DISCRETE TIMBER ASSEMBLY

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Digital Materials

Using a number of built demonstrators, this paper describes a computational design and fabrication method for timber assembly, based on the notion of discreteness. This research attempts to combine aspects of the field of Digital Materials and Programmable Matter with the architectural field of Prefabrication and Modularity. While these two fields are at opposing ends of the spectrum in terms of scale and functional operation, this research proposes that many of the properties and challenges are transferable.

Neil Gerschenfeld and the Centre for Bits and Atoms at MIT have developed the notion of 'Digital' Materials, which can be understood as an approach to Programmable Matter. Programmable Matter is a wider field that straddles robotics, computer science, material science and engineering, and focuses on the creation of materials whose properties can be adapted and coded (Gerschenfeld et al., 2015). This includes MetaMaterials, certain Soft Robotics, Self-Assembly and Self-Reconfiguring Modular Robotics.

Digital materials can be precisely defined as a discrete set of parts, which are reversibly joined with a discrete set of relative positions and orientations (Cheung, 2012). These can then be assembled into larger scale wholes with functional performance, such as robots, aeroplanes or infrastructure. Gerschenfeld proposes that 'digital fabrication' is a process that compiles these discrete building blocks, whereas analogue fabrication is based on continuous subtraction or deposition of matter. For example, 3D printing and robotic milling are considered analogue fabrication methods.

Some of the challenges digital materials attempt to tackle in robotics and mechanical engineering are highly relevant to architecture and construction. Digital Materials and Programmable Matter aim to automatically or autonomously manufacture functional machines or infrastructures from smaller base units. Architecture in its most basic sense attempts the same: assembling functional buildings from smaller parts. However, programmable matter is more focused on the active and immediate performance of a whole, its mechanical operation. In architecture, the functionality is concerned with change over a long period of time. Adaptability, assembly and disassembly are processes taking place over weeks, months or years, rather than seconds. Primarily, the transferable aspects from programmable matter and digital materials are a short and integrated production

chain, the potential for automation and the concept of limited modular parts establishing vast variation, complexity, versatility, adaptation and re-assembly over time.

Programmable Matter and Modularity

Digital materials attempt to overcome the discontinuity present in analogue fabrication where unrelated processes have to be combined. These result in expensive, time-inefficient and inflexible production chains, where every machine needs its own customised fabrication process (Langford, 2019). Just like robotics and manufacturing, architecture and construction suffers from a similar analogue syntax with resulting discontinuities, unrelated processes and errors. On average, buildings are composed of over 7000 different parts and processes which need to be assembled together into a functional whole. This makes construction slow, expensive and difficult to automate. To achieve full automation, every part and process would need its own unique species of robot.

In a context of increasing cost of labour and decreasing robot cost, this so called 'Automation Gap' (Claypool, 2019) leads to an ever-decreasing productivity in construction. The construction industry has flat-lined since 1947, whereas manufacturing has radically increased its productivity through higher degrees of automation (McKinsey, 2017). As building is slow and expensive, only a limited number of actors can take the risk to construct. This in turn keeps the market limited and scarce in supply of housing and puts the decision-making of housing construction in the hands of the few – government and large developers. Cooperative efforts to construct housing have proven difficult to scale, again partially as a result of complicated construction and procurement.

In response to the housing crisis and flat-lined productivity, there is a renewed interest in Modularity and Prefabrication as an alternative. For example, Design for Manufacturing and Assembly (DfMA) and modular timber construction aim to take as much labour off site as possible. However, these approaches can't radically improve productivity as the production chain is still discontinuous, analogue and difficult to automate. Moreover, the associated business model is reactive and service-based. Modules are one-offs that have to be redesigned for every site and every project.

