degrees elements.

A second project at the Royal Academy in London builds upon the same design methods developed for the TAB Installation. Rather than a frame-like typology, it's based on a more vertical column-slab organisation. In this case, the design is derived from the original Diamonds House project, mentioned earlier in the paper (Figures 13-14). The definition of the elements was slightly changed, these are now conceived as an internal cross-shaped frame of 12mm plywood, wrapped with a light 9mm skin. While both installations make use of a family parts, including straight and L-Shaped elements, two later installations built at Tongji University in Shanghai (2019) make use of only one repeating part.

REFLECTION
Robots and Labour
While this research is set in a framework of automation, controversially, no actual robots have been used in both projects. The cutting is done with a CNC machine, but prefabrication and on-site assembly is still done manually. The prefabrication of timber building blocks from CNC'd parts is more labour intensive than their on-site assembly, but also easier to automate. This stage is set in a factory-environment and is based on highly repetitive operations and relatively light and simple parts. Project ALIS, current research in the Design Computation Lab looks into robots assembling simple plywood box elements, which is a process already used in industry to assemble for example pallets (Figure 3).

The assembly on-site, with human labour, was quick and straightforward for both projects (Figure 8). Some of the digital material-like properties, such as the seriality of the elements and their limited connection possibilities clearly enabled a quick, LEGO®-like assembly process. These properties reduce the amount of human labour required on site, as opposed to the labour intensive assembly of mass-customised forms. Skylar Tibbits has referred to this as the "assembly problem," when it is quick to cut thousands

of unique components, but it takes weeks or months of manual labour to assemble (Tibbits 2017). However, the on-site assembly of these elements is much more difficult to automate, as we are dealing with much heavier and larger elements. The discrete parts have a low tolerance, which is in conflict with the unstructured environment.

Resolution and Scale

To remove more human labour from the workflow, two main strategies can be identified. One option is to work with the previously mentioned distributed robots, which pick and place the elements. However, this would require either much smaller and lighter elements or much heavier robots—both problematic scenarios. Heavier robots are exponentially more expensive and difficult to build. Smaller elements would imply a much longer assembly time and more robots on-site. Moreover, the accumulation of joints between the elements becomes problematic for structural reasons. Neil Gerschenfeld et al. have argued that the bene-fits of these systems in extreme scenarios, such as large landscape features like flood barriers, or extra-terrestrial construction. In these scenarios robotic assembly of digital materials is more feasible than conventional assembly with human labour (Gerschenfeld et al. 2015).

However, the most pragmatic and immediate option to increase assembly speed and reduce human labour on site would be to increase the size of the parts and work with a simple crane for assembly. One of the installations in Tongji University makes use of extra-large parts with a 40cm cross section. The inherent benefits of building is
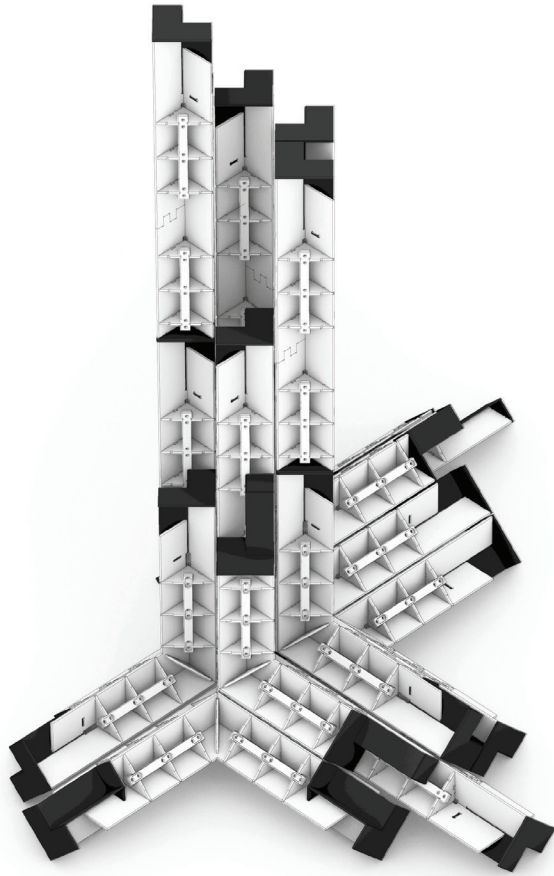
clear: the cost, weight, and labour ratio per cubic meter is substantially lower than with smaller parts. Moreover, the reduction of joints reduces the structural challenges and increases the control over tolerances.

Recent work from the office, such as the Nuremberg Concert Hall proposal with Stephan Markus Albrecht, favours this scenario (Figure 15). In this case, elements are based on up to 9m long CLT sheets (Figures 16-18). The existing production line for CLT is already relatively automated. The subsequent automated cutting of sheets is as well available in the industry. The repetitive pre-assembly of parts into building blocks could as well be automated in a structured factory environment.