An approach based on a digital understanding of parts and assembly offers a promising alternative. The work of Alfred Bemis and Leonardo Mosso present a historic precedent of a voxel-based architecture (Botazzi, 2018), as well as Frank Lloyd Wright's Textile Block houses. More contemporary, Philippe Morel (EZCT) developed the Universal House as a discrete voxel-based building system (Morel, 2011), while Jose Sanchez' Polyomino project proposed discrete building blocks as platforms for collaborative design (Sanchez, 2018). The interest in this approach is reinforced by the theoretical and historical work on Discreteness and Computation by Mario Carpo (Carpo, 2014).

Digital Modularity

This research attempts to transfer some of the core-concepts of 'digital materials' to architectural modularity, establishing a short, integrated, continuous production chain based on generic, serialised versatile building blocks cut from two-dimensional sheet materials, with limited connection possibilities and passive error correction. These building blocks are function-agnostic – function is only established after assembly. The parts therefore exist independent of an actual building and should be able to construct a complex variety of outcomes. This idea is often compared to molecular biology, where all of life is assembled from just 20 standardised amino acids as modular building blocks (Langford, 2019).

The notion of digital fabrication is then redefined as the assembly or compilation of these building blocks into a functional structure. An example of an actual 'digital' fabrication method could be, for example, Jonathan Hiller's and Hod Lipson's proposal for 3D-Voxel Printing, where physical voxels are defined as 'physical, self-aligning, fundamental units' (Hiller and Lipson, 2009) that are assembled by a printer. Can the construction of buildings become like an additive manufacturing process, based on the continuous assembly of discrete parts? This process allows for a high degree of automation, both in the prefabrication of the parts and in the assembly of the parts into buildings.

This research further questions a cost-effective, scalable method of production, the scale of the building blocks themselves and the amount of variation within sets of elements. The large-scale, 1:1 prototypes aim to test the use of two-dimensional base material, limited connection possibilities, repeating units which are invariant to rotation, complexity and variability from repeating units, structural capabilities, tension joints and the potential for automation.

Tallinn Architecture Biennale Installation

The question of an organic assembly of serialised, digital-material like hollow timber building blocks was first framed with the Diamonds House, a 2015 project for a multi-family dwelling in Belgium by Gilles Retsin Architecture (Fig. 3). In collaboration with the UCL Design Computation Lab

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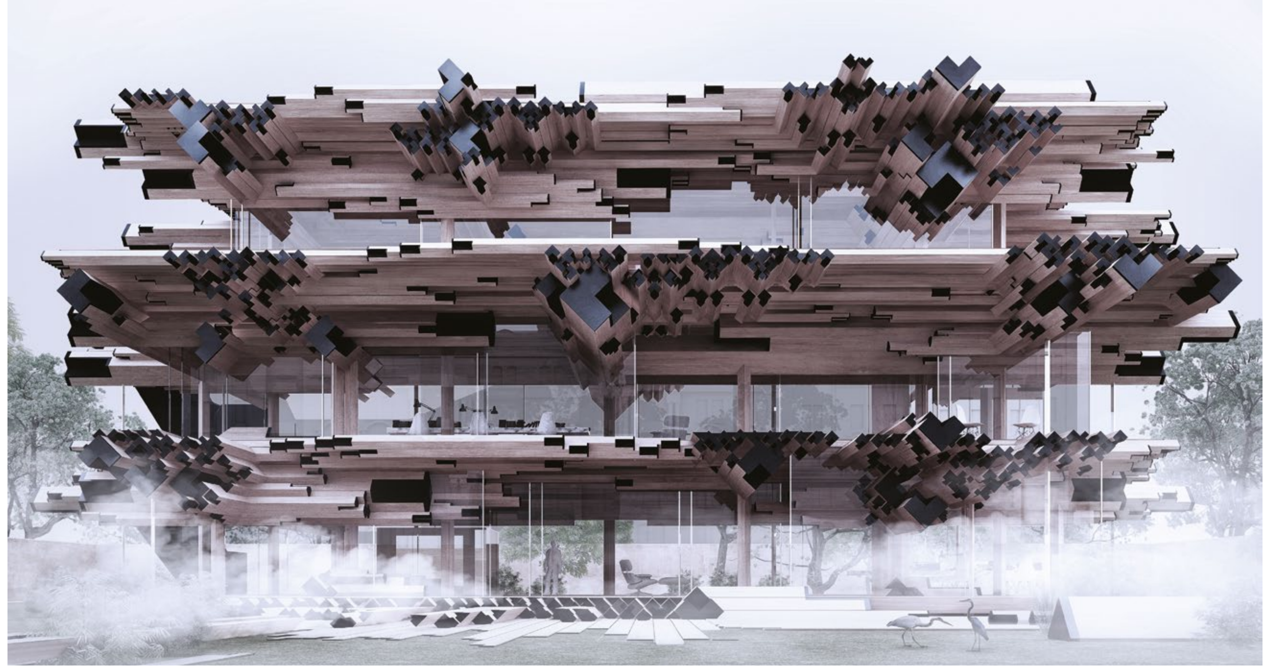
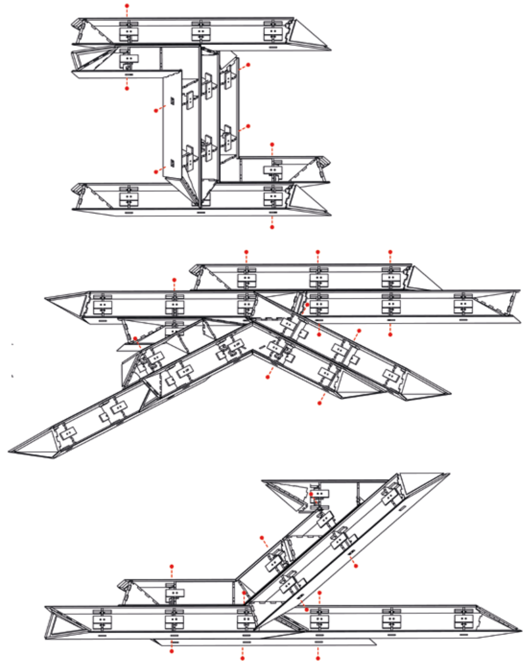


1 & 2. Gilles Retsin, Tallinn Architecture Biennale Pavilion, 2017. Photo: NAARO.

3. Gilles Retsin, Diamonds House, Belgium, 2015.



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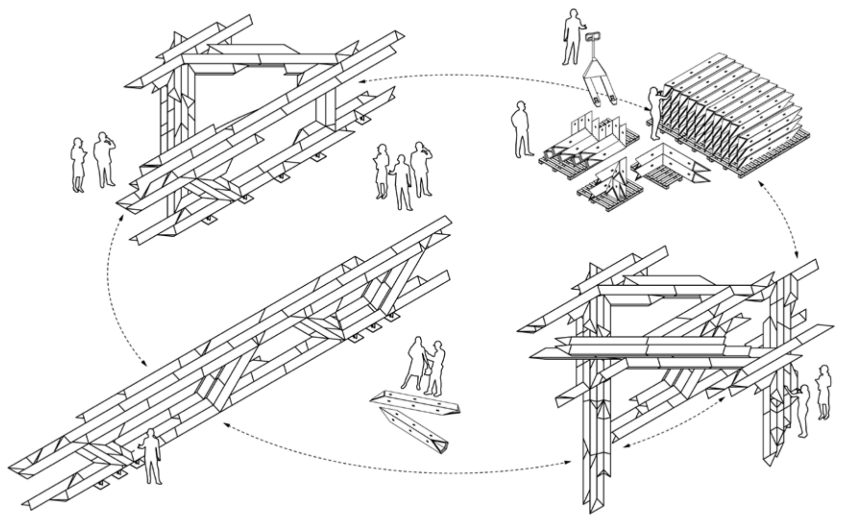

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(DCL), an installation for the Tallinn Architecture Biennale (TAB) in 2017 formed the opportunity to prototype and test this idea on a 1:1 scale. The installation is a fragment of an abstract larger housing block, a fragment of which was then selected and further detailed (Figs 1, 2).