Therefore, it can be argued that to reduce human labour on- and off-site, the most pragmatic strategy for most of the everyday building stock is to use larger parts and automated prefabrication. This approach to automa-tion is along the lines of a Design for Manufacturing and Assembly workflow, but removes the emphasis on formal differentiation and mass-customisation of parts, instead favouring seriality and modularity with a computational understanding of parts. At the same time, differentiation can be accommodated for at no extra cost on-site by merely varying the organisation of the parts.

Incremental Variation

Of course the debate is here whether the Discrete doesn't lend itself better to pre-cast concrete elements, rather than CNC-milled timber. Aren't we misusing the CNC as a

12 Build-up of a an assembly for the Royal Academy Installation, showing the underlying modular connectivity of stiffening frames

13 Installation at the Royal Academy in London (2019); this installation is in direct relation to the Diamonds House project

14 Installation at the Royal Academy in London (2019)

more along a multitude of buildings, or along the city. This understanding therefore shifts the notion of time within digital fabrication, from the immediate internal differentiation of a one-off building to the longer term differentiation of a multiplicity of buildings.

Within a single building, differentiation can be easily achieved through the organisation of repeating parts, rather than through the customisation of parts. Across multiple buildings, different families of parts and approaches can easily be used. This is a short and agile production method, all together very different from the modernist cookie-cutter precast concrete industry.

It is worth to note that there is a historic precedent for this notion of incremental difference. Pre-Modern cities are based on serial repetition with difference emerging from minor changes in the organisation of parts rather than in the form of the building as a whole. From a social and political perspective, every citizen has in principle the same right to the same accommodation, while remaining individual through the subtle change in part organisation. This is dialectically opposed today's neo-liberal city where every building is different, for reasons of branding and marketing. In this model of neo-liberal difference, the citizen is reduced to a consumer and housing an investment stock. This then results in a city of extreme difference, or ironically what free-market advocate Schumacher calls "garbage-spill urbanism" (Schumacher 2013). Since the demise of social democracy and modernism by Reagan and Thatcher, the subsequent Post-Modernisms (historical or parametric) cater to and implicate the architect in this neo-liberal desire for marketable variability and difference.

computer controlled tool when we cut hundreds of identical elements? In automation, the CNC is primarily considered as a machine to replace human labour rather than to achieve formal difference and variability for the sake of it (Noble 1984). As Kiel Moe puts it, "[t]he history of Numerical Control is a history of a technique that is used most effectively to regularize, routinize, and quantify that which otherwise is qualitative" (Moe 2006). Digital machines can therefore also be understood as machines that can create incremental difference, project by project rather than creating difference within one project. For example, a CNC could cut 100 times one serially repeated part for one building, but without any changes in the factory setup, cut another 100 times a different serially repeated type of part for another building. Moreover, one factory could work on multiple different parts for different projects at the same time. The architectural argument here is that differentiation is not necessarily so important within a single building, but

The Automated Forest
The choice of timber for discrete building elements has some other advantages. The plywood installations discussed, can be considered as scalable. As demonstrated by the Nuremberg Concert Hall proposal, the parts could be produced at much larger scales using CLT sheets. Importantly, the use of timber puts into question the notion of material optimisation, which is one of the most commonly used conceptual arguments in digital design. Rather than minimising material to reduce cost, cost is minimised by reducing human labour and machine time. It is more cost and time efficient to use more of the same parts rather than optimising and customising every and each part to save material.

It has to be noted that this is in fact already the reality of the building industry today—it's more efficient to waste material than labour. While this may be problematic for concrete,

given the climate crisis, ironically, wasting timber is actually beneficial for the planet. The more timber we use, the more CO_2 is extracted from the atmosphere and the more we need to reforest. For example, in the past decades, Sweden has more than doubled its total area of forest to answer the demands of the timber and paper industry. Whereas in modernism, the rationality was to try to express thinness and become immaterial, this discrete timber architecture does the opposite. In light of sustainability and the climate crisis, architecture becomes chunky and fat, storing CO_2 in its body while creating thermal mass to isolate and store heat.

Architectural Consequences

This fully automated architecture, with its reduced parts, materials, and production chain can be understood as monolithic. Rather than the 7000 different parts and processes that on average make up a building, we now have only a few. However, this is an assembled monolith, a contradiction in terms, but with radical properties. To understand these, we first need to look at the status of the discrete parts itself. The discrete building block is situated somewhere in between a particle and a building element. A particle is an almost immaterial bit, so small that is hierarchically completely subjected to the whole. Think of a particle of sand in relation to a sand-dune. It matters, but it makes more sense to understand the sand-dune on the level of a field of forces rather than at the level of the particle of dust. A building element on the other hand is

what we perhaps associate most clearly with modernism: a single element optimised to perform a specific function within an assembly.