A family of discrete building blocks was developed: a straight element, a 90˚ corner element, a 45˚ corner element and its inverse, a 135-degree corner element. The straight element's proportions are derived from one sheet of exterior plywood (3300 x 1350 x 18mm). All toolpaths were designed assuming a simple 3-axis CNC machine, using a standard and 45˚ drill bit. The toolpath was kept as simple as possible, to allow for quick cutting. The decision was made to avoid any visible finger joints or notches, details typical for CNC plywood projects. While there are internal notches, the sides of the elements are cut under 45˚ and connected with PVA glue and a series of 30mm nails. The part is designed as a box beam-like element, consistent of a skin and three interior frames to stiffen the box. The interior frames are notched in the skin and hold a small plate with two 14mm-diameter circular openings. These function as inserts for mild steel threaded rods (M10), which connect the parts laterally. The rods are fixed with polymer-insert lock nuts, to resist turning which could result from vibrations during the assembly. The internal stiffening frame coincides with the position of the rods, forming a continuous stiffening frame throughout multiple elements. These stiffening frames set out the modular rhythm and limited connection possibilities for the building blocks. The overall tolerance for the installation is defined by the 4mm difference between the circular opening for the steel rods and the rod diameter. A 36mm-thick shear-key element is inserted in the opening left for the rods, preventing lateral movement between building blocks.

The male-female endings of the building blocks have no mechanical connectivity, but together with the tension rods and stiffening frames allow for passive error correction throughout the installation. Moreover, by alternating the orientation of the 45˚ element, a substantial amount of geometric interlocking is achieved. The different corner elements follow a similar build-up, but also incorporate an additional internal stiffening frame, a continuous piece of plywood orientated in the long direction of the part. This frame allows load-paths to shift and establishes structural continuity (Fig. 4).

All elements are flip-invariant and appear multiple times in different load cases and positions throughout the installation. By staggering and overlapping the parts, the combination of steel rods and shear keys combines the initially discrete building elements in a continuous monolithic structure.

4 & 5. Gilles Retsin, Tallinn Architecture Biennale Pavilion, 2017.

6. Gilles Retsin, Tallinn Architecture Biennale Pavilion, 2017. Photo: NAARO.

7. Gilles Retsin, *Real Virtuality*, Royal Academy of Arts, 2019.

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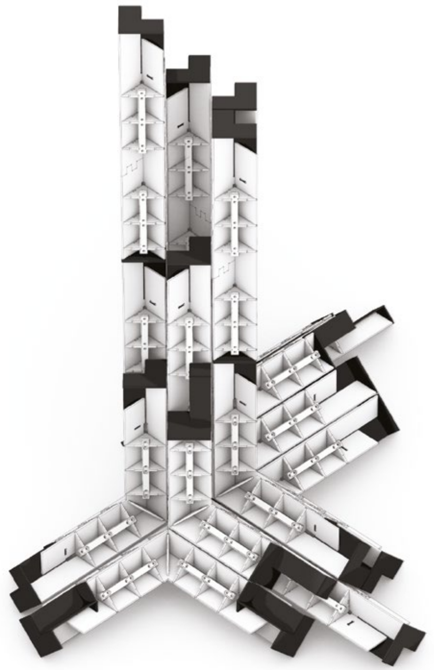

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Cost-efficiency, variation and complexity

The TAB installation negotiates the challenges of building complex, variegated large-scale structures out of serialised, function-agnostic, discrete building blocks. It presents a method for building discrete parts from a single, two-dimensional base material, using only one machine. The installation suffered minimal deflections and deformations and was completed with an overall tolerance of 4mm along a maximum length of 12.5m. Large cantilevers of up to 4.5m were achieved, without notable deflection (Fig. 6). The biggest difference with digital materials is that the elements are not regular, space-filling polyhedra or sphere as in most examples of digital materials, but are asymmetrical. The decision for a beam-like element has certain advantages on a large, architectural scale: it allows for staggering and overlapping and it reduces the number of joints.