Just as the particle, the digital discrete part has no predefined function or role. However, it is not subjected to overall form or singular function either. It remains independent of the architectural whole. It is only after it is combined together with other elements that it establishes functional features and properties. The part is, therefore, agnostic to architectural function.

There is no longer an overarching super-form that defines the position of the parts. The parts maintain their auto-nomy and effectively diffuse the architectural whole. The resulting architectural syntax is no longer familiar with the Corbusian Domino: there are no longer columns, floor-plates, or beams as such.

It's also helpful to make the comparison with bricks, which are essentially also discrete parts before they are combined together with mortar. However, a brick is not a discrete building block as described in this paper. It can only act in conjunction with an already pre-established formal whole. To span a space, it needs to be organised in a vaulted form. When forming a wall, it can not cantilever. Its position is always derived from the whole, and therefore, always establishes an architecture of continuity. Without mortar or continuous form, a brick is just a piece of fired

clay—not an architectural building block or autonomous part, independent of the whole. Discrete parts can be programmed with specific properties, while bricks can not. While discrete building blocks can therefore also scale, the scale of a brick is fixed.

Breaking the modernist form-function logic, which resulted in a hierarchical assembly of fixed architectural types, this discrete architecture is now almost organic: one element and its properties define everything. As the discrete part is universal and versatile, it appears in every instance. This ironically establishes what the digital work of the '90s was after: a space that is phenomenologically continuous.

CONCLUSION
Robots and Labour
This paper has outlined a framework for automation and discreteness and explored the deep architectural consequences of this shift. The built timber installations reveal a changing attitude towards digital design and fabrication, coming from an engagement with automation and discreteness. Architects have previously considered robotics as a project with an interest in craft, curvature, and formal differentiation inherited from parametrics and continuity. This paper has outlined how these inherited tropes, with their consequences, such as material optimisation, variability, and mass-customisation, are put into question once we consider automation as the framework.

The installations and projects discussed reveal a new notion of the architectural part as a discrete building block, which combines Programmable Matter thinking with Prefabrication and Design for Manufacturing and Assembly workflows. This combination reveals promising advantages, both in terms of efficiency and automation, but also architecturally. A radically new type of architecture, with its own syntax and unique qualities emerges, breaking both with the modernist precedent and the paradigm of parametric continuity. The built installations discussed in this paper are situated in continuous dialogue with larger projects and demonstrate the scalability of this method in the immediate here and now.

While these paper is initially mainly concerned with issues of production and architecture, it currently only hints at the much larger social consequences related to automation. As a next step, the most important questions relate to digital economy—the structures of property, the logistics of ownership and occupation. The digital economy is, without any doubt, where processes of automation are most intensively reconfiguring our lives and cities, while it is also the area that architects have least engaged with. However, the research into a disruption of production and architecture itself is fundamental to this shift and not additional. While this paper explores the technical and architectural implication of Discreteness and Automation, further development will attempt to identify which types of platforms are best suited to organise its deployment into the world.

ACKNOWLEDGEMENTS

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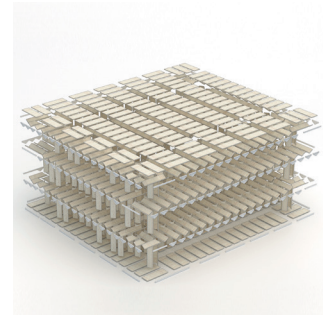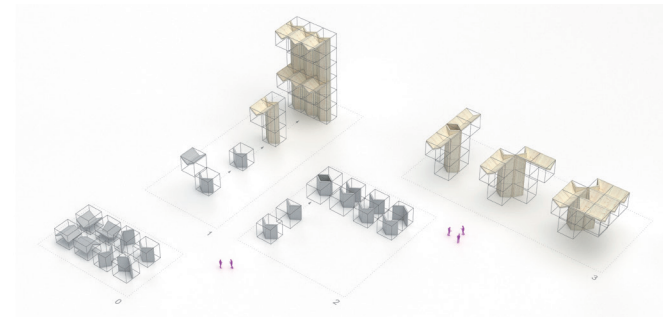
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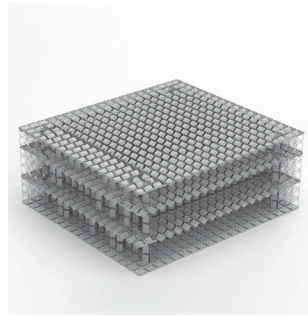
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IMAGE CREDITS

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