The seriality of the elements and their properties of self-alignment and error correction allowed for a quick and efficient assembly, with only a small crew of four people in a space of five days – including site-preparation and finishing. Automation of on-site assembly is a long-term possibility, but doesn't appear as an absolute necessity. If the scale of the parts is large enough, pre-assembly with a simple crane could be more efficient. The seriality also enabled adaptation on site.

It was decided to deviate from the design model and move one element on site to reinforce a cantilever which displayed deflection.

Another installation at the Royal Academy (2019) questions the structural topology of the building block and the amount of material required (Fig. 8). Parts are designed as a 12mm plywood internal stiffening frame in three directions, connected to a light external skin of 9mm plywood (Fig. 7). This significantly reduced the weight of the elements. A Hololens was used to stream instructions to the build crew, further reducing the assembly time.

In both cases, the lack of mechanical connection in the male and female endings of the elements is problematic and ultimately resulted in the need for the additional corner-elements to transfer forces between different planes. While the corner elements are efficient and of architectural interest, they do complicate the process. A subsequent installation developed for Tongji University in Shanghai (2019) introduces this connection, reducing the total number of elements to just one. If only one element is used, it's worth investing in robotically pre-fabricating the part.

This was tested with the project ALIS, developed in the context of the Architectural Design MArch (B-Pro) Programme at The Bartlett School of Architecture with

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8. Gilles Retsin, *Real Virtuality*, Royal Academy of Arts, 2019. Photo: NAARO.

Master's students Joana Correia, Evgenia Krassakopoulou, Akhmet Khakimov, Kevin Saey and Estefania Barrios. Two industrial robots were used to pre-assemble a box-like element. The robots pick and place pre-cut material from a pre-cut stack of components and assemble these on a central pedestal using a nail gun. This process could be further improved with the use of press-fit joints, as demonstrated by the research of Christopher Robeller et al. (2017).

Towards discrete automation

This research reveals a new notion of the architectural part as a discrete building block, combining aspects of digital material and programmable matter with architectural prefabrication and modularity. Discrete timber assembly offers multiple potential answers to falling construction productivity, the housing crisis and global climate crisis.

Once discretised, construction is more integrated and assembly becomes a continuous and organic process, similar to additive manufacturing. The part hierarchies and types commonly associated with assembly disappear. Physical and digital reality overlaps completely, there is no more representational gap between both. What is computed is what is assembled, and what is assembled in return computes. This method therefore enables increased automation of construction, requiring potentially no minimal handling off site and only minimal manual handling on site.

By using timber, we make optimal use of large-scale industry for the fabrication of sheets and localised, small-scale manufacturing for the customisation and assembly of building elements and buildings. Each building could be assembled differently, to a granular level, without increasing the production chain. This can happen at no extra cost, as the customised placement of elements is merely an informational task. Compared to modernist and current modular prefabrication, the function-agnostic, serialised parts demonstrate increased variability, versatility. This short production chain, only based on sheet-materials, is in turn agile and easy to customise to different building blocks. It does not propose a centrally controlled, universal, objective building block as a single solution.

The small-scale infrastructure needed to construct building blocks and assemble buildings could make construction more accessible, faster and therefore less capital intensive, opening the market to a larger group of house-builders. Housing could be assembled, disassembled and adapted much faster, which in turn puts into question modes of ownership, forms of domesticity and procurement. The possibility to disassemble, moreover, has important ecological implications, where building blocks can be continuously recycled into other buildings.

As a further outlook, building blocks could become 'smart bricks', integrating mechanical functionality such as the transfer of heat, air, water or electricity. These could then be continuously assembled into fully-functional buildings. Mechanical functionality then becomes emergent and decentralised. Ultimately, the aspects presented here are the easiest part of construction, most labour is consumed on the fit-out of technical devices. However, it's with this initial abstraction that automation begins. Without first redefining the syntax of how we build, any attempt to automate is futile.

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